Graz University of Technology
Institute of Highway Engineering and Transport Planning

Dynamics of Travel Demand Growth in Indian Cities with Limited Data Resources

DISSERTATION

Submitted by
Dipl.-Ing. Alexander Moser-Parapatits

under supervision of
Univ. Prof. Dr. Ing. Martin Fellendorf
Graz University of Technology
Institute of Highway Engineering and Transport Planning

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"In the field of transportation research nothing is more valuable, yet simultaneously more limiting in the validation of theory and models than are data. In many applications, it is the constraints of time and cost that limit our ability to gather the data needed in research. In emerging research areas, however, the critical question is precisely what sort of data are necessary in developing and testing theory and models. This is perhaps most relevant in the study of travel behavior." [McNally, 2000, p.60]

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The thesis in hand was produced as a student at the Doctoral School of Civil Engineering Sciences at the Graz University of Technology. During my time as a researcher at the Institute of Transport Planning and Highway Engineering, I also held a position as an analyst at the industrial research partner Magna International, Inc.

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Alexander Moser-Parapatits

Executive Summary

India has experienced rapid urbanization and economic growth in the last decades. Mobility and private vehicle ownership increased significantly, resulting in traffic congestion, deteriorated air quality and reduced road safety in many Indian cities today. These developments are expected to continue in the future, confronting municipalities with the great challenge to satisfy an ever-growing demand with adequate transport infrastructures. In order to formulate effective strategies, urban planning bodies require a versatile toolset to evaluate the implications of policy options in a holistic way.

State-of-the-art travel demand models are a powerful decision support tool and have been set up for a larger number of cities in the last years. With them, data on urban mobility in India has become available, too. However, these models do not capture how the urban transport system, particularly travel demand, evolves over time. In contrast to the situation in Europe and North America, for which these models have originally been designed, urban growth in India happens at an exponential rate and in a comparatively short period of time. This thesis investigates the system dynamics and the associated feedback structures in different scenarios. For this purpose, we develop the "*Dynamic Urban Transport Model for India*" (DUTM-i), which is based on *System Dynamics*, a modeling framework particularly useful to investigate temporal behavior of systems both qualitatively and by means of computer simulation. We build on data extracted from the Comprehensive Mobility Plans (CMP), which have been prepared for cities across the country and are based on common guidelines devised by the central government of India, which makes the results comparable to each other. In this research project, data availability was identified as a key constraint to the modeling process. Many of the CMP models were not fully documented or found to be in the hands of private third-party consultants, which made it difficult to access the primary data sets and build a richer model.

The DUTM-i is designed to make use of public CMP data and equip decision makers with an easy-to-use tool to analyze the dynamic implications of policy options. The DUTM-i should, thus, be viewed complementary to CMP models: it offers a high-level simulation of travel demand and supply equilibrium over a long period of time. For the purpose of this study, we selected six cities, which vary in population, geographic location, and urban form. For each of them, we build a base scenario, which simulates unconstrained road travel demand growth. The simulation results confirm our first hypothesis that available infrastructures will not be able to absorb this demand in the future. We, therefore, close the open-loop baseline with three feedback scenarios typically observed in case of traffic congestion and significant travel time losses.

First, we investigate mode shift to public transport as a means to balance road travel demand and supply at acceptable levels. This is particularly interesting, because mass transit networks (e.g. metro systems) need significant lead time for planning and construction before they can become fully operational. The DUTM-i gives urban planners a valuable indication, whether the time horizons for major projects are sufficient or if they need to be finalized more quickly. Second, we look at reduced vehicle ownership. Generally, this feedback is weaker as car ownership is considered a status symbol for the aspiring urban middle-class in India. From our simulations, reduced ownership growth does not solve the congestion problem, but slows the dynamics down. Finally, we assess the policy of road building, which has been the preferred strategy, for example, in Delhi. Our simulations clearly confirm the second hypothesis that road network expansion alone is not effective to mitigate congestion, because it only offers short-term relief and leads to even more traffic in the long run.

The trend scenarios combine all of these feedbacks. We find that for five study cities, significant investments in public transport are needed and some kind of vehicle ownership control is highly advisable. Construction efforts should focus on a capable road network with ring roads distributing the traffic flows around the densely populated urban cores. In direct comparison, we find that large metropolitan areas need to devise their strategies faster than medium-sized cities. What is more, not all cities will need high-capacity mass transit (i.e. metro systems), because they are able to absorb a higher share of private vehicle trips.

We conclude our analysis with a review of alternative transportation concepts and their ability to contribute to the urban transport challenge in India. Particularly car- and ride-sharing services have the opportunity to take a relevant share in the future modal split. Summoned under the term "Intermediary Public Transport", very similar services are already available in Indian cities today, but they are viewed as unsafe and uncomfortable. Mobile devices, smart software applications, and better vehicle offerings could be an attractive, space- and cost-efficient alternative to driving and searching for parking spaces with a privately owned car.

The DUTM-i is a core model for travel demand growth dynamics in India and may be extended in different ways. A stochastic mode choice model can be integrated in the model framework and would further enhance the explanatory power of the DUTM-i. Furthermore, the exploration of feedback between congestion and economic development or population growth would be interesting to improve cost-utility calculations for investments in urban transport infrastructures and to ensure the competitiveness of Indian cities in the long-term.

For public bodies, this study offers relevant findings for future policies. We confirmed that urban space is the key restraint for travel demand growth in Indian cities. But more importantly, we can show in the different scenarios that building new roads cannot solve the problem. From a system perspective, mode shift is the most powerful lever to manage expected travel demand efficiently in the future. This typically involves both push (e.g. parking charges) and pull (e.g. public transport offering) measures to be taken and requires a strategic approach to transport and land use planning. Unifying competencies in a single transport authority and providing for sufficient funding are two further critical success factors in this context. A shift away from private motorization also offers big opportunities for the private sector. Innovative mobility concepts, such as car and ride sharing have a greater chance of becoming a viable business, as the main barrier for mass adoption is typically the convenience and low cost of vehicle ownership. Restricting private vehicle traffic opens the space for new transport solutions. India, with its strong background in the global Information Technology (IT) industry, is also well positioned to take advantage of Intelligent Transport Systems (ITS) that help to smartly manage traffic in the city. Enabling infrastructures are not paved roads, but high-speed (mobile) telecommunication networks and smart software solutions.

India, similar to China, is in the unique position to avoid the mistakes from the past and shape the future of urban mobility. The simulation results presented in this study point at the major fields of action and contribute to the discussion with a dynamic perspective on the urban transport challenge in India.

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Abbreviations

ABM	Activity-based Models
ATL	Average Trip Length
BAU	Business-as-usual
BRT	Bus Rapid Transit
CAGR	Compound Annual Growth Rate
CDP	City Development Plan
CLD	Causal Loop Diagram
CMP	Comprehensive Mobility Plan
CNG	Compressed Natural Gas
CTS	Comprehensive Transportation Study
CTTS	Comprehensive Traffic and Transportation Strategy
DUTM-i	Dynamic Urban Transport Model for India
FSM	Four-step Model
GDP	Gross Domestic Product
GIS	Geographical Information Systems
GoI	Government of India
IPT	Intermediary Public Transport
ITS	Intelligent Transport Systems
JNNURM	Jawarhalal Nehru National Urban Renewal Mission
LOS	Level of Service
LRT	Light Rail Transit
LUTI	Land Use Transport Interaction (Models)
MNL	Multi-nomial Logit (Model)
MoRTH	Ministry of Road Transport and Highways
MoUD	Ministry of Urban Development
MTR	Motorized Trip Rate
NAPCC	National Action Plan on Climate Change
NMT	Non-motorized Transport
NUTP	National Urban Transport Policy
OECD	Organization for Economic Co-operation and Development
PCTR	Per-capita Trip Rate
PCU	Passenger Car Unit
PT	Public Transport
SD	System Dynamics
SP	Stated Preference

STC	State Transport Corporations
TW	Two-Wheelers
UN	United Nations
V/C Ratio	Volume/Capacity Ratio
WHO	World Health Organization
WUP	World Urbanization Prospects

1 Introduction

1.1 Motivation

The world has been undergoing fundamental changes in the last decades. The traditional industrial nations are challenged by emerging countries, of which India and China are the largest and expected to be driving the global economic growth in the future. Cities, the centers of commerce and trade, are at the forefront of this transition and projected to attract millions of people seeking job opportunities and higher incomes. Urbanization, albeit being a global phenomenon, is of particular relevance for these emerging countries: the scale is unprecedented in India, where nearly 400 million new urban residents are expected to accrue by 2050, surpassing China in terms of incremental growth rates in 2025. City governments in India are challenged to provide adequate infrastructures for the needs of their residents. Already today, many cities lack of these infrastructures and are confronted with deteriorating standards of living.

On the other hand, economic development leads to rising household incomes and an expansion of the domestic consumer base. Research by Dargay, Gately and Summer [Dargay et al., 2007] suggests that this implies a significant increase of vehicle ownership levels for the future. Transport is a key area for offering a livable and functional city. Urbanization and economic development urge city authorities to come up with smart and innovative solutions in order to cope with higher demand and find adequate planning tools to assess the impact of different policy interventions. Existing studies make use of macroscopic transport models (predominantly the four-step algorithm) to estimate transport demand, but this approach is limited in two way: first, the model is static; it calculates an equilibrium state under given boundary conditions, but does not account for their dynamic interactions over time in projections and is susceptible to errors in the input data set. Future scenarios require a detailed description of land use, available infrastructure and mobility patterns, in order to obtain good results. However, most of these factors are actually highly uncertain in the local context. Second, the model is limited to transport-related input variables. Socio-economic changes, which have an effect on these model variables, are not explicitly included in the model. A more flexible modeling approach is required to improve the planning process and narrow down the scenario funnel. Policies found to be effective on this level, can then be assessed in more detail in traditional models.

1.2 Objective and Scientific Questions to be Answered

In this thesis, a quantitative computer simulation model is proposed to investigate urban mobility in selected Indian cities between 2001 and 2031 to answer the following scientific questions:

- What are the implications of urbanization and economic development for the transport system in cities – notably travel demand and vehicle ownership?
- What are the key target conflicts for urban mobility and what are the opportunities and limitations of existing technologies or regulatory measures to solve them adequately?

With this model, we provide a high-level representation of urban travel demand growth in Indian cities and introduce dynamic feedback to investigate short- and long-term effects in defined policy scenarios. By this, we are able to generate a deeper understanding of the dynamics in the urban mobility system and can critically review proposed solutions in the available planning documents and alternatives to them.

For the purpose of this study, six example cities of different population size, geographic location and wealth (measured in average household income level) were analyzed in more detail. The models are calibrated using data from previous transport studies. Assumptions for the presented scenarios are based on individual city plans, and statistics from international organizations in the respective time-frame. For each of the cities, different scenarios are presented in more detail. The base scenario looks at the implications of unlimited growth in private motorization and minimal policy intervention. The alternative scenarios investigate the effectiveness of three defined feedback structures to reduce road traffic and their impact to public transport capacities necessary to satisfy the demand shift. The trend scenario combines these feedbacks and includes soft assumptions, (e.g. minimum vehicle ownership per capita), which should be considered to obtain realistic results.

Within these scenarios more detailed problems should be covered. In particular,

- What policy instruments are feasible for planning authorities?
- What are the limits to road travel demand growth?
- What are the necessary public transport infrastructures?

Our model approach allows us to answer these questions based on data and transparent assumptions, thereby contributing to the discussion on the future of transportation in India.

The objective is to introduce a generic framework that can easily be adapted to different cities in India. Compared to conventional macroscopic transport models, the requirements for input data are significantly lowered, without compromising the advantages of quantitative modeling over qualitative scenario techniques. The core model simulates increasing road travel demand driven by a growing population, higher vehicle ownership, and the limits to this growth, particularly scarcity of urban (road) space. This core model is embedded in the specific boundary conditions of the city: spatial properties, available infrastructure and planned measures. Feedback loops capture the temporal dynamics resulting from the interaction of supply and demand. Strategies presented in the planning documents are discussed qualitatively against the simulation results, in particular, their sustainability beyond the simulated time-frame.

1.3 Scope of Research

1.3.1 Content

This thesis has the objective to provide a modeling framework to holistically analyze urban mobility and capture dynamic behavior of the transport system on an aggregate level. The model can be utilized to reveal the trends of motorized transport modes in urban areas in terms of expected modal shares and vehicle kilometers travelled under different scenario assumptions. The model does not represent the network level, and therefore, cannot give any indications on local congestion problems or effects of particular road construction projects. It refers to a qualitative model of urban transport dynamics found in literature and was adapted to the Indian context. Furthermore, data was collected manually from transport studies of the investigated cities in order to set up a functional (quantitative) computer simulation model.

1.3.2 Time Frame

For all investigated cities, the analysis spans over a 30 year time frame. We start in 2001 because Census of India was conducted in this year and provides useful reference data for the initial values of the model. It ends in 2031 because the available transport studies and city planning documents do not provide forecasts beyond this year. As detailed time-series data for urban development in India does not currently exist, the model can only be calibrated with data from these two points in time, complemented by the year the reference study was carried out.

1.3.3 Space

The analysis in this thesis covers six selected cities in India (Bangalore, Chandigarh, Delhi, Hyderabad, Indore, Jaipur). The spatial boundaries are defined on a per-city basis and align with the respective transport study or city planning document available. The cities vary in geographic location and population size in order to reflect the urban heterogeneity in India.

1.3.4 Model

The urban transport model introduced in this thesis links the key driving forces for growing (road) transport demand – population growth and rising income – with local constraints (infrastructure, legislation) and exposes their mutual interaction over a longer period of time for Indian cities. For this, a system dynamics (SD) model is proposed, as the methodology allows for flexibility and scalability in formulation over the simulated time-period. Compared to existing travel demand forecasting models, the SD framework is simpler and aims to identify trends, instead of representing future demand on the network level. The objective is to make travel demand growth drivers explicit in the model (output). In the case of India, urban population growth and rising incomes have a significant impact on vehicle ownership levels. In the state-of-the-art approach, the growth functions are derived from econometric analysis, isolated from one another. In different scenarios, options on the supply side are then simulated and analyzed. However, balancing feedback structures might come into effect at a different point in time. Furthermore, the growth scenarios itself are subject to uncertainty in India. Our model provides an easy-to-use tool to test and simulate a number of different scenarios quickly and present the findings to decision makers in an intuitive way. It does not substitute macroscopic modeling, but offers a powerful complement to explore the system response to demand growth and narrow down the scenario space for more detailed analysis.

1.4 Structure of the Thesis

The thesis is composed of three sections. The first section elaborates on urbanization in India and characteristics of their mobility systems based on a comprehensive analysis of previous transport studies. Challenges and opportunities for public and private stakeholders in the Indian mobility sector are presented, as well as key transport indicators compared among cities across the country. This analysis includes a literature review on the theoretical background of transport modeling and forecasting, as well as previously existing system dynamics applications in transportation research.

Following the analysis, section two describes in detail the Dynamic Urban Transport Model for India (DUTM-i), its structure and the causal relationships. The feedback structures of urban transport systems are discussed in more detail, as well as the integrated sub-models which form the functional relationships between the model variables.

Section three presents the selected study cities and the simulation runs from the different scenarios. This is complemented by a cross-city analysis to identify common challenges and differences between them.

Finally, the implications for urban mobility in India in 2031 and the corresponding transportation solutions are discussed in more detail on a qualitative level. The study ends with a summary and outlook for future research activities in this field.

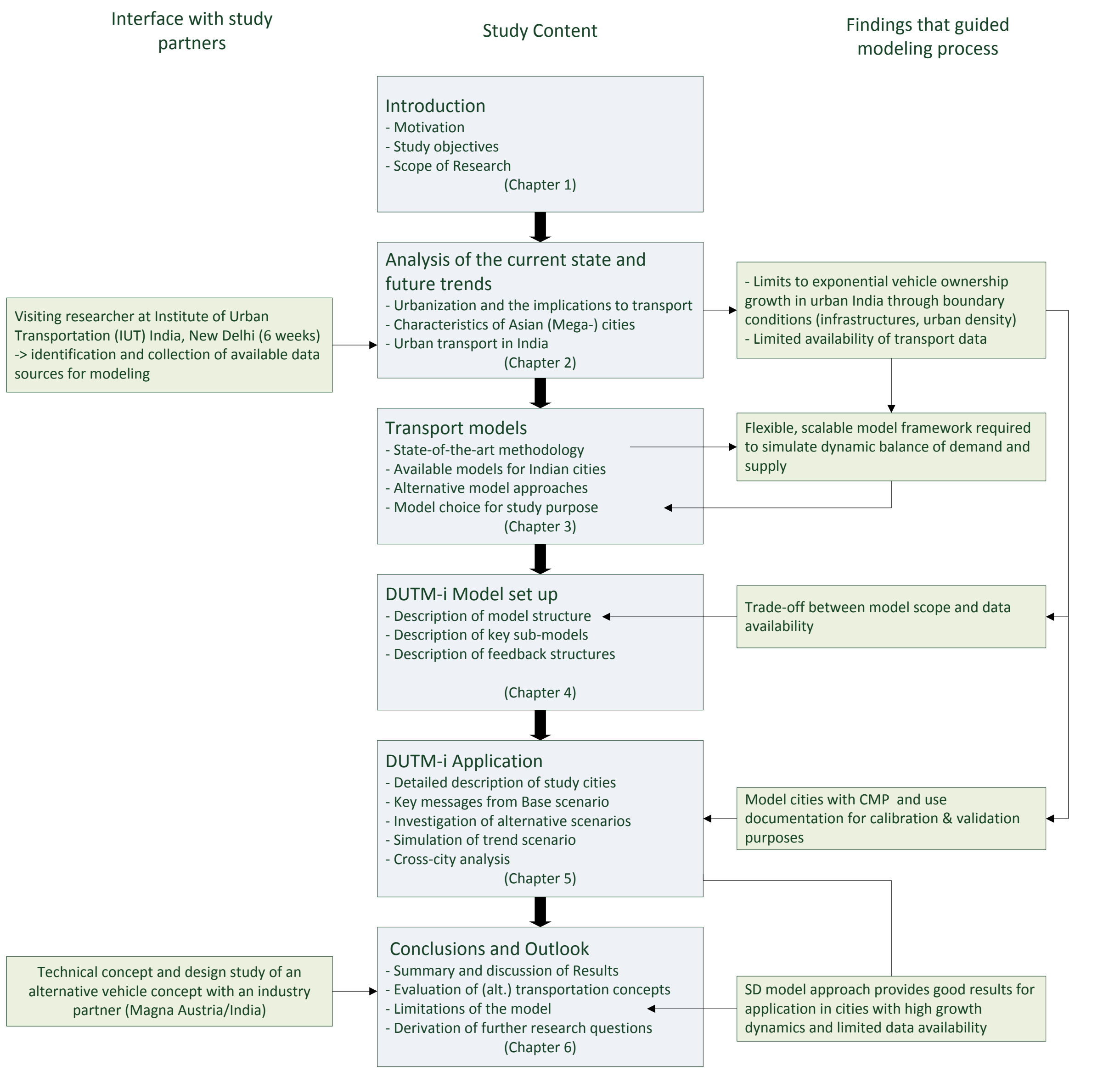


Figure 1: Structure of the thesis

2 Megatrend Urbanization: the Case for India

The demographic shift of a primarily rural to an urban population can be observed throughout history. Cities have been the cultural, political and economic centers for many ancient civilizations and continue to maintain their importance for humanity today. Generally speaking, urbanization describes the increasing share of the world's population living in cities, but the phenomenon expands well beyond the movement of people alone. It changes the way people live their life and what resources are required to provide for a good standard of living. In the case of transportation, the separation of office and home location creates a demand for daily commute, which is not there for self-sufficient farmers and, hence, generates a need for an appropriate transport system that is able to satisfy this demand. Reasons for urbanization are manifold, but particularly for developing and emerging countries, the hope for prosperity is the main motivation for the rural population to move to cities. Where sufficient opportunities for jobseekers cannot be provided, slums come into existence, leading to social tensions as a result of the imbalances in income distributions.

The following chapter gives a more precise definition of the term urbanization. It presents the projections from international organizations on a global scale and specifically for India. This is followed by a brief historic review of industrialized nations that have already undergone demographic change, a discussion that countries like India could learn from and why simply copying their strategies will not be sufficient. In addition, the chapter provides a comprehensive overview on the current status and anticipated challenges of urban mobility in 25 Indian cities.

2.1 Definition of Urbanization

In the literature for urban development, the term "urbanization" is used ubiquitously, but actually lacks a clear definition of what this comprises. In his work on the political economy of urbanization, Roberts [in: Drakakis-Smith, 2011, p.7] specifies urbanization as follows:

> *"Urbanization in its most formal sense merely constitutes the increase of the urban population as compared with the rural one, but it includes and results from far-reaching economic transformations on the national and international plane."*

This definition reflects two dimensions of urbanization: one formal, relating to the demographic aspect and a second, wider definition of the related large-scale socio-economic transition. Still, certain aspects remain unclear. First and foremost: what "urban" exactly is?

In the Demographic Yearbook published by the United Nations Department of Economic and Social Affairs [United Nations, 2005], the definitions presented by the different national statistics offices reveal that there is no global standard for "urban". A common approach is to take administrative units or easily measurable properties, such as minimum population size and density, or a certain share of non-agricultural workers in total employment. In the case of India, both approaches are combined and the statistical definition reads as follows:

> *"Towns (places with municipal corporation, municipal area committee, town committee, notified area committee or cantonment board); also, all places having 5 000 or more inhabitants, a density of not less than 1 000 persons per square mile or 400 per square kilometer, pronounced urban characteristics and at least three fourths of the adult male population employed in pursuits other than agriculture." [United Nations, 2005, p.105]*

For statistical purposes, this may be sufficient, but, in many cases, does not correlate with either the actual metropolitan area or the socio-economic functions of the settlement [Drakakis-Smith, 2011, p.2]. A good example is India's Capital city Delhi: National Capital Territory (NCT) Delhi is the actual city constituted by 9 districts with a population of around 13.85 million. However, Delhi is surrounded by 14 districts in three neighboring states and together they form Delhi National Capital Region (NCR) with a total of 37.1 million inhabitants, which might be the more relevant scope for analysis and planning purposes. The same is true for other metropolitan areas, hence, we can conclude that a standard definition of "urban" does not exist, which makes a comparison between cities difficult. For the simulation models in this thesis, boundaries were defined on a per-city basis, according to the local planning documents.

2.1.1 Causes for Urban Population Growth

Another aspect of urbanization is population growth itself. Relevant databases (i.e. World Urbanization Prospects [United Nations, 2012]) publish net growth figures in their long-term forecasts. Although the projections implicitly consider the underlying reasons in their models, the valuable information is not disclosed. Net population growth constitutes four variables:

$$Pop.Growth_{Net} = (Birth\,rate - Death\,rate) + (Immigration - Emmigration) \qquad (1)$$

Organic growth indicates that the birth rate exceeds the death rate, a fact that is true for most developing countries[1]. The total replacement fertility[2] for Asian countries is estimated to be 2.32, whereas most industrialized nations display values around 2.1, due to lower mortality rates [Espenshade et al., 2003]. Half of the population growth in Third World cities is accounted to natural growth, because of sharp declines in mortality (particularly infant mortality, due to improved hygienic and medical conditions) and remaining high levels of birth rates. A fact, however, that was long neglected in the population growth models is the observation that fertility rates decline with increasing urbanization:

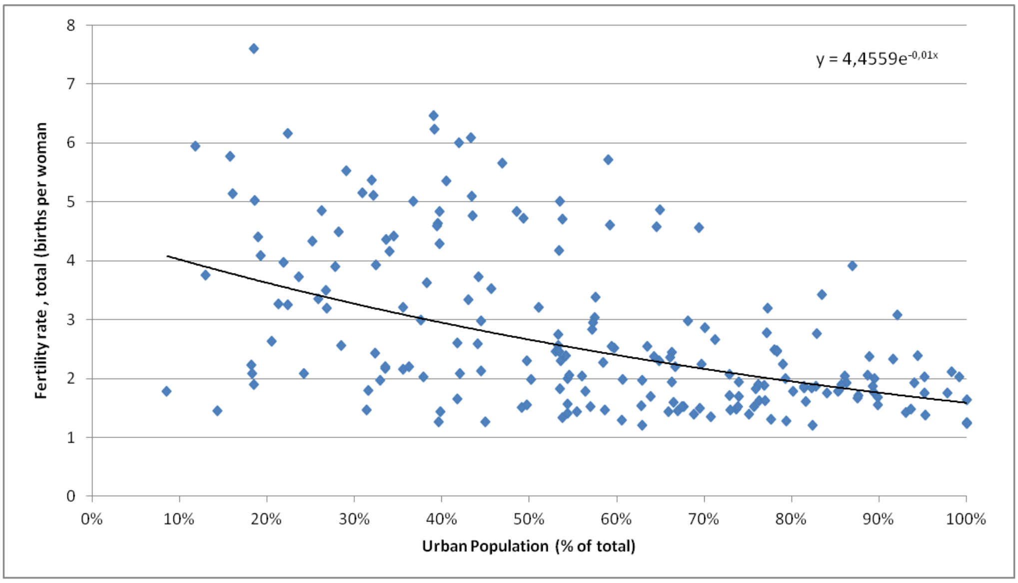


Figure 2: Declining fertility with higher urbanization [Data: World Bank, 2015]

The urban movement has changed many of the traditional attitudes towards family size and function. In rural areas large families ensure cheap labor, but in a city they increase the dependency and make

[1] With the prominent exemption of China due to state birth control ("One-child policy")

[2] Total fertility rate at which women give birth to enough babies to sustain population levels (also called *replacement rate*)

housing more expensive. What is more, city life increases access to all of the other factors which are related to diminishing birth rates [Drakakis-Smith, 2011]. These findings led to revised global population projections and yielded the finding that total world population will balance at around 9 billion by 2050 [United Nations, 2013].

The second driver for growth is migration. In most developing countries poverty and the hope to improve quality of life is the main motivation for people to move away from rural areas. This poses great challenges for cities to integrate the new citizens successfully, both spatially and culturally.

For certain transportation research questions, the reasons behind population growth can be relevant, for instance if mobility patterns are influenced by them. For the scope of this research project net population growth is treated as an exogenous variable to the simulation model and data retrieved from the city planning documents for the analyzed scenarios.

2.1.2 Scale of Urbanization

The United Nations Department for Social and Economic Affairs is the reference source for world population data. It aggregates national statistics and estimates forecasts on an annual basis. The World Urbanization Prospects [United Nations, 2012] give a complete picture on city population projections. Estimates suggest that more than two-thirds of the world population will be urban by 2050. This would add 2.7 billion people to the urban population of 3.56 billion in 2010.

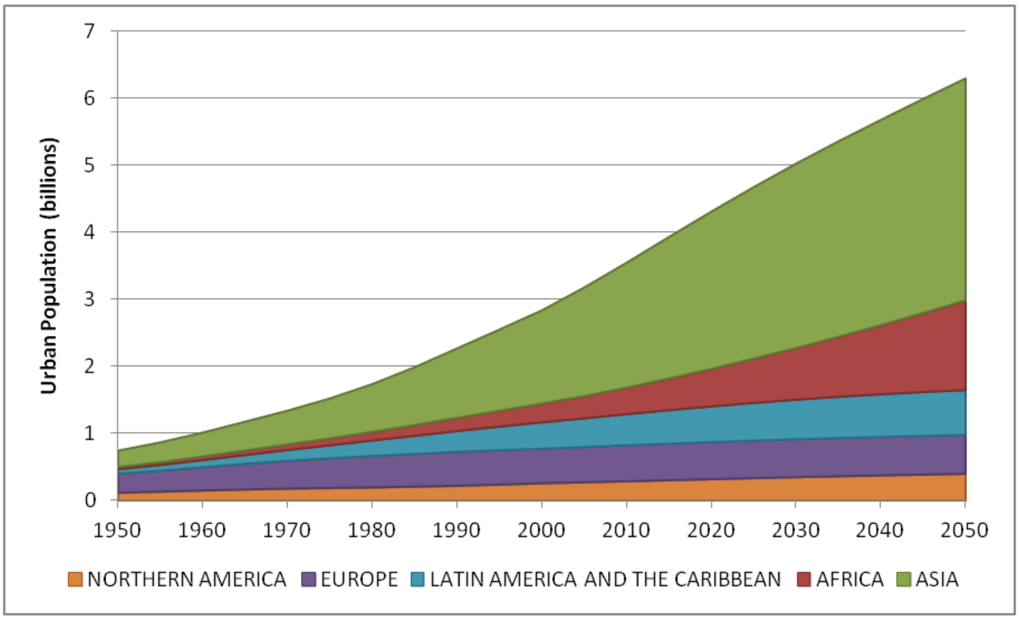


Figure 3: Urban population growth 1950-2050 by region [Data: UN, 2013]

As can be seen in Figure 3, there are big differences for this trend per region. North and South America already have comparatively high urbanization levels today. Countries like Brazil or Chile are concerned with handling the implications of rapid urbanization in the last decades, but they will not face high growth rates in the future anymore. In contrast to this, Africa's urban population is going to triple from around 400 million in 2010 to 1.2 billion in 2050. The region with the highest incremental and absolute growth is Asia: in China and India alone, the urban population is projected to increase by 837 million.

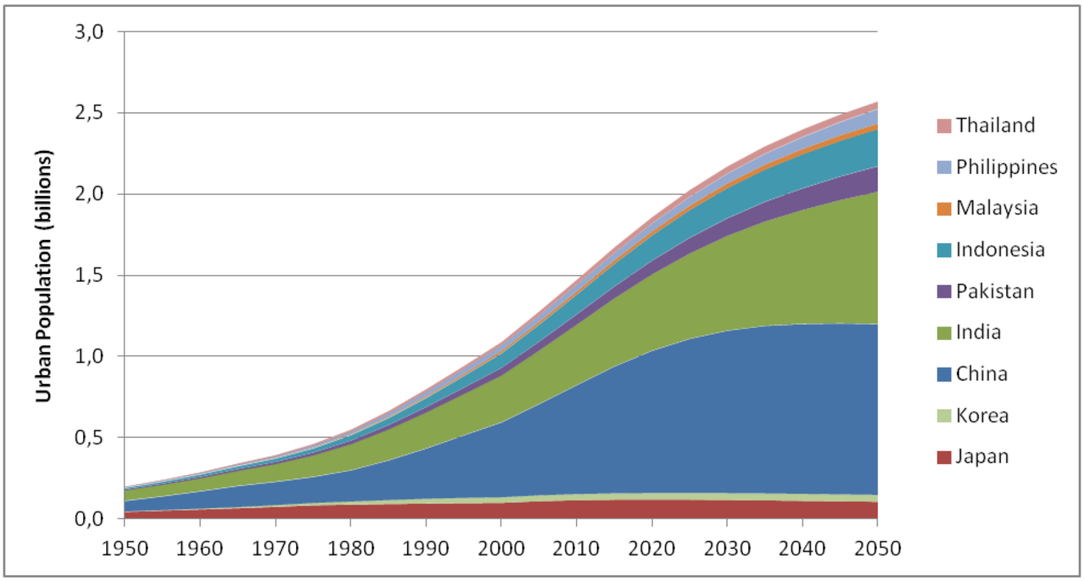


Figure 4: Urban population growth 1950-2050 for selected Asian countries [Data: UN, 2013]

In terms of scale, urbanization in India is unprecedented [Booz&Co., 2010], which makes it particularly interesting as a study country, not to mention its great economic potential. In this research project, we analyze the impact of urbanization on the transportation sector in different scenarios.

2.1.3 Specialties of Asian (Mega-) Cities

In the last decades, Asia has undergone rapid economic development and is also characterized by a consistent trend of urbanization with concentration of large populations in so-called "Megacities" [3]. Among the world's 30 largest cities, 16 are in Asia [United Nations, 2012], some of them already megacities and the rest poised to become so in the future. Past experience of managing this rapid growth is not very encouraging. Traffic congestion, pollution, poor urban services and increasing slum population have become the defining features to many of them. The large scale magnifies the challenges and complexities, and is the root of many of the observed problems.

Among the different infrastructures, transport is so important because it also defines spatial structure. Although many Asian cities have taken initiatives to improve their transport system, the outcome is rather incremental and, given the future population growth projections, insufficient to meet the demand, both quantitatively and qualitatively. A look into the past reveals that there are diverse urban mobility profiles across cities worldwide, whereby some seem more desirable and sustainable than others. American cities, for example, display the highest car ownership, even when compared to well-developed Asian cities (i.e. Seoul, Hong Kong), which remained at a much lower level. Europe lies in between with a tendency to lower ownership in large cities. As shown by Kuhnimhof et al. [2014] boundary conditions and mobility cultures lead to different development paths. Developing cities in Asia can learn from these past experiences, but must also come up with new, proprietary solutions.

[3] By definition these include cities with more than 10 million inhabitants [Morichi and Acharya, 2013, p.1]

2.2 Urban Mobility in India

2.2.1 City Characterization and Travel Patterns

There are 7,935 urban agglomerations (UA) and towns identified by the latest Census of India [Census 2011]. The distribution of cities by population size is given in Table 1 and shows the morphology of urbanization in India. Nearly 50% of the population actually lives in small cities (< 0.5 million), whereas 15% live in the country's large metropolitan areas with populations exceeding 10 million.

Table 1: Classification of cities by population size [Tiwari, 2011]

Category	Population (million)	Total no. of census cities	% of total population in different cities
1	< 0.5	4.304	53
2	0.5 - 1	39	10
3	1 - 2	22	10
4	2 - 4	6	6
5	4 – 8	4	8
6	> 8	3	15
Total		**4378**	

Both the challenges and potential solutions for these city types are very different and demand a differentiated analysis of urban mobility, depending on the boundary conditions. Problems in many of them have common sources, which are discussed in detail, for instance, by Tiwari [2011], Pucher et al. [2005] and Singh [2012].

The interaction of land-use and transport systems is well recognized and therefore important to frame the analysis correctly. In their research, Tiwari [2011] and Mohan and Tiwari [2000] find that Indian cities dominantly have mixed land-use structures with substantial informal settlements (15-60% of population living in slums) and short trip lengths, even in big cities like Mumbai and Hyderabad (80% of trips shorter than 10km and 70% shorter than 5 km). Moreover, the average trip length in small and medium sized cities is even less than 5 km.

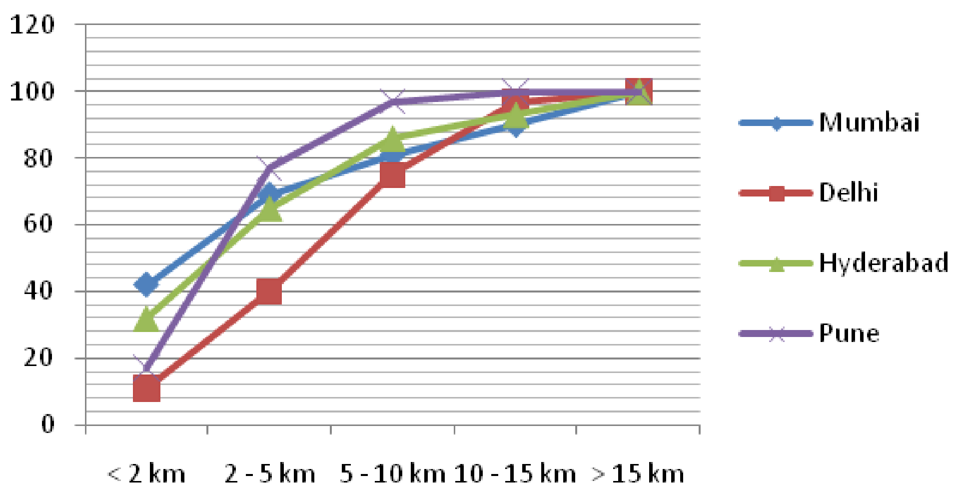


Figure 5: Trip Lengths in selected cities in India [Tiwari, 2011]

As Indian cities have grown, they also spread outward. Lack of effective planning and land-use controls have resulted in sprawled development extending over the city boundaries into the countryside [Pucher et al., 2005]. This has greatly increased the number and length of trips for many Indians, making them dependent on motorized transport. Most public policies encourage sprawl. In an attempt to reduce highly dense city centers, government regulations limit the height of buildings. The “floor space index” (ratio of floor space to land area) in sampled city centers in India was merely 1.6, whereas in other Asian city centers, this index ranges between 5 and 15 [Bertaud, 2002]. For suburban areas, however, the regulations permit higher ratios, thus, further encouraging developers to invest. This is actively advertised by local governments on the city fringe to promote economic development in their administered community. Moreover, they promoted commercial and residential developments in remote areas (i.e. industrial parks), without premising for necessary infrastructures, which causes longer trips for many travel purposes.

These findings seem to be contradictive at first glance, but are consistent, if the income distribution for the urban population is added to the equation. As in many developing countries, a high percentage of the population is too poor to afford motorized transport and is mostly dependent on walking and cycling with shares ranging between 30% in large cities and 60% in small cities [Tiwari, 2011]. Public transport users are captive, too. Despite overcrowded buses and poor road safety for non-motorized transport, people must utilize these modes because of lack of alternatives [Singh, 2012]. This limits the range within which low income groups can pursue their activities and hence, lowers their average trip distance. While the urban poor are particularly disadvantaged, the emerging Indian middle class also struggles to find adequate housing in the city centers. Such peripheral locations require long, exhausting commutes, either using slow, overcrowded public transport or motorized vehicles, as soon as they can afford to. Even affluent Indians are confronted with highly congested and unsafe roadways.

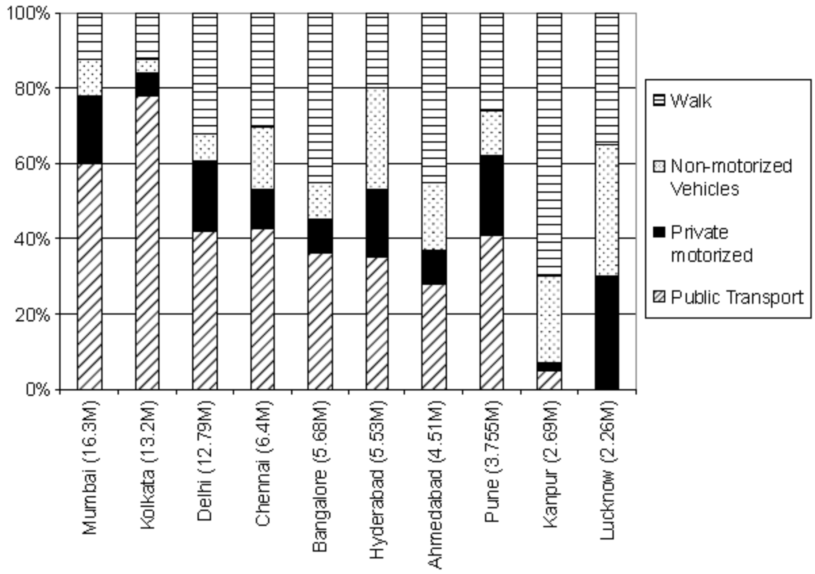
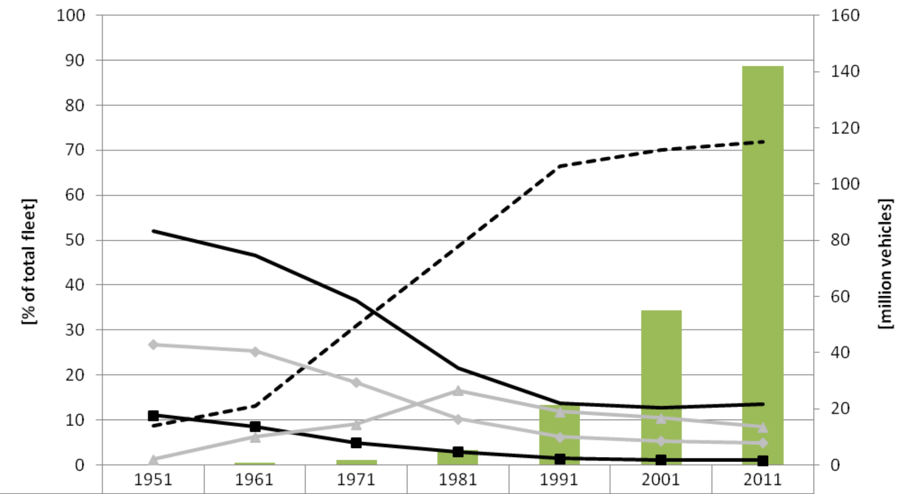


Figure 6: Modal split of urban trips for selected Indian cities [Pucher, 2005]

As of today, cars and motorcycles account for a small, but rapidly growing share of all trips (about 10-20%). There is little available time-series data on modal split, but vehicle ownership statistics provided by the Ministry of Road Transport and Highways, Government of India, reveal a rapid motorization and a particular sharp rise of motorcycle ownership in the last decades.



	1951	1961	1971	1981	1991	2001	2011
Total (miilion)	0,3	0,7	1,9	5,4	21,4	55	141,8
2-Wheelers (%)	8,8	13,2	30,9	48,6	66,4	70,1	71,8
Cars, Jeeps and Taxis (%)	52	46,6	36,6	21,5	13,8	12,8	13,6
Buses (%)	11,1	8,6	5	3	1,5	1,2	1,1
Goods Vehicle (%)	26,8	25,3	18,4	10,3	6,3	5,4	5
Other Vehicles (%)	1,3	6,3	9,1	16,6	11,9	10,5	8,5

Figure 7: Size and composition of the Indian vehicle fleet 1951-2011 [Data: MoRTH, 2012a]

Between 1981 and 2011, the motorcycle fleet increased 38-fold and the car fleet more than 16-fold. The low-density development around Indian cities has made private motorized transport a necessity, especially given the unsatisfactory alternative of inconvenient public transport services. At the same time, rising incomes make these vehicles affordable to a growing middle and upper class in India. The basic problem is not the number of vehicles in the country (car ownership level is around 10 vehicles/1000), but their concentration in a few (especially) metropolitan cities. From 1999 to 2009, number of vehicles per 1000 inhabitants in those cities has more than doubled from 132 to 286 (Figure 8), and in major cities, including Delhi, has already crossed the mark of 400. Interestingly, nearly 35% of the total vehicles in the country are plying in metropolitan cities alone, which constitutes just around 11% of the total population [Singh, 2012].

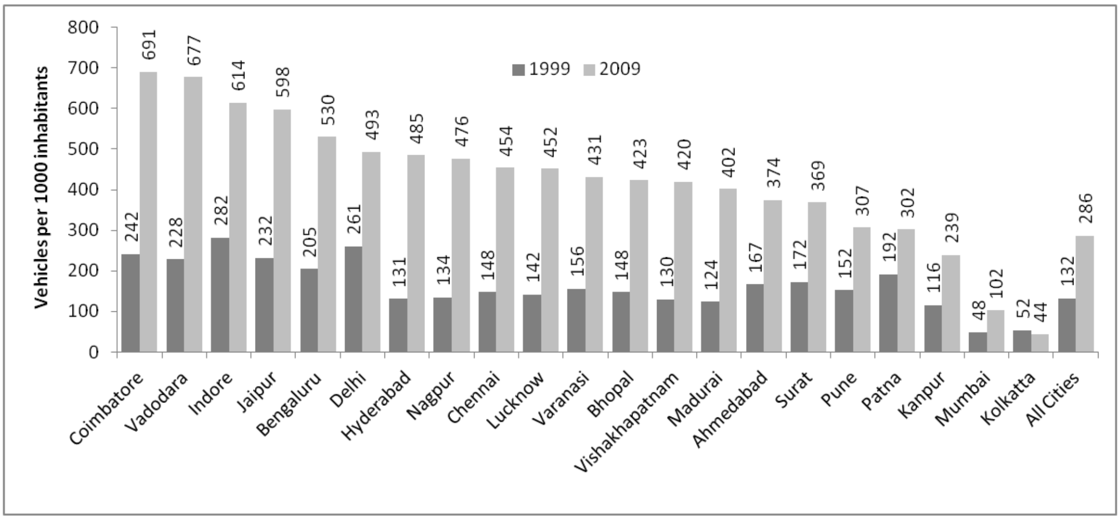


Figure 8: Vehicle ownership in selected metropolitan cities in India 1999-2009 [Singh, 2012]

In contrast, the public transport fleet has not kept pace with these developments in the past. Percentage of buses on India's roads declined until 2001, but stabilized at a low level of 1% in the last decade [MoRTH 2012a]. Urban rail transit is currently available in 7 cities[4] serving millions of trips per day. Further (sub-) urban rail systems are installed or under construction in other cities, but do not yet have the capacity to meet the bulk of public transport demand.

Buses are the backbone of the urban public transport system in India. Launched in 2005, Jawarhalal Nehru National Urban Renewal Mission (JNNURM) made bus services, operated by state or municipal transport undertakings, available in many more cities across India as a move to improve urban transportation. However, the mismatch between transport demand and supply is still existent in most Indian cities, resulting in intermediate public transport (IPT), such as auto rickshaws, taxis or minibuses filling the gap. Such a proliferation of vehicles results in congestion, delays, road accidents and pollution of the environment.

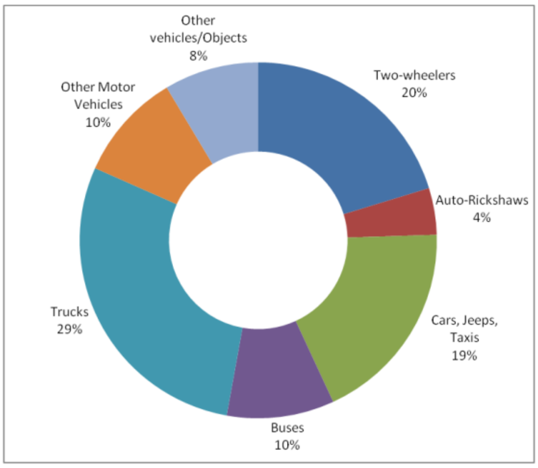
2.2.2 Road Safety

Many developing countries face serious road safety problems. Annually 126,900 people die and more than 460,000 are injured in traffic related accidents in India [Singh, 2012]. In contrast to other emerging countries like China, the situation in India has worsened in recent years. Fatality risk (defined as road accidental deaths per million population) has jumped from 64 in 1990 to 109 in 2009. In the last decade, road fatalities have increased at a rate of 4.6%. The nature of the problem is, in many ways, different than in industrialized countries. Because pedestrian and bicyclists share the road with high speed vehicles without a dedicated infrastructure for them (i.e. bike lanes), they are exposed to a higher risk of being involved in serious or deadly accidents. These vulnerable road users constitute 75% of road fatalities. In addition, the proportion of commercial and public service vehicles involved in crashes is also greater than in developed nations (60% of fatal road incidents include trucks or busses) [Mohan and Tiwari, 2000]. Clearly, the significant amount of motor vehicles on the road is the main reason for poor safety conditions. Fatalities, in particular, increase with rising vehicle use, since the likelihood of an accident to be fatal increases with speed [Mohan, 2004]. However, aside from growing vehicle ownership, other factors are accountable, too [Pucher, 2005]:

- Inadequate road supply and quality, badly maintained or unpaved
- Unsafe driving behavior – as a result of lenient licensing procedures, weak law enforcement and deficient driving skills
- Unsafe, poorly serviced vehicles
- Insufficient or non-existent traffic signals and signage
- Lack of infrastructure for pedestrians and cyclists
- Reduced right of way by parked vehicles, roadside hawkers and pavement dwellers
- Overcrowded road transport vehicles (practically all modes, even motorcycles)

India also lacks effective road safety policies. Although basic measures like use of safety-belts and helmets are mandatory under Motor Vehicle Act 1988, they are not properly enforced. Indian government has identified this as a key policy area and drafted a new piece of legislation that will be more comprehensive in terms of safety including improved law enforcement. The draft bill [MoRTH, 2014] was under public review for more than two years, and is effective since 2017, with some deductions (i.e. a central road safety agency like in the United States) was not set up).

[4] Delhi, Mumbai, Colcatta and Chennai, Indore, Hyderabad, Bangalore



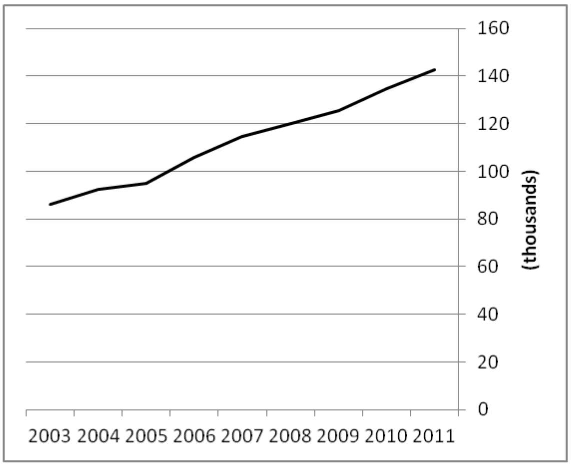


Figure 9: Number of persons killed from accidents by mode [Data: MoRTH, 2012b]

Figure 10: Total number of persons killed from accidents in India [Data: MoRTH, 2012c]

The bill adapts best practices from developed nations (i.e.: Germany, USA) in an attempt to update the regulatory measures in the transportation sector. Safety plays a key role in this document. For the first time, fatality reduction targets are formulated, which marks an important step to introduce respective policies.

2.2.3 Environmental Pollution

Pollution is a serious problem for quality of life in many Indian cities, and transportation contributes to it in different ways. The most reliable and comprehensive statistics exist for air pollution.

Table 2: Air pollution levels in Indian cities [Agarwal, 2006, p.3]

City	SO_2 (µg/m³)		NO_2 (µg/m³)		SPM (µg/m³)	
	1993	2003	1993	2003	1993	2003
Delhi (Nizamuddin)	13.7	12.2	30.1	43.3	362	315
Mumbai (Bandra)	49.5	7.7	32.3	18.7	475	219
Kolkata (Lalbazar)	65.1	18.0	62.0	75.5	507	244
Chennai (Gen. Hospital)	10.3	6.6	27.1	7.5	73	149
Bangalore (Anand Rao Circle)	--	10.8	--	44.9	--	198
Hyderabad (Abids)	7.3	9.7	11.0	19.5	156	139
National Ambient Air Quality Standard (Residential Areas: annual average)	**60**		**60**		**140**	

As shown in Table 2, levels of air pollution concentrations are highest for suspended particulate matter (SPM) and respirable suspended particulate matter (RSPM), which exceed World Health Organization (WHO) standards, as well as official Indian government standards in practically all cities. In the country's three largest cities, the levels are three to four times higher than the WHO's minimum standards[5], and Delhi has lately received the dubious title of being the world's most polluted city, surpassing Beijing in this respect [WHO, 2005]. Levels of CO, NOx and SOx are generally considered moderate to low in most of the cities, but ozone levels have been increasing, causing a range of respiratory illnesses and irritation [Pucher, 2005]. Airborne lead pollution dropped significantly by phasing out leaded gasoline in 2000. Similarly, Indian government has reduced the allowable sulfur

[5] WHO PM_{10} Interim target-1: 70 µg/m³

content in diesel and gasoline, which helped to significantly lower SOx emissions in all large cities since 1995. Nevertheless, sulfur content in diesel fuel in India is presently still too high for advanced diesel engine technology, but was announced to be introduced with the new vehicle emission standards in 2020.

One major reason for high air pollution caused by the transportation sector remains the large fleet of motorized two-wheelers (motorcycles and scooters) and three-wheelers (auto-rickshaws) with very inefficient, poorly maintained and highly polluting 2-stroke engines. Table 3 presents a comparison of exhaust emissions for different vehicle types under typical traffic conditions:

Table 3: Emissions per mode in a typical Indian city (in g/km) [Sibal and Sachdeva, 2001]

Vehicle	CO	HC	NO_x	SO_2	Pb	TSP
Two-wheeler	8.30	5.18	--	0.013	0.004	--
Car	24.03	3.57	1.57	0.053	0.012	--
Three-wheeler	12.25	7.77	--	0.029	0.009	--
Bus	4.38	1.33	8.28	1.441	--	0.275
Truck	3.43	1.33	6.48	1.127	--	0.450
LCV	1.30	0.50	2.50	0.400	--	0.100

The emission rate, defined as quantity of pollutants emitted per vehicle-km, pertaining to carbon monoxide and hydrocarbons is very high for personalized (e.g. car, 2-wheeler) and intermediary public transport (IPT) modes in comparison to buses, trucks or light commercial vehicles (LCV). In light of increasing use of personal motor vehicles, the air pollution from transport is expected to become a more serious problem in the future.

With the objective to mitigate air pollution, more stringent emission norms[6] have been introduced for passenger cars in Indian cities. Their effectiveness is, however, limited because no regular roadworthiness test is mandatory for registered vehicles. Legal compliance is confined to the vehicle purchase, with no standards for the usage phase. Considering the great stock of old or poorly maintained vehicles on the road this is very clearly an area upon which has to be enacted. In the draft bill for road transport and safety these kinds of regular checks are proposed, but the problem remains that motorized two- and three-wheelers are not subject to this emission legislation against the background that they constitute around 70% of India's total vehicle fleet.

2.2.4 Governance & Responsibilities

Under the Constitution of India, the State governments are responsible for urban development and urban transport. Yet, the central government plays an important role in many aspects. The main piece of legislation that governs road transport, namely the Central Motors Vehicle Act, is administered by the central government. Production and quality specifications for fuels are within the responsibility of central agencies, as are standards for the automotive industry. The Indian Railways works under the central government, and all kinds of rail bound public transport systems fall under their authority. Finally, but most importantly, the central government possesses the funds to invest in larger scale mass transit infrastructure, which many states do not possess.

[6] Bharat Stage IV, equivalent to EURO 4 emission norms in EU

On the state level, responsibilities for urban transport are also not subject to a single department. In some states, the urban planning/municipal administration department undertakes urban transport planning and in others, the transport department is responsible. On the municipal level, little authority for transport planning exists in general. In the central government, as well, the subject is divided among the Ministry of Urban Development, which has been entrusted to plan and coordinate urban transport systems, and the Ministry of Railways, which is responsible for the technical planning of rail-based systems.

The entire set of activities required to manage and operate urban transport systems can be structured in three levels: first, the strategic and policy functions that will have to be directly executed by a government department, and which are, in most cases, decided and coordinated on the state level; second, the regulatory and short term planning functions which can be performed by a government department or a dedicated public agency; third, the actual operation of transport services, which can be undertaken either by public or private agencies [Agarwal, 2006].

Regulatory functions themselves can be divided into two categories: one involves safety, such as driver licensing, driver training, proper vehicle maintenance, enforcement mechanisms, penalties, vehicle registration and standards protecting health, like emission or fuel norms. The other covers commercial issues, such as fares and quality monitoring. The key document for safety regulation of motor vehicles is the Motor Vehicles Act 1988, which is effective for the entire nation. This is supported by the Central Motor Vehicle Rules 1989 and further supplemented by state-specific rules that apply within the individual state jurisdictions. The draft road transport and safety bill, currently under public review, is going to replace the Motor Vehicles Act 1988 and introduce some significant changes for the regulation of road transport in India as, for example, a unified driver licensing system or a roadworthiness test for all cars and two-wheelers every five years.

Commercial regulation covers setting the fare structure and ensuring service quality. Fares for road transport are fixed by the State Transport Authority (STA), which also grants permits for operation on certain routes. Rail fares are determined by the Ministry of Railways. In order to fulfill its provisioning function, public transport has to ensure that there is adequate coverage at all times of the day and does not strive to maximize profits. This implies a systematic exercise for network and route design and assigning this responsibility to a public agency, both of which is currently not in place. The State Transport Corporations (STC) decide on which routes to operate rather by reacting to public pressure, while private operators have to be profitable and apply only for routes that are economically feasible. This results in a sub-optimal allocation of routes and poor level of service for public transport in most of India's cities. Common services are essentially those that cannot be offered by multiple agencies. Passenger information services, provision and maintenance of common infrastructures, and multi-modal transportation hubs all require integrating the operations of stakeholders, so that the user perceives a unified public transport system in which he can seamlessly switch from one operator to another. With regard to passenger information, STC's do provide this for their own services, but private operators do not. In terms of sharing infrastructures, the responsibilities are diffused as well. In Delhi, for instance, bus terminals and stations are run by the STC, whereas DMRC[7] is building stations for Metro operations. This leads to separate stations, which hinders the desired integrated use of different public transport modes.

[7] Delhi Metro Rail Corporation

Table 4: Agencies responsible for different aspects of urban transport [Agarwal, 2006, p.9]

Central Government		State Government	
Agency	Responsibility	Agency	Responsibility
Ministry of Railways	Technical planning of urban rail transit systems	Department of Transport	Licenses and controls all road vehicles, inspection of vehicles, fixing motor vehicle tax rates
Ministry of Road Transport and Highways	Administer the Motor Vehicles Act and notify vehicle specifications as well as emission norms	Public Works Department	Construction and repair of major roads
Ministry of Urban Development	Overall responsibility for urban transport policy and planning	Local Municipality	Mgmt. of smaller roads and traffic lights, licensing and control of non-motorized vehicles, clearing encroachments, provision of water, sewerage and drainage services
Ministry of Environment and Forests	Recommend emission norms for motor vehicles and administer the Environmental Protection Act	Police	Enforcement of traffic laws and prosecuting violators
Ministry of Finance	Responsible for fiscal policies	Department of Environment	Monitoring air quality
Ministry of Industries	Responsible for the Industrial Policy	Land Revenue administration	Allocation of land and land acquisition
Ministry of Petroleum	Controls all the oil refining companies	State Transport Undertaking	Operation of bus services
Planning Commission	Provision of funds for capital investments	Development Authority	Land use planning and regulating the growth of a city

The current situation of governance is a legacy of the past, when India did not face the challenges it encounters today. There are several weaknesses which limit the ability to effectively manage the problems of urban transport. Regulatory and management responsibility is spread over a multiplicity of agencies, comprising several ministries and jurisdictions, although intra-city transport would require several functions to be performed in a well-coordinated manner. The distribution of responsibility clearly brings out the inefficiencies in planning and management of urban transport. While the state transport departments are responsible for vehicle licensing, registration, inspection and road taxation, the legislative framework is enacted on a central level. The responsibility for road construction is shared by at least two agencies – the state department for more important roads and the municipal government for smaller roads. In larger cities, several central government agencies (i.e. National Highways Authority) get involved, too. Unfortunately, there is little or no coordination between these stakeholders and there exist no central planning authority that keeps the overall goal in mind. This weakness is accounted for in the National Urban Transport Policy (NUTP), which recommends state governments set up Unified Metropolitan Transport Authorities, particularly for large cities, to ensure effective planning and implementation of transport initiatives, but virtually none have followed this recommendation – whereby other cities in the world – for example, London – have proven the success of such governance systems.

A second weakness is the limited authority at the local level, despite being the logical jurisdiction level to make decisions on how to manage and regulate city transport. The city government would then be held accountable for good management by being elected or rejected by citizens. But the city government is usually unable to commit to this task, due to a very weak revenue base and dependency on state or central government for funding. Benchmarking with other cities in the world shows that strong and financially powerful city governments are crucial for effective management. Furthermore, urban transport remains a rather marginal role for many of the official stakeholders involved. There exists ambitioned initiatives on different political levels, however, fundamentally changing organizational structures and re-distributing authority to different agencies is a lengthy and laborious process in a free democratic state, as in India.

2.2.5 Strategies for Urban Transport in India

Literature review shows that a number of papers on policies to manage the transportation challenge in Indian cities are available already. In the following section, we summarize and present the strategies proposed by Agarwal [2006], Pucher et al. [2005] and Singh [2006].

- **Contain travel demand**

The first and most important step to meet future travel demand is to aim for reducing the demand itself through innovative means, without impeding the overall economic development of the city. Travel demand, in essence, is a function of population, per capita trip rate and average trip length. Obviously, population growth is difficult to regulate and per capita trip rates are unlikely to reduce in a developing economy, where a growing share of the population is seeking economical activities. Efforts to contain travel demand, therefore, have to focus on reducing trip lengths. The key to reach this objective is a good integration of land-use and transport planning. Mixed land-use structures, comprising business and residential areas convey cities with short distances for daily commute that can even be performed by non-motorized modes of transport or a sound public transport system. Hence, as a city expands, it is desirable to organize growth around a number of self-contained clusters, connected by transport corridors along which new settlements are developed. This kind of city structure is known as polycentric.

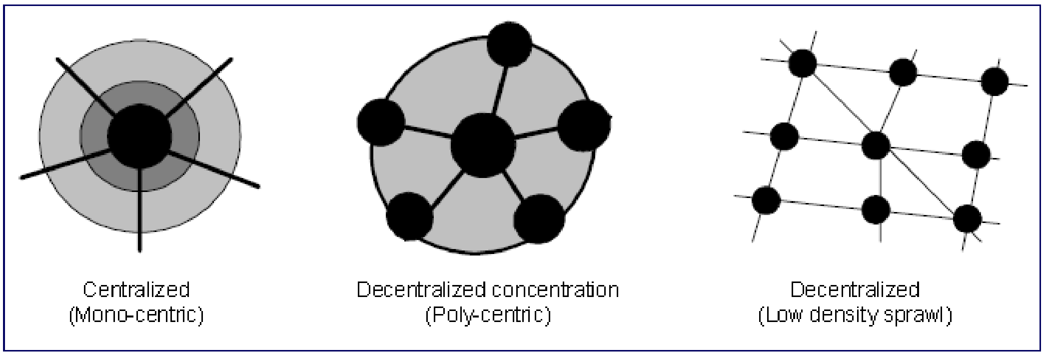


Figure 11: Typical patterns of urban development [Morichi, 2005, p.10]

It is essential that transport guides the urban form, rather than the opposite way. Unfortunately, this is not a viable strategy for all Indian cities, particularly those that have already grown quickly in the last decade, but should be imperative to the ones that are projected to witness considerable population growth in the future. Nevertheless, there remain obstacles to realize such urban forms, mainly the rent control and property legislation that makes it difficult to easily shift houses and move to a residence closer to the place of work.

A possible indicator to benchmark transport efficiency of cities is "accessibility", measured by the distance within public transport access is available. Typically, such distances should be in the range of 0.5 to 1 km in central areas, and 1-2 km in periphery areas. Safety and convenience are decisive factors for those who have the other travel options and need incentives to use public transport [Agarwal, 2006].

- **Improve public and intermediate public transport**

The next step in developing a strategy is to formulate an optimal mode mix in order to meet expected travel demand. This requires assessing the travel patterns for different categories of city residents and promoting the optimal and most sustainable forms of transport to perform the trips. Non-motorized modes occupy the least amount of road space and emit no pollutants, but these modes are not desirable for all trips, due to length or climatic conditions. Hence, there is a need for motorized modes, whereby public transport should be promoted because emissions, road space usage and fuel consumptions are significantly lower than for private motor vehicles. Considerable progress has been made in this area, but much more improvement is needed. In India's largest cities, metro and suburban rail systems have been expanded. Delhi's metro network has planned to span around 430 km after completion of Phase IV in 2021, and Bangalore will have its own metro system by this time as well. In other metropolitan cities, such as Mumbai, sub-urban rail corridors are extended. However, over 90% of public transport users travel by bus [Pucher et al., 2005]. By comparison, very little has been done to improve bus services, in terms of ride comfort and safety, as well as giving traffic priority to achieve higher travel speeds. On a national level, Jawaharlal Nehru National Urban Renewal Mission (JNNURM), launched by Government of India in 2005, was the strongest initiative to actively promote public transport systems, as formulated in the National Urban Transport Policy (NUTP) [NUTP, 2006]. Overall, 67 cities were eligible to participate in this scheme, and many took advantage to implement or upgrade their fleet with modern low-floor buses. But the scope of the executed projects was too small to really make a difference. In April 2015, Government of India announced a new urban development mission, which will replace JNNURM, despite the fact that around 50% of the granted projects – also covering non-transport related areas, like water sewerage – are still incomplete. One recent development is high-capacity, express bus systems – also known as Bus Rapid Transit (BRT) – which are already successfully operated, for example, in Ahmedabad, and planned or proposed for other cities, as well. These systems could prove ideal in the local context, since they provide many of the benefits of metro rail systems at a much lower cost. The international role-model for BRT is the TransMilenio system in Bogota, Columbia, which has a peak capacity of 45,000 passengers per hour and direction, and carries around 1,200,000 passengers per day [Hidalgo and Graftieaux, 2008]. Another possible approach to improve public transport at affordable cost is partial privatization of bus services. Several Indian cities have already privatized major shares of their total bus services, whereby Delhi and Kolkata have the largest private bus fleets [Pucher et al. 2005]. Compared to the publicly owned, operated and subsidized bus operators, privately run services have higher productivity, lower costs, more passengers per bus and higher revenues per vehicle km. While privatization appears to provide significant savings potential, there is a need for public regulation of safety, route and schedule coordination and service quality from a cost perspective.

- **Promote non-motorized transport modes (walk, cycle)**

The great potential of public transport in India remains to be recognized, but even more there is a crucial need to improve rights of way for pedestrians and cyclists. In fact, it is very rare to find designated, segregated facilities (e.g. crosswalks, cycle paths, wide sidewalks, pedestrian/bike traffic signals, etc.) for non-motorized transport in Indian cities. While there sometimes may just not be enough road space to allocate exclusively to NMT, the bigger problem is that policy makers have a tendency to favor motorized traffic [Padam and Singh, 2004]. This is related to the fact that vulnerable road users are mainly the urban poor, whose needs are given very little attention by urban planners and policy documents. Yet, these individuals account for about half of all trips made and constitute a large share of the population in Indian cities.

- **Improve traffic management**

Improved traffic management is recommended to ease the current situation. Larger cities have benefitted from the introduction of more advanced technology and stricter enforcement of regulations in recent years. In contrast, small and medium-sized cities often lack even basic provisions, such as traffic signals, stop signs, lane striping, and other kinds of traffic signage. The basic provisions have to be accompanied by strict law enforcement (particularly those related to safety) and proper driver training to raise awareness for the traffic regulations among motorists. Clearly, the three steps, better driver training, traffic signage, uniform regulations and enforcement are inter-dependent to another and need to be approached simultaneously. In the draft Road Transport and Safety Bill [MoRTH, 2014] a unified driver licensing scheme is proposed and law enforcement as a key policy focus is identified. Another aspect of efficiently managing traffic is to provide priority for public transport. Bus lanes or preferred signaling are very common in Europe, but practically non-existent in Indian cities. There is an obvious need to speed up buses stuck in congestion, since this would improve travel time and encourage public transport use. The premise, of course, is that such regulations are also properly enforced. Bus lanes that do exist have been poorly designed, with slow-moving traffic, two-wheelers and auto-rickshaws jamming the way. Since the principle idea of priority is ignored under such conditions, they provide little speed advantage to buses. A dolorous example in this context is the South Delhi Bus Rapid Transit (BRT) corridor, where motorists use the dedicated bus lanes to avoid traffic jams and no surveillance system hinders them from doing so. In the case of being stopped by police, fines are not prohibitive. Great potential for Indian cities is also found in implementing demand-side management measures, such as parking fees or road pricing. Although policy measures that involve restricting the use of private vehicles are very likely to be unpopular, a gradual improvement of public transport services could lead to greater acceptance and help to facilitate less use of cars and two-wheelers [Singh, 2006].

- **Reduce environmental pollution; improve vehicle technology, fuel quality**

With the increasing number of vehicles on India's roads it becomes more and more important to improve motor vehicle technology and fuels in order to increase efficiency while combating air pollution and noise. Strong actions have already been taken, but more stringent regulations have to follow. The complete phasing out of leaded gasoline fuels was an important milestone. Further lowering of allowable sulfur levels in diesel and gasoline is required for advanced combustion technologies in passenger cars, which are already state-of-the-art in more developed nations. Furthermore, stringent Euro IV emission standards for cars, trucks and buses have been adopted in major cities and are going to be mandatory over all of India in the next 2-3 years. The more difficult task remains: how to regulate the two-and three-wheelers which are powered by highly polluting two-stroke engines and constitute of two thirds of the entire vehicle fleet in India. To protect the environment, it seems inevitable to require these vehicles to have much cleaner engine technology. Such policies are unpopular, as it would make vehicles more expensive and, even if adopted, would take many years for the regulations to take full effect, since it takes time for the fleet to be replaced. With respect to three-wheelers, some cities have already acted: Delhi commanded all auto-rickshaws to run on compressed natural gas (CNG) to fight deteriorating air quality, and other cities banned two-stroke driven auto-rickshaws from city centers. For the future, the question also has to be raised to which extent fossil fuels are the right way to propel motorized transport in urban areas. New, clean technologies are going to be available, but still need research and development to lower the cost to an acceptable level for mass use in India.

2.3 Conclusions

The urban transport system in Indian cities is underdeveloped with inconvenient, unsafe and slow public transport services leading to an increased use of private motorized vehicles among the population. This is coupled with the decline of walking and cycling, higher level of road accidents and lower air quality. The reasons for the poor public transport systems are manifold, but lack of adequate planning and funding and scattered responsibilities for central, state and local government agencies are the most important reasons that make it difficult to formulate and execute sound transport strategies. Demand for urban transport is expected to double by 2030, hence there is an urgent need to develop strategies which can handle demand and create a unifying authority. Land-use planning should allow for short distances with mixed business and residential areas promoting walking and cycling. Road traffic has to be managed more efficiently by basic provisions of signage, dedicated infrastructures for pedestrians and slow moving traffic, as well as more stringent law enforcement. Motor vehicle technology must be improved to mitigate air pollution and improve energy efficiency. Obviously, these are great challenges for urban mobility in India, but they also provide opportunities to test and implement innovative strategies that could become role models for other developing and emerging countries facing similar boundary conditions and resource constraints.

3 State of the Art Transport Modeling

3.1 The Purpose of Modeling

A model is a simplified representation of a real world system in a particular field of interest which focuses on certain elements considered from a particular point of view. Models are, therefore, problem and viewpoint specific. Such a broad definition of models allows us to incorporate both physical and abstract models. In natural sciences and engineering we pre-dominantly find the first category of models, which are aimed at designing a system. The latter category spans from mental models we all use in our daily interaction with the world, to formal and abstract (typically analytical) representations of some theory about the system of interest and how it works [Ortúzar and Willumsen, 2011, p.2]. Mental models are important to understand and to interpret the real world, but they are difficult to communicate and to discuss because they are based on learning and experience. This creates the need to formally document mental models. An important class is mathematical models, which attempt to represent the system of interest by means of mathematical equations. They are also called “quantitative” models because of their ability to calculate a numerical output with a given set of input variables. They constitute an objective foundation for discussion and exploration of potential solutions in the search space. Another important advantage of mathematical models is that they force the modeler to test his assumptions, causal attributions and initial hypotheses during formulation, calibration and usage. In this way, the mental model is refined and a deeper understanding for the behavior and internal mechanisms of the concerned system is created.

Every model is only realistic within a pre-defined context. As an example, it is widely accepted that (mechanical) force equals mass multiplied by acceleration. But this model is insufficient to explain the force needed to move a vehicle on the road because it omits other influencing forces (air resistance, rolling resistance, inclination) that have to be accounted for in the final equation. The ability to understand the modeling task and choose the appropriate model for a particular context is a crucial element in a planner’s skill set. Many models exist to address various transport problems, but before we discuss the approaches in more detail, it is worth outlining the characteristics of transport systems and their associated problems.

- **Characteristics of Transport Demand**

The key characteristic of transport is that it is not demanded in its own end, it is derived. With some exceptions (e.g. sightseeing) people travel to satisfy a certain need (e.g. work, education, leisure) by undertaking an activity at a particular destination. The trip itself should be as short and cheap as possible. In order to understand the demand, we have to examine the distribution of these activities over space and time. A good transport system is characterized by being able to satisfy these needs in an efficient manner; a congested or sparsely connected system restricts options and limits the economic and social development. It is no coincidence that the many influential cities all over the world have historically evolved around major transport hubs, either at the crossroads of important commercial routes or at the coast as a gateway for international trade. The challenge for transport services is that there exists a whole range of specific demands which differentiate by time, journey purpose, type of cargo, importance of speed, etc. A transport service that is not flexible enough to meet this differentiated demand may well be considered useless [Ortúzar and Willumsen, 2011, p4]. The second trait of transport demand is its distribution over space and time, which often leads to problems of lacking coordination, and strongly affects the demand-supply equilibrium. For example, a subway line could be congested at peak hours, but running empty most of the remaining day. Similarly, a taxi service may be demanded unsuccessfully in part of a city, while in other areas, cab drivers are desperately trying to find customers. Peak and off-peak variations remain a central problem in transport planning because they determine for which demand level the system is actually designed. Information is considered to be essential to distribute demand more evenly, which is, essentially, the idea behind so-called “Intelligent Transport System” (ITS) concepts.

- **Characteristics of Transport Supply**

Transport supply must be viewed as a service, not as a good. Therefore, it is not possible to store and consume it at a different time or place of higher demand. A transport service must be demanded when and where it is produced, otherwise it loses its benefits. For example, a bus service is fixed to a certain route with stations and a time schedule. The second aspect of transport supply is that it requires fixed assets (roads, railway tracks, etc.) and mobile assets (cars, buses, trains, etc.) which provide the service together, but are entirely different in their nature. While transport infrastructure is usually very long-lived and expensive to replace, vehicles have a much shorter product life[8] and are replaced regularly. It is also relatively cheap, with the prospect of alternative employment, for mobile assets to adapt to changing demand. Unlike fixed infrastructure, the mobile components of road transport are subject to particularly low economies of scale [Button, 1993, p5], [Thompson, 1974]. These characteristics of fixed and mobile portions of transport leads to the case that infrastructure and vehicles are often not owned nor operated by the same group or company. The longevity cost of provision and scale economy of transport infrastructure tends to lead to natural monopolies, which are usually controlled by the state. Exceptions to this are public-private Partnerships (PPP), which grant the private sector the right to control and levy tolls. In many cases it is converted in a public utility after a certain period of time. On the other hand, low barriers to market entry, flexibility and lack of scalability tend to stimulate competition in the mobile sector and the regulation of such through government in order to protect public interests.

Degree of public ownership and regulation vary per nation, but the separation between supplier of transport infrastructure and provider of the final transport service generate a rather complex set of interactions and target conflicts between all stakeholders which are involved. Moreover, it induces economic complexities because end users and service providers not always acknowledge – or pay for – the total costs related to the service they use. Directly charging for road space is rarely exercised, and even if, does not include congestion or other external effects. Road pricing schemes usually put a stronger focus on traffic management than on cost transparency. The question may arise, why this is so important for transport planning and modeling. The answer to this lies in economic theory. In a perfect market, an optimal allocation of goods and services is achieved when marginal costs equal marginal utility. This is why the price of a good or service should ideally be set at its marginal costs. Of course, real markets are never perfect, nor can all costs be quantified (the pitfall for most external effects, such as greenhouse gas emissions). Nevertheless, this fundamental idea provides the basis for many policies and regulatory intentions aiming to improve the allocation of scarce resources.

Because of its very nature, transport is very important for the welfare of cities, but also consumes great amounts of resources. If those, who use transport services, do not perceive the resource implications of their choices, the entire system is likely to balance supply and demand in an inefficient way, which may hinder it to unfold its economic potential.

[8] Average age of passenger cars in the United States is 11.4 years [US DOT, 2015]

- **Demand-Supply Equilibrium**

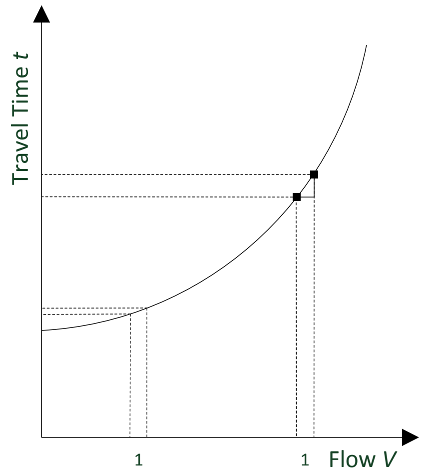


Figure 12: Demand-supply equilibrium [Ortúzar and Willumsen, 2011, p.6f]

In general, the role of transport planning is to satisfy a heterogeneously distributed demand with a set of available transport modes, given a transport system with a certain operating capacity. The level of service (LOS) is often specified as the time it takes to reach any destination within this system, including walking and waiting times. For this, we consider a set of volumes on a network ***V***, a corresponding set of (vehicle) speeds ***S***, and an operating capacity ***Q***, under a transport management scheme ***M***:

$$\boldsymbol{S} = f\{\boldsymbol{Q}, \boldsymbol{V}, \boldsymbol{M}\} \quad (2)$$

The capacity Q depends on the management system M, which may include traffic management schemes, mode-specific regulation and area control, and on the levels of investment over the years:

$$\boldsymbol{Q} = f\{\boldsymbol{I}, \boldsymbol{M}\} \quad (3)$$

The management system can also be used to redistribute capacity (***Q’***) among the infrastructure (e.g. pedestrian zones), for environmental, efficiency or equity reasons. As is the case for other goods and services, one would expect the level of demand ***D*** to be dependent on the level of service provided by the transport system and the spatial allocation of the people’s activities ***A***:

$$\boldsymbol{A} = f\{\boldsymbol{S}, \boldsymbol{A}\} \quad (4)$$

Combining equations (2) and (4) for a fixed activity system yields a set of equilibrium points between transport supply and demand. However, there are feedback structures between transport and the activities, leading to an adaptive behavior of its agents. It is, hence, a dynamic and constantly evolving system. The task for transport planners is to forecast and manage this evolution of equilibrium points over time so that social welfare is maximized. This is, of course, not a simple task; different modeling frameworks support the decision making process by simulation of various development scenarios and testing strategies to find adequate solutions for future states of the system.

3.2 Prevalent Demand Modeling Techniques

The description of the state-of-the-art transport demand models is derived from the textbook *Modeling Transport* by Ortúzar and Willumsen [2011], the comprehensive work of Cascetta [2009] and selected chapters from the *Handbook of Transport Modelling* edited by Hensher and Button [2000].

3.2.1 The Four-step model

The history of demand modeling for person travel has been dominated by the modeling approach known as the four-step model (FSM). The method focuses on trips, rather than activities from which demand is theoretically derived. The application of this modeling approach is near universal, as are its large number of critics. The reason the model is still widely in use, lies in its logical appeal and relative ease of handling.

Intuitively, it addresses sensible questions: how often are people traveling, where are they going, what mode are they using and which route will be chosen? Much of the criticism is directed towards the "sequential" structure of the FSM, also because in its beginning it was applied in this exact order. In reality, there exist feedbacks between the stages and their order may be subject to variation, too. Figure 13 depicts the general form of the model:

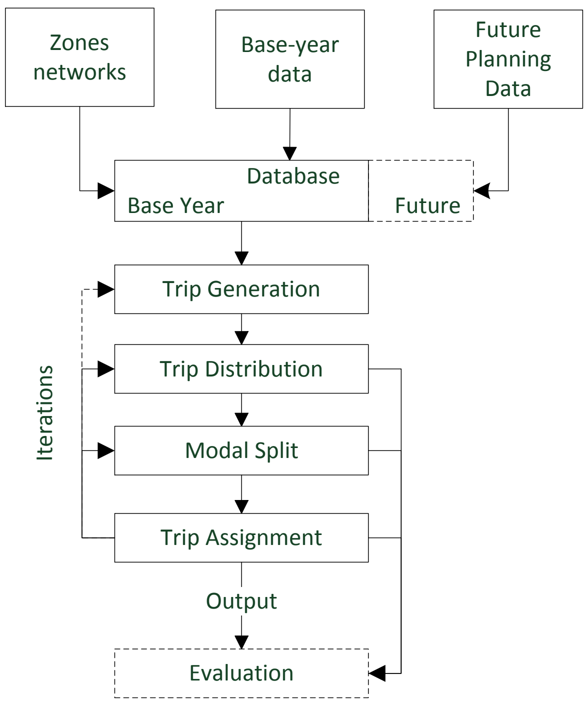


Figure 13: The four-stage model [Ortúzar and Willumsen, 2011, p.21]

The sequence starts by zoning the study area, mapping the network system, and collecting data for planning, calibration and validation. This data would include base-year population of different groups per zone as well as levels of economic activities including employment, shopping space, educational and recreational facilities. This feeds into a model to estimate the total number of trips originating and ending in each zone (*trip generation*). The next step is to allocate the pattern of movement between zones, in other words the *distribution* of trips over space, yielding the trip matrix (F_{ij}).

$$F_{ij} = f * \frac{(P_i * A_j)^\beta}{{\omega_{ij}}^\alpha} \quad (5)$$

With: F_{ij} Movements between zone i and j
P_i Productions in zone i
A_j Attractions in zone j
ω_{ij} Resistance between zone i and j (measured in time or distance)
f, α, β Empirically estimated coefficients

In its basic formulation, the distribution model adheres to Newton's law of gravitational attraction and is commonly known as "*gravity model*". While household surveys provide good data to estimate productions, it has proven more difficult to develop models for attractions, with the notable exemptions of the journey to work, where attractions are essentially the number of workplaces. Therefore, productions are usually considered well-defined, whereas attractions are merely viewed as relative attractiveness of different zones. In its earliest form, the model used zonal population and employment weights for P_i and A_j and simple forms for ω_{ij} based on distance or time. With the development of the concept of generalized cost, more attention was given to the functional form. One of the most enduring forms is the so-called negative exponential "deterrence function":

$$\omega_{ij} = e^{(-\lambda c_{ij})} \quad (6)$$

where c_{ij} is the generalized cost between zones i and j and λ is a positive valued parameter, determining the slope of the curve. Also referred to as "entropy" model (in another analogy) it can be shown to be consistent with the "logit" model, found in discrete choice theory [Ben-Akiva and Lerman, 1985], which forms the theoretical foundations for mode choice. [Bates, 2000, p.28] concludes:

> *"In spite of this, the general problem common to all "deterrence functions" is that they are attempting to explain a large amount of variation (effectively, the distribution pattern among N² cells, where N is the number of zones) using a very small number of parameters. Even if the parameters satisfy statistical requirements in terms of significance, the overall level of explanation tends to remain small. Hence, the distribution component of the four-stage model, if developed only on the basis of productions, attractions and a generalized cost matrix, cannot be expected to deliver a matrix that is sufficiently realistic to carry forward to the remaining stages of the model."*

Following *trip distribution*, the third stage of the FSM calculates the *modal split*, i.e. the share of different modes in total number of trips that have been previously distributed in the study area. In contrast to the problem of distribution, models of mode choice are much better to handle because the variation (effectively the number of viable options) is much lower compared to the number of parameters in the model. In its fundamental form, the model can be written as

$$p^k_{(m|ij)} = f(C^k_{ijm}, C^k_{ij\,\{m\}}) \quad (7)$$

where $p^k_{(m|ij)}$ denotes the proportion of all travelers of type *k* moving between origin *i* and destination *j* using mode *m*, whereby C^k_{ijm} is the associated generalized cost and *{m}* the (finite) choice set of available modes. Parameter variation is mainly performed with regard to the number and type of modes and the level of detail for the generalized cost. Most four-stage applications do not distinguish beyond "private" and "public" modes on the demand side (although different public transport modes may be accounted for assignment). The share of households that do not own a vehicle are considered "captive" to public transport. Therefore, mode choice is essentially limited to predicting the proportion of people using public transport, albeit having access to a car. More recently, carpooling (or ridesharing) have been added to the analysis.

In its simplest form – discrete binary choice – different mathematical functions[9] have been proposed to model the probability of the decision maker to select an alternative. Hereby, S-shaped curves (e.g. logistic) have proven very good results, where the probability of choosing a mode decline when its generalized cost are in excess to the second mode, but still allow for reasonable elasticity when the costs are comparable. In the binary case, entirely empirical functions can be estimated, however, the desire to generalize modal split to more than two modes leads, based on its tractability, to the logit-model. The multinomial logit model (MNL) is formulated as

$$P_{(m|ij)} = \frac{e^{(-\lambda^k * C^k_{ijm})}}{\sum_{r\epsilon\{m\}} e^{(-\lambda^k * C^k_{ijr})}} \tag{8}$$

One of the most discussed aspects of the multinomial logit is the *independence of irrelevant alternatives*. This property holds that for any two alternatives, the choice probability is completely unaffected by the generalized cost of any other alternative. A widely known example for this is the *red/blue bus paradox* [Ben-Akiva and Lerman 1985, p.48ff]. The nested multinomial logit model is the simplest form to overcome the shortcomings of the MNL, by grouping ("nesting") similar alternatives into sub-categories. Other common model functions are probit and mixed logit. Parameters for the generalized cost functions are estimated using the maximum likelihood method. Data for estimation are readily accessible, demands for computational power are not too high (because of limited choice sets), and methodology itself is well accepted. However, despite the intriguing idea of explaining consumer choice by measurable variables (e.g. travel cost or travel time) they are not sufficient to reproduce modal shares precisely. Experience shows that there are mode-specific properties, which are unique to the study area, and significantly influence the decision as well. As an example, people in Brussels may have a different opinion on what "crowded" public transport is, than an average commuter in Delhi or Tokyo. Modern choice models attempt to include these subjectively perceived (dis-)advantages in the general cost function, however, results are very location-specific and, therefore, not transferrable.

In the final step of the sequence, the modal trip matrix is assigned to the existing transport networks. While the underlying principle remains the same, the different characteristics of roads and public transport lead to two very different kinds of problems. As outlined previously, most FSM focus solely on these two systems, however, the same principle can be applied, for example, to cycling. In general, a network is represented as asset of *links* (L) and *nodes* (N). A link connects two nodes and a node connects two or more links. Links can either be directed (i.e. one-way streets) or undirected and generally have the following attributes [Willumsen, 2000, p.165]:

- *Length* (usually in meters or km)
- *Cost* (similar to mode choice generalized cost including time, distance, or other relevant properties of the infrastructure are commonly used as a metric)
- *Capacity* (i.e. the maximum flow that can pass through per unit of time)

Nodes may refer to single buildings or to zones, depending on the level of aggregation. They may as well be cities or even nations, depending on the purpose of the model. Accordingly, link characteristics are very different, ranging from detailed road information to very general representations featuring

[9] For a comprehensive discussion see [Ben-Akiva and Lerman, 1985, p.59ff], [Cascetta, 2009]

only time and cost. Flow capacity of (transport) links is typically constrained by the physical properties (e.g. width, number of lanes, gradient, etc.). This has important implications for modeling assignment, because it limits the supply side and makes the process to find the system equilibrium an iterative process. A typical free-flow capacity of a two-lane road with 50/50 directional split is around 1,400 passenger cars per hour [TRB, 2010] or about one car every two seconds. If the lane is used by other means of transport, like buses or motorcycles, a conversion factor, the so-called *passenger car equivalent unit* (PCU) is used. They are estimated for different traffic conditions and readily available for the planning purpose. Due to limited capacity, the level of service (LOS), often measured in travel time per unit of distance, decreases as the number of vehicles using the link increases. This does not happen linearly, a functional form of volume-delay is given in Figure 14:

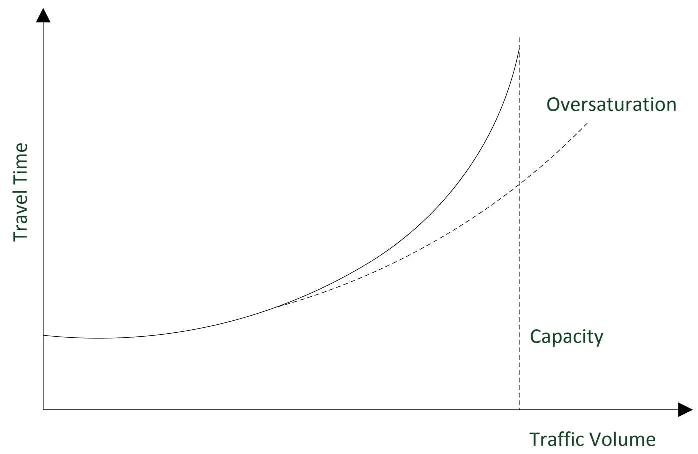


Figure 14: Travel time and flow relationship

The form of the curve is monotonically increasing, thus, there is no decrease in travel time in the flow range. Different approaches have been proposed to model volume-delay (also known as Capacity-Restraint (CR) functions), of which the following is commonly used in practice

$$t_{actual} = t_0 * \left(1 + \alpha * \left(\frac{q}{\gamma * q_{max}}\right)^{\beta}\right) \quad (9)$$

With:
- t_{actual} Actual travel time [s]
- t_0 Free-flow travel time [s]
- q Actual traffic volume [PCU/h]
- q_{max} Free-flow capacity [PCU/h]
- α, β, γ Empirically estimated coefficients

Parameters α, β and γ are estimated and determine the curvature of the function. If traffic flows exceed the designed link capacity, *queuing* will take place, which leads to reduced travel speeds and delay on the network ("*congestion*"). In oversaturation, the link disposes over a certain queuing capacity in terms of how many vehicles can literally be stored. Once this capacity is reached, the link has reached its physical limits ("*gridlock*") and the queue will spill over to the adjacent links. In practice, this delay is never infinite, as oversaturation and congestion mostly arises in peak traffic, which is limited to certain times of the day. Transport authorities, depending on their objectives, can decide to base their planning either on average daily or peak-hour demand. Speed-flow curves are estimated for every link separately, and are usually available for standard road sections. Most of them assume that the only cause for delay is the link itself, which is true for long links with grade separated junctions, such as highways (historically the main field of application for transport engineering[10]), but not in dense urban areas, where delays are more significant and depend on other conflicting links to a much higher extent. Through modern micro simulation methods, volume delay functions can be estimated more accurately for a particular road, based on cross-section measurement data, as shown by Neuhold and Fellendorf [2014]. Still subject to discussion in the scientific community is which volume-delay function reproduces reality in the best way, but common to all of them is that they are continuously differentiable.

Once the networks and their link *resistance* are laid out, the trips contained in the trip matrix are allocated to their routes, resulting in an overall "load". Most traffic assignment methods constitute three basic steps, often iteratively, to reach a convergent solution [Willumsen, 2000, p.165ff]. First, a set of routes for any traveler of type *k* is identified. As for mode choice, travelers are assumed to be rational in making their decision which route to take and seek to minimize their generalized cost (i.e. time, distance). Second, the according shares of the trip matrix are assigned to these routes. Here, different approaches exist. The simplest form is the "all-or-nothing assignment", which neglects any form of congestion effects and assumes that all drivers perceive the cost in the same way. Obviously, this method is not suitable for road traffic, but may be useful for cycling, where infrastructure is generally not a limiting factor. Another approach is "successive" assignment. Hereby, total demand is split up in pre-defined segments and demand distributed one after another. Once the capacity on the preferred route is exceeded, the next segment will choose the second-best option and so forth. The disadvantage of this method is that the sequence strictly follows the pre-defined segmentation and, thus, influences the final result. To overcome this shortcoming, iterative optimization techniques are required. The third step is therefore to check convergence to a given objective function (equilibrium condition). The description of such a state was given by [Wardrop 1952]:

> *"Under equilibrium conditions, traffic arranges itself in congested networks in such a way that no individual trip maker can reduce his path costs by switching routes."*

If all trip makers perceive costs in the same (i.e. assuming no stochastic effects), Wardrop concluded that

> *"Under equilibrium conditions traffic arranges itself in congested networks such that all used routes between any origin-destination pair have equal and minimum costs, while all unused routes have greater or equal costs."*

This is usually referred to as *Wardop's first principle*, or *Wardrop's user equilibrium*. Under this condition, no driver is able to reduce his (generalized) cost by switching to another route in the network. However, there exist a second way of assigning traffic to the network alluded to in *Wardrop's second principle*:

> *"Under equilibrium conditions traffic should be arranged in congested networks in such a way that the total travel cost (all trips) is minimized."*

In contrast to his first principle, this objective is an optimal *social equilibrium*, which minimizes total travel costs in the network. The individual traveler could improve his situation by switching to another route, but would induce a deterioration of the system.

[10] E.g. the BPR (Bureau of Public Roads) function utilized by the Chicago Area Transportation Study (CATS) in the 1960's

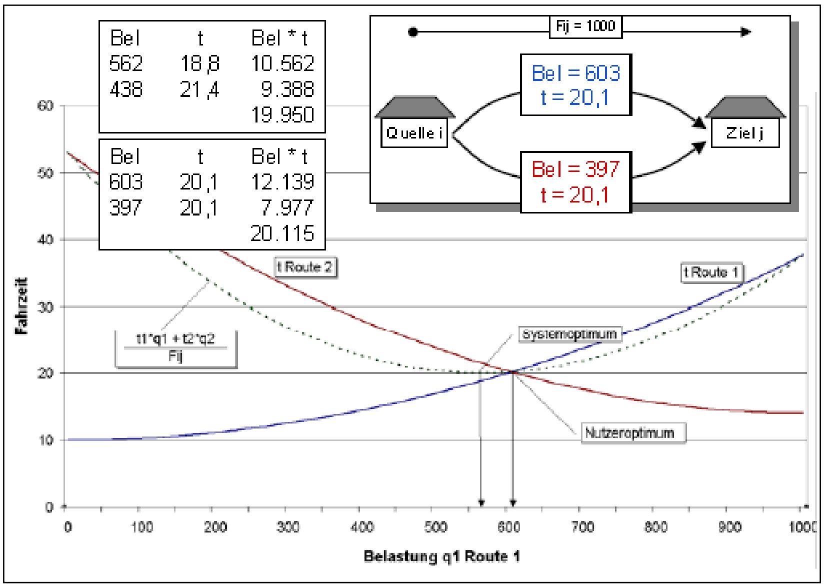


Figure 15: Difference in user and system equilibrium [Fellendorf, 2012]

As shown above, the system is optimal at lower loads than the user equilibrium, which leads to a target conflict in traffic management. In this context, Global Navigation Satellite Systems (GNSS) are a prominent example: most algorithms from private service providers are programmed to optimize individual travel time. However, if connected to a central traffic control, future systems could be programmed to follow the system optimum because the objective of any traffic management solution is to improve the system, not the individual user. The most prevailing solution method to solve the mathematical program is the *Frank-Wolfe algorithm.*

Once the model is calibrated and validated for base-year conditions, it is applied to one or more planning horizons. For this, characteristics of the transport system and planning variables have to be described in alternative scenarios. The preparation of such scenarios is not a simple task as it is easy to create futures that are neither financially or politically viable, nor likely with regard to land use and activities in the studied area. After having selected the scenarios, the entire demand model is run again to test its performance. A comparison is then made between costs and benefits of the different proposed schemes under the different scenarios. Within this solution space, the objective is to decide for the most appealing program of investment and transport policies, which can meet the estimated transport demand in the study area.

Much of the criticism of the four-stage model is directed towards detail, rather than the structure itself [Bates, 2000, p.20]

- Four-stage models are usually programmed for daily average traffic or peak hour traffic demand and do not account for changes in this profile (e.g.: “peak spreading” through changes in traveler behavior or induced by pricing policies).
- Individual factors affecting modal choice are not considered, mainly because of limited dimensions related to the traveler. The concept of bounded rationality also assumes perfect information, which is, in practice, not the case. Habits and imperfect information are strongly influencing individual decision making.
- Usually non-motorized transport modes are not represented in the model, apart from being a mean to access public transport.
- Many models are not run iteratively to reach equilibrium, partly because of the high computational power required to simulate larger (or detailed) networks.

Furthermore, there are limitations in the node-link model representing the travel network: not all real links are modeled (incomplete networks); there are “end effects” which occur because of the aggregation into zones (or centroids); banned turning movements are usually not represented; and intra-zonal trips (although existing) are neglected in the assignment. This criticism is well recognized and different methods have been proposed on the academic level to provide an interface between macroscopic transport demand and microscopic traffic flow models, but they are not used in practical applications of the FSM (for further reading see Huang [2013]).

Within the context of scenario planning, another weakness of the four-stage model is that it is static: an estimated future transport demand (usually obtained by trend extrapolation) is assigned to a defined future supply (a proposed set of schemes and policies). However, it does not incorporate any interaction between the transport system, land use and activity patterns in the time between the base and the horizon year. Land use transport interaction models are one approach to resolve this issue, with certain limitations (see Chapter 3.2.3).

3.2.2 Activity-based Demand Modeling

The conventional trip-based approach, envisaged in the four-stage model, is best regarded within the overall framework of transport systems analysis. Travel demand and network performance procedures are determining flows that tend towards equilibrium based on input from land use and transport supply. These models are entirely trip-based, although the notion of *Productions* and *Attractions* in the first stage (trip generation) can be regarded as a simplified way of handling the link between travel and activities (effectively the reason why we move between any two points), under the condition that trip purposes that can be quantified in the structural data. In the assignment stage, the FSM returns to being only trip-based, but travel demand is “derived” therefore it seems obvious to understand the reasons why we travel and not to limit ourselves to the resulting transport flows. The activity-based models (ABM) were inferred from these considerations; Mitchell and Rapkin [1954] established the first links between travel and activities, and also called for a comprehensive framework and inquiries into travel behavior. At the time, however, their ideas were not further developed, mainly because there was more policy interest in determining total demand and providing the infrastructures, rather than understanding why people actually travel. With significantly reduced infrastructure expansion, demand management schemes have come to the forefront, and with them ABM, because the conventional model does not deliver satisfactory results (due to its theoretical deficiencies). Fundamental contributions for activity-based approaches come from Hägerstrand [1970], Chapin [1974] and Fried et al. [1977]. These contributions were then picked up in the first comprehensive study of activities and travel behavior at the Transport Studies Unit at Oxford [Jones et al., 1983], where the approach was defined and empirically tested, and where initial attempts to model complex behavior were first completed.

Activities take place in space and time and in order to access them, people have to travel. In conventional approaches, descriptive and predictive models only consider activity attributes such as mode, travel time or, perhaps, activity type. However, looking at trips alone misses some of the behavioral richness of linking activities in different locations and periods of time. While trip-based models are satisfied with generating the trips, activity-based approaches include what actually caused the trip. Understanding how people organize activities and the tours associated with them provides, at least in principle, a more solid basis for travel demand modeling. The *travel-activity pattern*, defined as the revealed travel decisions and activities over a specified period of time (often a single day), constitute the basic unit of analysis of the ABM. They are referred to as household activity patterns, from which the individual activity patterns are then inferred (assuming there is some kind of decision process for allocating the responsibilities under constraint). Some activity-based models use tours (or, equivalently, trip chains) as the basic unit of analysis, an approach that reflects some, but not all, of the aspects of a travel-activity pattern.

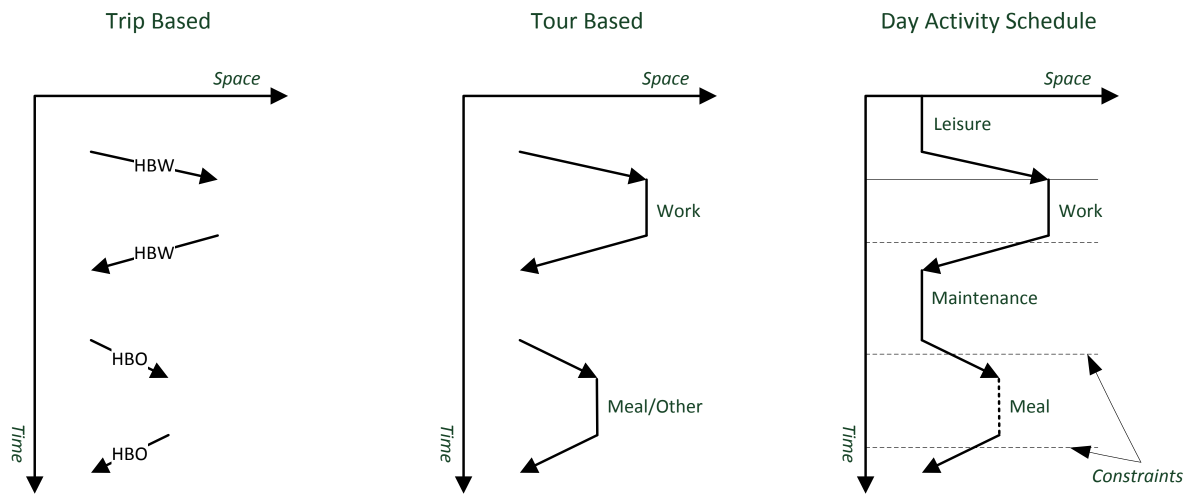


Figure 16: Information contained in trips, tours and activity patterns [Based on: Ortúzar and Willumsen, 2011, p.476]

Figure 16 illustrates the different levels of information contained in trip, tour and activity based analysis of travel behavior. The key aspects of activities and behavior is summarized by Ortúzar and Willumsen [2011, p.476]

- Travel is derived from the need to alter locations between any consecutive activities.
- Scheduling activities involve choices in time, duration, location and access mode for preferred activities.
- Some activities are compulsory (work, education) and set limitations in terms of location and duration; others are necessities of human life (sleep, eat, grocery shopping, etc.) but offer more flexibility; finally, there are activities which make life meaningful (social, recreational, entertainment) and therefore, have high value to be pursued.
- Individuals have time and money constraints.
- Individuals schedule their activities in co-ordination with other members of the household or of their social network in order to maximize satisfaction.
- Individuals have constraints in their schedules by the resources available to them, in particular means of (public and private) transport.
- Longer term commitments, such as residential location and work/educational places denote additional constraints to individual choices.

The challenge is to convert them into a workable and robust activity scheduling process in any given study area. The advent of readily available computer power has made it possible to come up with sound solutions. The following section provides an overview on how activity-based models are actually applied [Cascetta, 2009, p.229ff].

Activity-based models convey travel demand and its characteristics from people's involvement in activities, considering locations and scheduling. They may take place at home or may require travel and are collected by means of a comprehensive household travel survey (travel diary), on a daily or weekly basis. In most cases, work and residence locations are treated as given, although some researchers have proposed to incorporate long-term decisions into the modeling framework. The disaggregated focus is a distinctive feature of ABM, thinking of households and individuals as the decision-making units. With the data obtained from the survey, a *synthetic* population is created. For this, individuals or households are commonly aggregated to classes or "*homogeneous behavioral groups*", which reflect their mutual activity needs, commitments and constraints, in addition to conventional classification criteria, such as income or age. Their predicted activity patterns are transformed to trip-chains with corresponding starting/end points, time periods, modes and other attributes of the single trips in the chain.

Generally speaking, there are two approaches for activity-based models. Econometric ABM uses mathematical expressions that can be estimated through econometric methods. They hold many advantages, including a well-established theoretical basis, a mature methodology, and professional familiarity [McNally, 2000, p.63]. The models are often of random utility type, with the systematic utility functions and the associated distributions of the random residuals specified in a utility maximization problem. The approach proposed by Bowman and Ben-Akiva [2000] can be viewed state-of-the-art in this group of models. Alternatively, ABM may be implemented in a microscopic computer simulation model. These simulations may include random utility to model parts of the decision processes, but typically employ complementary logic and rules to reflect aspects from the household's protocols that may, or cannot be, expressed in purely mathematical form. Effectively, the simulation model can include any decision process that households, or members thereof, apply in their activity pattern. Obviously, this generic property causes considerable challenges in specifying, estimating and validating the model and its components. Most of them use Monte Carlo simulation to represent individuals (or user classes) and their behavior in the transport system. The designation "*Monte Carlo*" comes from using random numbers (as in a famous casino game) to sample from a population with a known distribution of the attribute or characteristic (e.g. 0/1 distribution for Sex, Log-normal for Income, etc.). This is repeated for every individual and then samples are taken for tour length and other attributes of trip making. Given the probabilistic nature of simulation-based models, repeated executions with identical data give different outputs. Therefore, these models have to be run multiple times to generate a set of realizations representative to compute sample distributions, mean values, or other statistics of the output variables. Econometric models may provide probabilities directly, however, because complete ABM are comprised out of a number of separate econometric models, or may incorporate models for which probabilities cannot be computed analytically, determining the distribution or statistics of the model may again require multiple calculation runs. Most applications of such models confine themselves to mean values as output. Similar to conventional trip-based models, there is increasing interest in an integrated supply-demand framework, where the model's trip-chains are assigned to the network, and the resulting level of service fed back to the activity-based model in an iteratively (converging) process.

Regardless of the model type, the development and application of activity-based models is associated with a number of challenges, most notably data collection. In addition to the information gathered in conventional transportation surveys (revealing origins, destinations, purposes, times, etc.), ABM requires data on household characteristics, in-home and outside activities, constraints to decision making for estimation and validation and sometimes more. Provided this data is available, the possible number of alternatives to organize activities and decide where and when to do them is large - not to mention combination of activities, their ordering in time, their scheduling and location, as well as the mode and route taken to access them. Therefore, ABM has to implement a choice set generation step that scales down solution space to a smaller and computable size. In econometric models, heuristics are mostly utilized to generate a reasonable set of alternatives, whereas probabilistic simulation models employ more complex search and selection rules. Another difficulty arises from the fact that ABMs are applied on the individual household level and then aggregated. Hence, they also demand very detailed information on the geographic level of model zones. Typical sources of current and forecast population and household data (primarily census data) do not have this level of detail. Therefore, a synthetic population who's aggregated attributes matches those of known household and population data has to be generated.

To tackle these challenges different techniques and methodologies have been developed. Much of the criticism on activity-based models is directed towards the lack of a consistent theoretical background, which is an unfair statement as human behavior is, in fact, not predictable because it does not follow deterministic decision rules. While attempting to understand such complex behavior is a valid effort, the question arises whether such level of model complexity is necessary to meet the institutional objectives of travel forecasting and policy analysis [McNally, 2000, p.59]. At present, it can only be concluded that the level of abstraction found in the four-step model is inadequate and behavioral information is needed to enhance the quality of results. Activity-based models mark the frontier of travel-demand model development and application. They offer the prospect of representing very complex aspects of travel behavior and providing more informational richness, but are still subject to a number of challenges that researchers and practitioners are actively working to overcome.

3.2.3 Land Use Transport Interaction (LUTI) Models

In the previous section, we argued that activities are pursued in time and space and people travel to access them. Consequently, spatial development (or land use) determines the need for spatial interaction (transport). But by providing this accessibility, transport also determines spatial development. Although this interrelation is widely recognized, it is difficult to empirically isolate the impacts because of the multitude of concomitant changes in other factors. It presents challenges to anyone evaluating integrated land use transport policies aiming to reduce travel demand. Nevertheless, there is growing interest in developing and deploying integrated models in the urban planning context. Several operational models exist, worldwide, but the complexity of the relationships and the absence of a common theoretical basis have led to the situation that models and software have to be reviewed simultaneously. Some of the more commonly known models include MEPLAN [Hunt and Simmonds, 1993], TRANUS [De la Barra 1989], MetroSim [Anas 1995], MUSSA [Martinez, 1996], UrbanSim [Waddell, 2002], TRESIS [Hensher and Ton, 2002], IRPUD [Wegener, 2015] and recently SILO [Möckel, 2017]. A detailed review of these approaches is given by Wegener [2004] and Hunt et al. [2005].

The following section discusses the general requirements of integrated land use transport models [Miller, 2004, p147ff.]. Figure 17 exhibits an idealized model system on a high level:

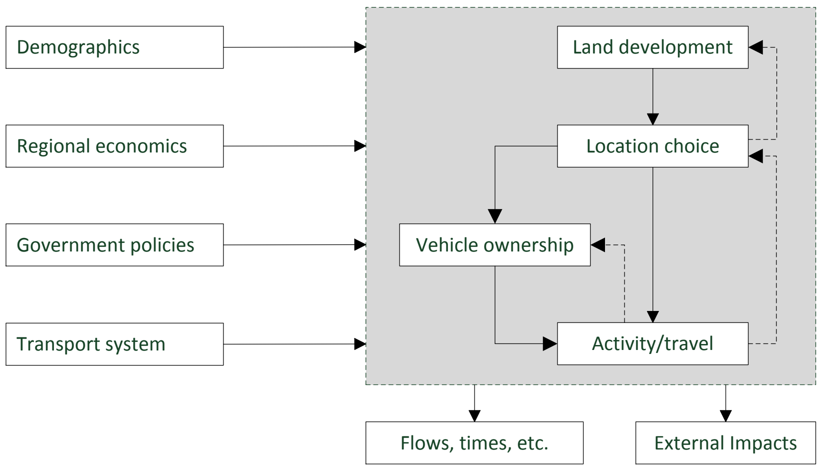


Figure 17: Idealized representation of a LUTI model framework [Based on: Miller, 2000, p.148]

At its core, the system consists of four components: *land development* models the spatial development of the study area over the examined period of time. It is influenced by the *location choice* of households, firms and employees, which again is affected by the trip-making behavior, or *activity* pattern of the population, expressed in terms of origin-destination flows by mode and time of day. In many cases, urban freight movement is included in the investigations, too. Finally, *vehicle ownership* is modeled – an important factor of household travel behavior and mode choice – which, itself, is dependent on the activities and where they are performed. The clear distinction between these components is important, as very different actors, decision processes and time-frames are attached to them. Each of the components constitutes a complex set of sub-models. Their dynamic aggregate behavior arises through the major supply and demand interactions, in and between them. In contrast to conventional and activity-based models, the LUTI approach tries to capture the dynamic evolution of the urban system, rather than searching for convergence in a specified year. In analogy to mechanical systems, the urban system can be viewed as a set of elements with distinct "mass" and "inertia" which dynamically adapt to the forces outside of the system (demographics, regional economics, government policies and transport infrastructure) to produce a defined output (traffic flows, times, external impacts). Obviously, a simple flowchart cannot capture all of the temporal complexities of a dynamic system; however, the vertical hierarchy is chosen to indicate the long- and short-run conditioning effects. That is, most location choices are made within a building stock supply that is "fixed". Similarly, most activity/travel decisions are made given a pre-defined distribution of activity locations (particularly home and work location) and availability of private vehicles. In the long run, all of the four components evolve and are subject to feedback from lower levels of the hierarchy. Financial constraints and other resource constraints lead to time-lags in these feedback loops which generate undesirable supply-demand dynamics. The housing sector is particularly vulnerable, as its ability to quickly adjust to demand volatility is limited. The results are either soaring property prices or abandoned districts. Car ownership is treated separately, because of its special role in connecting urban form with travel behavior (as shown by Ben-Akiva [1974]).

If we turn to the driving forces that influence the urban system, demographic change (age/sex distribution, population size, education level, household composition, etc.) and economic development (economic size, number of jobs, industrial distribution, etc.) have the greatest impact to the overall state of a city. Government policies provide the boundary conditions and the transport infrastructure has an enabling function for activities. Urban development and prosperity is therefore, dependent on all four components. Despite being represented as independent, these external forces are interrelated in complex ways. Government policies and changes to the transport system are almost exclusively viewed as defined model inputs; demographic and regional economic processes are, at least partially, included within the modeling system. However, non-transport related inter-dependencies are not accounted for in such frameworks. In theory, the full range of drivers should be included to ensure that the impact of any policy can be properly analyzed. In practice, this is obviously not possible, but it defines the goal in which all integrated urban models are striving to achieve: assessing short- and long-term impacts of transport alternatives in a comprehensive way.

Prior to setting up an operational integrated urban model derived from the ideal system illustrated above, a large number of design issues have to be considered. Proposed models will address these issues in a wide variety of ways. Here, it is important to assert that there is not necessarily a “right” answer to any of them. As with any modeling exercise, the “best” design depends on the specific application context (availability of data, computational and technical support capabilities, etc.). Moreover, not all of the design issues can be optimized individually; a good balance is required to obtain useful results. We can group the identified design issues into the following five categories. A more detailed discussion on this topic may be found in Miller [2004, p150ff].

- **Physical system representation**

Fundamental to any transport model is deciding how to design the physical elements of the system: land (space), buildings, transport networks and any other forms of physical infrastructure. The representation of the spatial properties (particularly the level of disaggregation) determines the complexities in the modeling and analysis of the urban system. Beside space, the treatment of time is included in this category, too. As in a conventional model, base and horizon year for the model are decided as a first step. In addition, the “dynamics” within the model have to be designed. Many models assume to reach equilibrium in each time step; others explicitly simulate the evolution of the system from one point in time to another as a result of various assumed processes in the model. The system dynamics are further complicated by different time-frames, in which the elements work. Land use decisions are made for decades or more, but many household decisions may be made on an annual basis, and activity decisions can change weekly, or even daily. Accounting for these dynamics within the overall model system is not a trivial task and is approached very differently in the existing integrated model approaches.

- **Representation of active agents**

Various decision-making units (households, firms, etc.) within the urban area with activity patterns and location-relocation behavior produce the movements required to access the desired activities. Other agents that have direct impact on land use/transport interaction certainly include public authorities. The extent to which these agents are incorporated in the integrated model varies: in most cases, government bodies are assumed to stand outside of the model domain and act as input to the model with their policies.

- **Representation of processes**

The most important processes that jointly define the integrated model system dynamics are listed in Figure 17. The role of activities and their spatial distribution was outlined in the previous section; further processes with great impact on the urban system are demographic change, regional economics, network performance and general market processes, representing, for instance, demand and supply in the housing/building sector. Despite lying outside the modeling system, regional economics, of course, directly impact the transport/land use interaction and the degree to which they are included in the overall model framework is an important design decision. The same is true for demographics: household and individual characteristics (education, age, etc.), and their change over time, are crucial to achieve a good model representation. Different approaches to model this are available: often, the demographic profile is treated as exogenous input, and spatial distribution of households made implicit to the dynamic interaction (e.g. a simple Lowry-type model, in which the residential population is distributed in the study area with a gravity or logit approach).

- **Generic issues and implementation**

Overarching the design of the physical system, the various agents and the processes at work are some generic choices in model design. First, the aggregation level has to be defined. We are most used to thinking of this issue in spatial terms (zoning), but aggregation decisions are made for every entity and process in the model, as well as with respect to time and its intervals. Second, boundaries are drawn to determine what is included (endogenous) and excluded (exogenous) from the model. Third, it has to be stated how to model each endogenous process within the model. Here, one can broadly distinguish between "transition" and "choice" models. Transition models are subject to deterministic or probabilistic rules to model changes in attributes, while choice models attempt to model explicitly the decision made by individuals or other entities (random utility models are a common example of this class of models). While some processes can clearly be assigned to one category or the other (e.g. ageing as transition process), others are allocated dependent on the application context, available data, overall modeling method, computational resources, etc. Consequently, implementation of integrated models are known to require a great amount of input data for being set up and calibrated. At any point in time, data availability may prove to be the single greatest constraint on model design and application. Although the situation for data availability has dramatically improved in the last decades in developed nations, this does not hold true developing nations that face equally daring transport planning tasks. Albeit big advances in computational performance, integrated land use/transport models generally need great amounts of memory and processing power. In most applications this is not a restrictive factor, but has to be accounted for in the application context. Finally, there remain technical support requirements, especially for the very comprehensive models. It comprises technical staff operating the model and other institutional resources to run and improve its application. Although these are inherent aspects of operations, rather than design, the complexity of such a model specifies the practical use and, ultimately the success, of the approach.

In summary, land use transport interaction models are aimed at representing the dynamic nature of urban systems in a simulation environment, for which no single modeling approach exists. The general design requirements are similar to non-dynamic transport models, but amplified by the processes that drive the urban system to transition to the next state. Available models (presented at the beginning) follow these general design criteria in a variety of ways, ranging from ignoring one or more completely, to treating the issues discussed in a very detailed way. It is fair to state that there is currently no operational model that fully incorporates all of the aspects mentioned above, but remains the ultimate target.

3.3 Data for Transport Demand Models

Data is the foundation of any transport model. Gathering data is an expensive task so that careful design and planning of survey instruments and procedures is important to avoid unnecessary cost and ensure that collected data is meaningful. Furthermore, survey data errors will provoke errors in the model, which can be more serious than they appear to be in the data itself. Because sample data will always have a certain amount of error, it is important to figure how to minimize them in order to produce expedient and valid models for the user. To understand what sort of surveys and sampling requisites are needed, it is useful to first review the nature of the data needs in transport planning. We then outline the most important issues of data collection and their processing for use in transport modeling, but this is by no means complete. Interested readers are pointed to the book of Stopher and Meyburg [1979], which gives a comprehensive overview of the subject.

3.3.1 Sampling Theory

At the outset, it is useful to distinguish between a census and a survey. A census involves the measurement or interrogation of every member of a *population*[11] of interest. A survey describes a sample from this total population. It may be small or large, depending on various factors, yet, the purpose is to draw a sample that may be considered representative of the entire population. Sample design ensures that the retrieved data provides the greatest amount of useful information at the lowest possible expense. Yet, two difficulties remain: how to ensure a representative sample and how to extract valid conclusion from the sample with respect to the entire population.

Most sampling methods are based on a type of random sampling, where every unit is being picked independently and has equal probability of being chosen. We can further distinguish between simple and stratified random sampling methods. The first assigns an identifier to every unit of the population and then uses random numbers to compile the sample. The weakness of this method is that minority options of particular interests, or very small groups in the population of interest, may be underrepresented. This issue can be handled by the second approach, where information is used *a priori* to form subdivisions of the entire population and then random sampling is performed within these subgroups using the same sampling rate. It is also possible to stratify in multiple (*n*) dimensions; however, the average number of sampling should not be too small. Besides the size of the sampling units, stratified sampling methods reach their limits when data about options with a low probability of choice in the population is required. In these cases, choice-based sampling is recommended. Being a subset of the previous method, the population is stratified according to the result of a certain choice process under consideration. The main advantage is that data can be produced at a much lower cost with the drawback that the compiled sample may be biased.

3.3.2 Model Errors and Complexity

Before we present different methods of collecting data for transport models in more detail, we elaborate on the important issue of errors in modeling and forecasting. The statistical methods used in demand models are valid under the assumption that the functional specification of the model, as well as the data for estimation, has no errors. These pre-conditions are often violated. The main objective of demand modeling is forecasting, and a key problem every modeler faces is which combination of model complexity and data accuracy is optimal to obtain the most precise results with

[11] Population, here, denotes any total of units which are subject to interest, such as people, buildings, vehicles, etc.

a given budget. For this, it is important to distinguish between different types of errors [Ortúzar and Willumsen, 2011, p65f]:

- *Measurement Errors:* occur due to inaccuracies in measuring the data in the base year, such as poorly documented interviews, network measurement errors, coding and digitizing errors, etc. They should be distinguished from the difficulty of defining the variables that ought to be measured and the problems of accurately forecasting variables.
- *Sampling Errors:* arise because models are estimated using a finite data set, representing the entire population of a subject of interest. Sampling errors can be calculated by statistical formulae and are approximately inversely proportional to the square root of the sample size.
- *Computational Errors:* in general, errors involve models that do not have an exact (analytical) solution, but make use of iterative processes. They are usually comparatively small, except for cases such as route assignment.
- *Specification Errors:* arise either because the study object is not well understood or because it needs to be simplified for whatever reason (e.g. budget, time and data constraints). Common mistakes are: inclusion of irrelevant variables, omission of relevant variables, wrong function specifications (e.g. linear vs. non-linear) or neglected variability (no stochastic element). Increasing the model complexity can mitigate the effects mentioned above, but require substantial additional resources and have the risk of introducing data errors.
- *Transfer Errors:* describes the error which occurs when a model which was developed in one context (time and/or place) is applied to a different one. Although adjustments can be made which account for this, the fact remains that behavior might be different in the new context. This must particularly be considered for temporal transfers (future predictions).
- *Aggregation Errors:* every model includes some sort of aggregation to represent the reality, which introduces an error (e.g. grouping certain individuals or zoning systems). Another is the aggregation of alternatives, which limits the range of options to travelers for practical considerations. A good example for this is mode choice, where similar vehicle types are grouped to a single mode (both for public and private). Finally there are errors in model aggregation as well (e.g. flows on links), which are inherent to the chosen method, and therefore not under direct control of the modeler.

Following the discussion about different sources for model errors above, it is legitimate to think about how to optimize the return of investing in increasing data accuracy, given a fixed budget and a certain level of complexity to achieve reasonable results and precision in forecasts. Particularly, the aspect of complexity is interesting because, in some cases, there might be other than financial constraints that limit the access to additional data. According to Alonso [1968], complexity is defined as an increase in the number of variables of a model and/or an increase in the algebraic operations within the variables. Obviously, in order to reduce the specification error (e_s), complexity must be increased. On the other hand, because there are now more variables in the model, the measurement error (e_m) will likely increase as well. If the total modeling error is defined as

$$E = \sqrt{{e_s}^2 + {e_m}^2} \quad (10)$$

it can be seen that the minimum of E does not necessarily align with the point of maximum complexity.

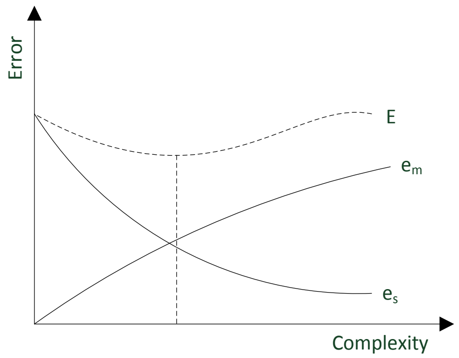


Figure 18: Model error and complexity [Based on: Ortúzar and Willumsen, 2011, p.70]

Figure 18 not only shows that this is intuitively true, but that as measurement errors increase, the optimum value can only be achieved at decreasing levels of model complexity. This finding is particularly relevant when discussing the use or relevance of simple models. Complex models call for a very high quality of data, which is not available for every study context. Under these conditions, simple models may still be very useful, despite their specification errors.

3.3.3 Survey Methods

Different kinds of surveys are available to collect the data for transport models. They can broadly be classified into two basic categories: in *participatory* surveys, the subjects of the measurement participate by answering questions or by other means of personal involvement (e.g.: by holding a GPS tracker). A classic example is a household travel survey, which will be discussed in some more detail below. In *non-participatory* surveys, measurements are taken without the subjects' knowledge. Traffic counts at intersections belong to this class of surveys: the objective is to count the number of vehicles crossing the junction, to determine the mix of vehicle type and the use of the intersection with respect to left turns, right turns and through movement [Stopher, 2000, p.231f].

The key survey format for transport modeling is the household travel survey. It is the most intensive and expensive effort, but produces a rich and valuable dataset. Others may be required for checking its data and to provide complementary information that cannot be collected from households. It is a demand-side participatory survey, which usually involves questioning some or all members of the household regarding the trips they made by all modes of transport both within and outside the study area during the defined survey period (often 24 hours in a given day). In addition, the survey gathers socio-economic information (age, income, car ownership, household size, etc.) and may include questions on opinions, attitudes or preferences relating to special issues of the transport system. Depending on the model type, the layout will vary significantly in level of detail. Trip-based surveys are also known as *origin-destination (O-D)* surveys, but more recently, they are designed to focus on the activities in which people engage, rather than just on their trips [Stopher, 1992]. What is more, the latest development are time-surveys, in which respondents are asked to account for each hour of the day and what they were doing. They include in-home activities and treat travel as a separate activity (which most activity diaries do not) [Kitamura et al., 1997].

Another important aspect of the survey is whether the respondents are asked to recall travel and activities of a previous day (*retrospective*), or are asked to record activities for a day in the future (*prospective*). In the past, travel surveys were conducted retrospectively, often without prior indication to the respondents. Today, we mostly find prospective surveys, as comparisons between these two types have shown that the latter provides more complete data [Stopher and Metcalf, 1997]. In addition to whether or not respondents are prepared for recording their travels, the household survey can be carried out in various ways: face-to-face interviews, telephone interviews, postal surveys and a combination of these methods.

Face-to-face interviews tend to be the most expensive to perform, because of the time the interviewer has to spend not only for the interview itself, but for finding the households, and possibly revisiting an address several times before completing the interview. They are also, in some cases, subject to interviewer cheating because there is no possibility for monitoring. On the other hand, refusal rates for face-to-face surveys are the lowest and the method allows the interviewer to explain more clearly the intent of the questions to the respondent and generally empathize more with the interviewing situations. Hence, face-to-face interviews produce the highest quality of data when done correctly. Technically, they can either be conducted using a paper survey form with the questions the interviewer should ask and space for noting down the answers, or by using a computer to do it. The latter method is known as computer-aided personal interview (CAPI) and offers enhanced flexibility of the survey form, check of conflicting responses, and the immediate entry in electronic form. Although not used in the U.S.A, for example, they are still very common in many other countries and also in India.

Similarly, telephone interviews are performed with the aid of computers (CATI), where the interviewer enters the respondent's answers directly into a data file or by using paper and pencil, which is still a very common method. They offer many of the advantages face-to-face interviews do, such as providing explanation of the meaning of questions to the respondents and probing for answers, when necessary, and they are cheaper to carry out. However, telephone interviews are biased towards households with such a connection (which is not an issue in study areas with high penetration rates), the response rate is significantly lower, and it is often difficult to reach all members of the household compared to face-to-face interviews. Telephone interviews can be retrospective and prospective, whereby in the latter case, the respondents are provided with the survey sheet prior to the call and the interviewer has the task to document the answers in the call.

Mail surveys are conducted using an address file and sending the survey forms to the households, including instructions on how to complete the surveys and a pre-paid return envelope. Very common is also a cover letter by the commissioning institution or government body explaining the background and objectives. They can be used for every type of household survey, be it retrospective, prospective, trip- or activity based. In some cases they are combined with a hotline or dedicated e-mail address to clarify open questions from the respondents. Response rates vary greatly, depending on how well the survey was designed and the general environment (e.g. there is a high public interest in transport-related problems), but they are, on average, lower than telephone or face-to-face methods. In solely mail-based surveys, data entry has to be performed manually after receiving the filled out responses. The high dissemination of internet access has made it possible to submit the data (often optionally) via a dedicated web link and corresponding unique identifiers. In addition to these commonly used methods and their combinations, there are experiments with alternatives. As shown by Reiter et al. [2013] mobile devices (i.e. smart phones and tablets) and wireless internet connectivity provide great opportunities to improve survey methodology.

In sum, household surveys provide very extensive data, which allows estimating trip generation and mode split models. Furthermore, this data provides good information on trip length distribution in the city, an important input to the estimation of respective models. Certainly, transport models need supplementary data, for which other surveys may be used. The most common ones are some form of traffic counts and on-board vehicle surveys. Here, a non-exhaustive enumeration of methods shall be presented:

- *Traffic Count Surveys:* are non-participatory demand-side data required primarily to validate and calibrate forecasting models developed from data obtained in household surveys. They are either conducted by fully automatic traffic counters (e.g. pneumatic tubes, magnetic loops in the road), or by human surveyors, video cameras and satellite imagery. Traffic volumes, vehicle mix, and speed of movements are obtained at the observation point.
- *Roadside Interviews:* give useful information about trips not documented in household surveys. They are often a better method for estimating trip matrices than home interviews because of larger sample sizes [Ortúzar and Willumsen, 2011, p.83]. They involve asking a sample of drivers and passengers of vehicles (private or public modes) to answer a limited set of questions, but in minimum origin, destination and purpose of their trip. Socio-demographic data (e.g. age, sex) may be added, too. As carrying out these interviews requires presence on the street, they have to be well organized, in coordination with traffic law enforcement.
- *Cordon Surveys:* provide information about external-external and external-internal trips of the study area. Their objective is to quantify incoming and outgoing traffic complementing the internal trip generation from O-D surveys. In order to minimize delays, a sample of vehicles is stopped at the control station and questionnaires given to the passengers. However, as Brög and Meyburg [1980] showed, this can lead to biased results. Similar to roadside interviews, it is common to ask some short questions directly.
- *Screen-line surveys*: Screen lines divide the investigated area into large natural parts (e.g. a river flowing through a city) with only a few points connecting them. The procedures are the same as in roadside/cordon surveys and have the objective to fill the information gaps from household and other surveys.
- *On-board surveys*: In some situations the only way to find a representative sample of people using specific means of transport is to survey them directly while they are travelling. Such surveys are mainly participatory, but can also be solely observatory. They are pre-dominantly carried out in public transport; either directly in the vehicles or at the stops and stations. Fare-box surveys which give information about user payment behavior belong to this class of surveys as well.

In addition, there exist surveys focusing on a particular aspect of transport, such as *commercial-vehicle surveys* or *workplace surveys*. These are employed in the case of a corresponding modeling purpose (e.g. journey-to-work) or if this particular aspect has a higher influence on the studied transport area than usual (e.g. a commercial hub or highly industrialized city).

3.3.4 Longitudinal Data Collection

All of the previously presented survey methods are conducted with the implicit assumption that travel behavior can be explained through cross-sectional data. In other words, transport models are developed based on statistical associations across observations obtained at a certain point in time. But researchers are becoming increasingly aware that adding the temporal dimension significantly improves the understanding of travel choices. Longitudinal analyses aim to collect data over a longer period of time to capture the dynamics for a given set of variables. Another reason for advocating the use of such methods is concerned with the statistical problem associated to any model estimation with cross-sectional data: not all variables affecting travel behavior can be measured when collecting data, either due to survey design or simply because it is not possible to do so. Suppose there exists an omitted variable which is correlated, in that cross-section, with a measured variable that is also part of the model because of its statistical significance. In truth, the omitted variable may be affecting the behavior instead. While the measured variable (and its incorrect correlation to the omitted variable) may well explain the variation in the cross-section, it fails to do so over time, unless the correlation between is time-invariant, which is exactly the information longitudinal data comprises.

One approach to gather data is to conduct a *repeated cross-sectional survey*; hereby, measurements from equivalent samples are taken at different points in time with the risk of including a respondent more than once. It is, essentially, a collection of a series of snapshots, rather than a continuous observation over time. The state of the art approach for longitudinal analyses is a *panel survey*: an invariable group of respondents interviewed at different points of time and responses to identical questions are then used to infer changes in the variables of interest. This yields a high consistency in the temporal dimension of the data. Further advantages include more efficient measurement of changes (e.g. by introduction of a certain policy measure), more coherent forecasting, tracking of dynamic travel behavior, control of effects of unobserved heterogeneity and insights on population trends [Kitamura 2000, p.114]. There are different types of panel surveys, like *rotating panel surveys* or *cohort studies*, with specific advantages and disadvantages which will not be discussed profoundly here. For the interested reader, Kitamura [1990] and Golob et al. [1997] provide a sound introduction to the subject including further literature.

3.3.5 Stated Preference Methods

All aforementioned survey methods share the assumption that travel behavior can be explained by observing the subjects of measurement, or in other words, by information on *revealed preferences* (RP). The data is, thus, collected from actual or observed choices by individuals. Interestingly, we seldom observe the choice process itself; normally we only get data on what people report they do (or more often, what they have been doing on the defined survey day). In terms of understanding travel behavior, there are certain limitations to this approach [Ortúzar and Willumsen, 2011, p.94]:

- Observations of actual choices may provide too little variation for building good models. Attribute level combinations may be poor in terms of statistical significance.
- Observed behavior may be dominated by a few factors. Secondary qualitative factors (e.g. public transit information systems, comfort, safety, etc.) are not detected to be important.
- Entirely new policies are difficult to assess (e.g. new mode, electronic road tolling).

These limitations could be resolved, if real-life controlled experiments in cities or transport systems would be carried out, which is not done in practice. Instead, researchers turn to *stated preference* (SP) surveys. SP techniques confront the respondent with a hypothetical (designed) choice set rather than recording his decisions in a given (generally uncontrolled) choice context. The three most common SP methods are *contingent valuation*, *conjoint analysis* and *stated choice*, whereby the latter has tended to dominate in transport research. Despite being commonly utilized in marketing or environmental economics, contingent valuation is not used for transport purposes, primarily because the method only assesses willingness-to-pay for an entire product or policy under investigation and does not provide any information on the individual attribute level. In comparison to revealed preference surveys the advantages of SP can be summarized as follows [Cascetta, 2009, p.537]:

- Investigations of choice alternatives not available at the time of the survey.
- Control of relevant attribute variation outside the presently observed range to obtain improved estimations for corresponding coefficients (e.g. fuel price scenarios).
- Introduction of new attributes not accounted for in the real choice context (e.g. vehicle air condition).
- Collection of more information (larger samples) per unit cost because respondents are usually questioned about several scenarios.

The fundamental problem with SP is how well one can trust respondents that they actually do what they stated. In fact, experience was initially not so promising, but in the 1980's sound agreement with reality was achieved [Louviere, 1988], by reason of far better data collection methods and survey design expertise, skilled survey staff and quality control measures. These discrepancies between stated and actual behavior may arise for various reasons: for example, the choice context might be or appear to be unrealistic, certain attributes which are important to the decision-maker could be missing or there may be fatigue effects after a greater number of presented choice situations. Deeper analysis of possible causes for this is not within the scope of this research, however, it should be noted that some of the problems are typical for SP techniques, whereas others can be avoided by careful survey design and execution. The interested reader is encouraged to consult the excellent book by Louviere et al. [2000] on this subject.

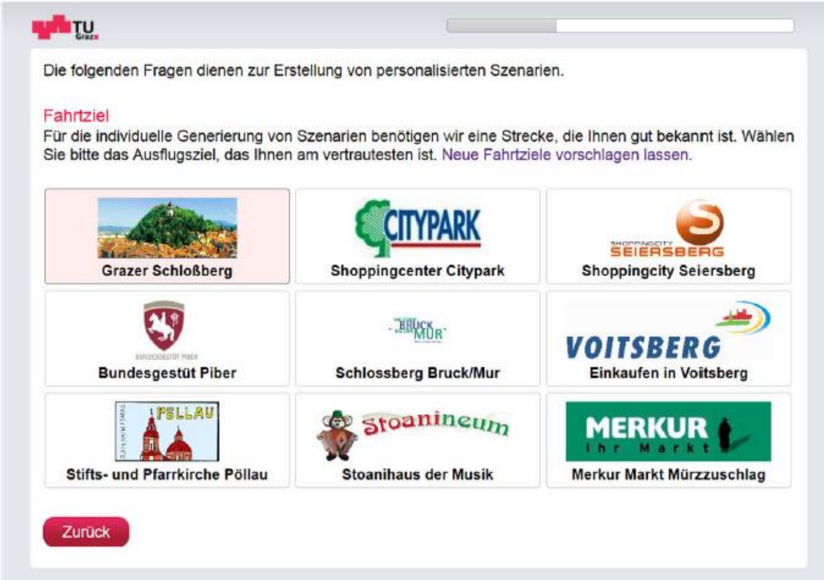


Figure 19: Stated Preference survey template [Reiter et al., 2013]

An innovative approach was introduced by Reiter et al. [2013], who utilized tablet PC's and mobile communication network technology to generate realistic choice sets (tailored to the respondents' input on the street) in order to survey willingness-to-pay for road pricing schemes.

3.3.6 Supply-side Data Collection

Until now the analysis has been focused around how to gather information on people's mobility behavior, so essentially, about travel demand. Obviously, transport modelers require an accurate representation of the supply side (transport networks, land use) too, in order to be able to set up a sound (transport) model. As with demand data, one of the early tasks of the modeler is to determine which level of detail is appropriate for the study purpose, considering the trade-off between costs and accuracy in the final decision. In principle, highly disaggregate zoning ultimately captures every single household, its location, access points to the network, etc. The great advances in *geographical information systems* (GIS) technologies have made digital map and its metadata abundantly available and offer a rich source for developing new models. Many of the software packages now offer interfaces to integrate GIS data and to create entire networks in a very short amount of time (see, for example, PTV [2015]). In this context, Sturm and Fellendorf [2016] have proposed a new approach, which allows generating productions and attractions for a conventional transport model on every link and a very detailed analysis of expected demand. However, the high accuracy on the supply side leads to reduced model stability over time because one would need to forecast, at the same level of detail, behavioral changes in the individual household. This is very difficult and mostly unnecessary to do. Therefore, whenever predictions on the future are involved, a lower level of detail is recommended. In this section, we want to give a brief overview on design guidelines for zoning and network systems and related survey methods.

- **Zoning Design**

A zoning system splits the study area in a manageable number of parts for modeling purposes. The individual households are aggregated within a zone and trip matrices are developed according to this level of aggregation. The two main dimensions that define a zoning system are number and size of zones. The two are obviously related: the greater the size of zones, the smaller the total number. In practice, it is common to develop a zoning system specific for each study context, which is inefficient if one seeks to perform several studies in an area. Moreover, it makes it difficult to use data from previous studies and compare results over time. The first step of zoning design is to define the study area itself. This decision is influenced by a number of factors, but pre-dominantly by the objectives of the investigation (short-/long-haul trips, intra-/inter-city trips, etc.). Moreover, it is defined by the general boundary conditions for traffic. For example, a smaller urban area might not generate much traffic itself, but has an interest to manage through trips and considers a bypass. Similarly, the study area has to be expanded when commuter traffic from sub-urban areas are under investigation. Usually, the external area is also divided into zones to allow for variations in the incoming traffic and possibilities for re-routing. In a computer model, zones are represented as if all their properties were concentrated in a single point, the *zone centroid*. These centroids are attached to the network through *connectors*, which carry the attributes of time and costs to access the network. Equally important is the node in the network it connects to. This should be a realistic entry (exit) point for the respective zone. A practical first approach is to take the center of gravity for each zone and measure its distance to key nodes in order to quickly produce centroid connectors. They are critical factors for the quality of the entire model because they influence to a high degree the route and mode choice. As there is no strict and objective design approach, the experience and skills of the modeler become very important. A useful list of design criteria may be found in Ortúzar and Willumsen [2011, p.131], but in general, it is advantageous to build up hierarchical zoning systems, which follow the political partitioning of the study area up to a certain extent, as well.

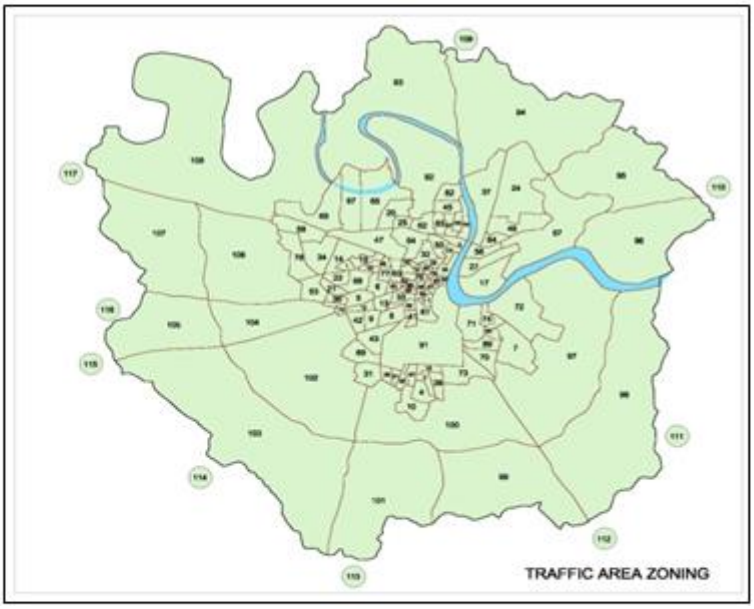


Figure 20: Study area zoning in Agra CMP [UMTC, 2011]

- **Network inventory**

The transport network may be represented at different levels of aggregation. In practice, the network is represented by directed graphs, i.e. a system of nodes and links joining them, where nodes usually stand for junctions and links for homogeneous road sections between them. Links have distinct attributes, such as number of lanes, length, travel speed, etc. and are usually unidirectional. Additional information includes speed-flow relationships, and road capacity in terms of passenger car units (PCU) per hour. This information is particularly important for the (iterative) route assignment model. A subset of nodes is associated with zone centroids; a subset of links to centroid connectors. Digital map data are vastly available and the primary source for network data. They remain to be erroneous, which means that manual checking and correcting are essential for any modeler. Furthermore, the centroids and the connectors may not be appropriate for the particular objectives of a study and have to be re-arranged. Another problem with link-node representation is that using a junction comes at no “cost” (in terms of lost travel time). In practice, some turning movements may be harder to perform than others or not even allowed at all. In order to represent these features, certain movements can be penalized or restricted by manual manipulation, but thereby the efficiency gains from digital map data are lost. The level of disaggregation can further be increased through traffic simulation models, which represent junctions and roads in a very detailed way to specify the capacity of the investigated road section. Latest developments in this research field are pointed towards integrating microscopic traffic simulation models in macroscopic transport demand models, as proposed, for example, by Huang [2013]. As the study area is bordered by the outside world, so are network systems, usually subsets, by larger systems. They may be cut off from them, thus defining access (or cordon) points with dummy links used to connect them to the external zones or simulate external demand flowing in and out of the represented network.

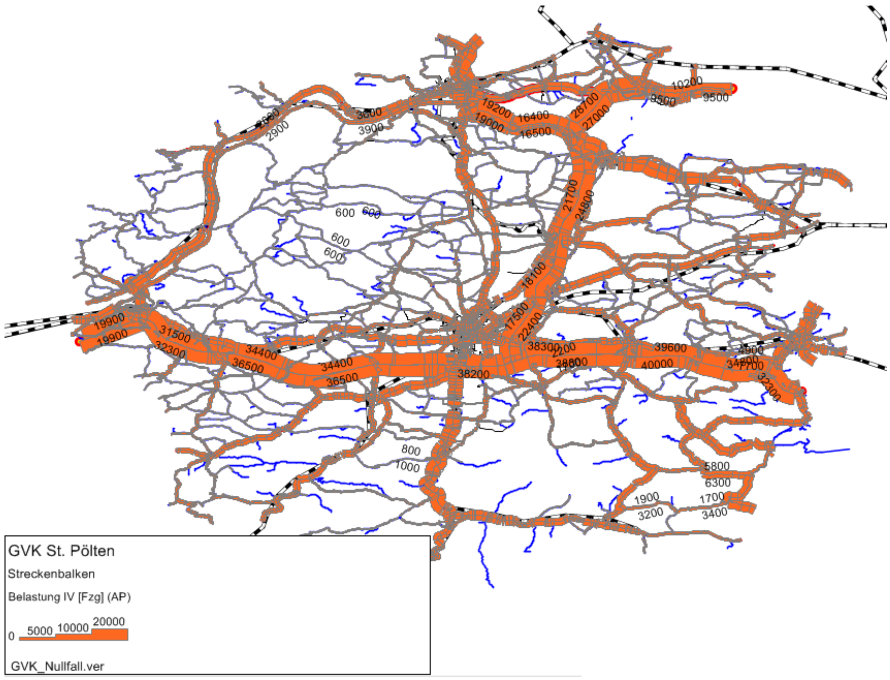


Figure 21: Representation of road network in VISUM including cordon points

Specific properties of public transport networks add complexity to the modeling process. They require an identification of the route taken by each service as a unique sequence of links. Moreover, stops and stations where interchange to other services is permissible have to be defined, as well as frequency, timetables and fares of a service included in the network description. Access to stops may be by foot or other mode, which is represented by centroid connectors in the simplest models and by auxiliary networks of access modes in more detailed models. For this reason, centroid connectors for public and road networks are always different. It also has to be determined, whether public and road networks shall be modeled independently from each other. In the case of metro systems or monorails this would be feasible; however, for bus and tram services, congestion effects are thereby omitted. In addition to road congestion, some models also account for passenger congestion effects, i.e. overcrowded buses lowering user comfort.

- **Land use survey**

Another important inventory that has to be carried out concerns land use because it ultimately determines the activities and the access to them in the study area. Unfortunately, it is often not documented so extensively and, in many cases, found to be outdated. Unlike household surveys, it is not possible to use sampling methods because the findings cannot be expanded to the entire study area. Therefore, a census is required, which typically uses both non-participatory (e.g. aerial photography, land-use maps) and participatory methods, such as questionnaires for building owners to assign current uses, floor area and employment [Stopher, 2000, p.237].

3.4 Dynamic Transport Models

The approaches presented hitherto are state-of-the-art in travel demand modeling. They depict in detail the movement of people and goods in a defined area, typically over the course of a day and produce the aggregate indicator of total daily travel demand. Hence, they can be dynamic, in terms of daily demand variation. But urban planning requires a second, long term, time perspective to be included in their models. Transport master plans look 10 or more years into the future. Conventional models resort to projecting the key boundary conditions (vehicle ownership, transport infrastructure expansions, new land development, etc.) and re-calculate demand based on these assumptions for the defined horizon year: but they do not include any interaction between the boundary conditions and, therefore, miss important information on the future state of the system.

Transportation systems are highly complex as they involve multiple stakeholders, various modes, incomplete information on the current traffic situation and significant time delays for measures to become effective. The problems of transport systems are rooted in its basic structure and dealing with one issue may very likely cause another one elsewhere in the network. Therefore, a system approach is needed that caters to the dynamic interactions that exist between the elements and reveals counterintuitive behavior entailed by them. To illustrate this, we refer to a common mistake of early transport planning: in order to mitigate traffic congestion, new roads were built or existing ones expanded. Increasing the supply side to meet growing demand seemed reasonable; however, higher journey speeds also attracted additional demand because accessibility had improved. After a few years, congestion levels were similar, or worse than they originally had been.

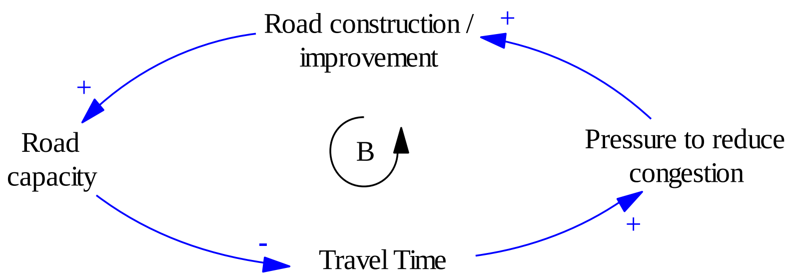


Figure 22: Vicious circle of road expansion

Today, this powerful feedback structure is well recognized and planning efforts focus on promoting shift to environmentally friendly modes (i.e. public transport), rather than road expansion. System analysis allows to treat problems in a holistic manner and comprises the long-term/short-term trade-offs that certain policy options are subject to. The System Dynamics methodology addresses exactly the shortfalls of the step-by-step approach and can help manage and control transport systems in a better way [Abbas and Bell, 1994]. We, therefore, elaborate on the suitability and appropriateness of System Dynamics methodology for transportation modeling and provide an overview of models from literature review in this section. A detailed introduction to SD is given in Chapter 4.

In general, transport models serve two main purposes. The first is to reach a better understanding and insights into the system itself, the second is to employ models for prediction and policy analysis. At this point, in accordance with Abbas and Bell [1993], it is fair to state that SD is considerably helpful for enhancing understanding and policy analysis, rather than precisely predicting future states. There is a common misunderstanding – also in other research areas – that System Dynamics models aim to be “better” in the sense that they deliver more accurate results, which leads to them being assessed merely on their numerical validity. However, the paramount aim of SD models is to unveil the feedback structures and counterintuitive system behavior. It is to provide a deep understanding of the system and a test bed for different policies. In the transportation context, SD should be viewed as complementary to state-of-the-art models helping to identify appropriate simulation scenarios and accounting for interactions which cannot be represented in equilibrium-based models. Table 5 lists some of the advantages and disadvantages of System Dynamics as modeling framework for transportation problems [Abbas and Bell, 1994, p.383ff]:

Table 5: Advantages and disadvantages of System Dynamics in transportation modeling

+ Systematic detailed representation of complex, large scale systems + Explicitly accounting for feedback and interactions (not equilibrium-based) + Time-dependent simulation + Holistic view on transportation including adjacent sectors (e.g. land-use) + Scalable model detail and data requirements + Highly efficient for a priori hypothesis tests + Enhanced communication and understanding of transport problems among stakeholders + Capturing of short- and long-term effects + "Real-time" policy testing and analysis	– Spatial representation and distribution effects difficult to account for – Mainly aggregate models (showing impacts in terms of magnitudes, not accurate numerical values) – Generally deterministic, but randomness can be accounted for – Validity of models / structural based models

A literature review reveals that a multitude of transport topics has been addressed applying System Dynamics. Building on the reference paper by Abbas and Bell, Shepherd [Shepherd, 2014] presents 50 additional studies from peer-reviewed journals and recommendations for future application of the SD approach. Here, we want to highlight a number of successful models with relevance to the objective of this thesis. In particular, we want to show the flexibility of the methodology in terms of model detail and outcome, and discuss the advantages and disadvantages of so-called hybrid models, which combine System Dynamics with other modeling techniques, typically agent-based models.

3.4.1 Large-scale Models

This cluster of System Dynamics models builds upon the standard macroscopic transport model approach and augments it through dynamic feedback structures between land use, economy and the transport system. The models require detailed set of data, as the transport demand calculation is based on the same sub-models (trip generation, trip distribution, mode and route choice), as the four-step algorithm. Depending on the model approach, variables are all endogenous in the SD framework or are interlinked with other software modules that perform a certain part of the calculations. Examples for such models are MARS (Metropolitan Activity Relocation Simulator) [Pfaffenbichler et al., 2010], AsTRA (Assessment of TRAnsport Strategies) [Fiorello et al., 2010] and UDM (Urban Dynamic Model) [Swanson, 2003]. We now briefly present their scope and structure.
The MARS model is a dynamic land-use transport interaction model, which is based on the principles of *synergetics*. It has been applied to cities across the world, such as Stockholm, Hanoi and Washington D.C in the United States, but also to national transport planning tasks (e.g. Austria). MARS consists of sub-models which simulate passenger transport, housing development, household and workplace migration; it also tracks assessment indicators, such as pollutant emissions. The main link between transport and the location choice model is achieved via accessibilities (defined as potential to reach places for work and leisure); the information is passed from the transport model to the location choice model, which defines the spatial distribution of households and employment, which again, constitute the input for the transport model in the next time step. The land price influences both the residential and workplace location choice models and vice versa by changing the availability of land. The transport model covers trip generation, trip distribution and mode choice, but does not include route choice. Available means of transport include walking and cycling ("slow"), public transport (bus and rail separately) and private vehicles. Mode choice is modeled using so-called friction factors, which were

developed within a long research program with a partner university. By drawing exclusively on the SD framework, MARS has the inherent disadvantage of not accounting for the available road network, but is useful to project long-term transport demand trends.

The Urban Dynamic Model, developed by John Swanson, closes this gap by linking the System Dynamics model to conventional transport models, which are very good at path finding through a network of thousands of links. The downside of the improved level of detail is significantly reduced computational speed for larger networks. The UDM caters for both applications by providing a generalized cost matrix for longer-term strategic studies as well. It has been in use since 2000, predominantly for cities in the UK. The critical factor for the UDM is supply of the necessary transport information. If a transport model already exists, it is possible to convert its network structures to a form that the UDM can use, but difficulties (e.g. model calibration) remain equal to other land-use and transport models. The largest System Dynamics transport model is AsTRA. Developed since 1997 by three partnering research institutions (Fraunhofer ISI, IWW Karlsruhe and TRT Trasporti e Terriorio), it is designed for the strategic assessment of transport policies at the European level. It takes into account feedback loops between the transport and the economic system and consists of 8 different modules, which are large SD models in themselves. The macroeconomic module, for instance, simulates the interactions between 25 economic sectors. The model provides simulations for all EU member states plus Switzerland and Norway. It covers a time-frame of 60 years (starting in 1990) and currently includes more than 30 million variables[12]. Over the past years, other versions of AsTRA have been developed (e.g. country-model for Italy). It is less detailed than traditional transport models and does not include route assignment. Its main field of application is analyzing the impact of strategic transport policies, such as pricing or taxation. Common to other large-scale SD models, traceability and validation is very difficult. The model, thus, becomes a "blackbox" which impairs one of the key strengths of the SD methodology: a deep understanding of the dynamic feedbacks that govern the system.

3.4.2 Small Models

The second family of models is often referred to as "small" models in the SD community. They mostly consist of few variables and make the underlying feedback structures very accessible for the model user. They are typically employed to highlight counterintuitive system behavior to a broader (even non-expert) audience and provide a powerful tool for communication of policy implications. We pick two examples, which also target urban transportation challenges for Asian cities. Wang, Lu and Peng [Wang et al., 2008] developed a simplified, high-level interaction model between population, vehicle ownership, tailpipe emission pollution, GDP, travel demand and available infrastructure, applying it to a case-study in Dalian, China. Car ownership policies are studied and the wider system effects on economic development and population growth. The study finds that restriction of vehicle ownership actually boosts city GDP and significantly increases its total population in the simulated time-frame. Despite its simplistic structure, the model revealed an important insight, that is, the recommendation to contain private vehicle ownership in high density Asian cities, due to the negative impacts of emissions to environmental quality. In a more sophisticated approach, Archaya [Archaya, 2005], [Morichi and Archaya, 2013] presented a model that looks at the issue of decreasing modal share of public transport in developing countries, caused by the pressure from private motorization, particularly in Asia. The model captures the key interactions between rising incomes, vehicle

[12] In Vensim (SD software package) terms: this includes all „auxiliary" variables which make certain calculation steps more explicit, but do not really increase the explanatory variables of the model

ownership, congestion and attractiveness of public transport. It is applied to a fictional city of 3 million inhabitants for a 50 year time frame and tests three policy options, namely high investment in road infrastructure (very commonly pursued by cities in developing Asia), as well as early and late introduction of mass transit options. Akin to the findings of Wang et al., the simulation results demonstrate that rapid transit is important to tackle the challenge of road congestion for such cities. In addition, the base scenario also provides an experimental platform to understand the complex dynamics of urban transport systems.

3.4.3 Hybrid Models

So-called "*Hybrid models*" combine the strengths of System Dynamics for deterministic macroscopic feedbacks with the capabilities of agent-based modeling to simulate stochastic, microscopic processes (e.g. mode choice, purchase decision). A model of this class has been developed, for example, by Kieckhäfer, Axmann and Spengler [Kieckhäfer et al., 2009] and Neumann [Neumann et al, 2014] to support powertrain strategy decisions in the automotive industry. In both cases, the model framework consists of two separate software modules, which are linked to each other by exchanging information. The customers are modeled as reactive agents that make their decision based on different information and if-then rules. Part of the information is provided from the System Dynamics module that models the change of the variables over time. While the information can change over the simulation run, the decision rules typically remain constant. Thus, the same agent is able to take different decisions at different points of time. Although there exist only few of these models and are laborious to set up (extensive data requirements and challenging to validate), they could become more relevant in the future to overcome the deterministic nature of SD models, which are often criticized in the system modeling research community [Scholl, 2001].

3.5 Transport Demand Models in India

This section and the outline on travel demand model application contained therein, was presented at the 95th Annual Conference of the Transportation Research Board in Washington [Moser et al., 2016].

Typical for many developing and emerging countries, urban growth in India has not been strategically managed in the past. Cities grew organically and authorities pursued an opportunistic policy approach with the goal of providing urban services according to the demand. However, the accelerated pace of urbanization and income growth, calls for a shift to strategic urban development. In this section, we present the fundamental federal policies that provide the guidelines for urban planning in India, and discuss the so-called *Comprehensive Mobility Plans* (CMP), which were derived from them. A detailed analysis of the CMP documents reveals the key metrics and properties of urban mobility in India and puts it into a global context. The data retrieved from this analysis forms the basis for calibration and validation of the simulation model presented in this thesis.

3.5.1 The Comprehensive Mobility Plans

Background

Historically, Indian cities focused more on improving basic services such as water supply and sanitation and did not look at transport as a key priority area. As a result, most cities did not have any strategic plan to assess their urban transport demand and the supply measures needed to cater it. Transport is only one part of the city Master Plans, which were intended to provide long term land use planning. Traditionally, they only covered the road area requirements of a given city, but did not include the mobility patterns and the mode specific requirements of public, non-motorized and private transport

[MoUD, 2015]. A few cities issued Comprehensive Traffic and Transportation Strategy (CTTS) reports, but they did not follow any particular template or standard in developing them.

Objectives & Guidelines

The Government of India, over the past decade, has undertaken many initiatives to guide urban development on an energy-efficient and low-carbon path like the National Urban Transport Policy (NUTP), National Mission for Sustainable Habitat (NMSH) under National Action Plan on Climate Change (NAPCC), Energy Conservation Act, and so on. Transport was included as a crucial component in each of these policy initiatives. NUTP was the most relevant among them, since, for the first time, it highlighted the need to provide people-centric mobility measures, rather than vehicle-centric mobility measures. It highlighted the need for cities to encourage usage of public and non-motorized modes of transport and simultaneously curb the rising demand for private motorization.

In order to make the implementation of sustainable transport practices advocated by the NUTP more attractive, the Ministry of Urban Development (MoUD), Government of India (GoI) initiated Jawaharlal Nehru National Urban Renewal Mission (JNNURM) starting in 2007. It was intended to provide financial support for various sustainable urban infrastructure projects (including transport) in 65 cities with a population greater than 1 million inhabitants. It aimed at developing physical infrastructure in cities on the condition that they carry out institutional and governance reforms. As a part of these reforms all eligible cities were asked to develop Comprehensive Mobility Plans, which would analyze the current mobility patterns of the city, provide strategic plans for the projected travel needs over the next two decades and identify pilot projects, which align with the action plan. MoUD would then provide up to 50% of the pilot project cost to support its implementation.

In order to help cities develop these plans, a detailed set of guidelines were provided by the MoUD [MoUD, 2008]. The guidelines covered multiple issues including setting the vision for the city, primary and secondary data collection, travel demand forecasting, pilot project identification and an implementation roadmap. This document should help a city grow on a sustainable transport pathway. In an international scope, comparable guidance for urban transport planners is provided by the Department of Transport in the United Kingdom [Department for Transport, 2015]. Transportation Master Plans issued by the various Metropolitan Planning Organizations in the United States, on the other hand, do not follow a standard manual.

Discussion

Review of these documents showed that the actual preparation differed substantially from the original intent and the methodology provided in the guidelines, particularly regarding data. Only a fraction of what the templates recommended, was actually collected and the samples were usually not as big as demanded. In fact, in most cases, documentation did not provide any justification for the sample size and field survey methodologies adopted. Furthermore, many cities did not maintain secondary information on the existing street and public transport infrastructure, land use patterns, etc. In summary, this resulted in the demand forecasting and planning being based on a macroscopic understanding of the existing demand and supply scenario in the cities but not much of a disaggregated set of explanatory indicators. The mobility indicators developed by various consultants working across Indian cities, though, is observed to be reasonably similar, making it possible to carry out a comparative analysis. The following points explain some key observations from the planning methodology and recommendations in different CMP's.

The delineation of the planning area varied from city to city. While MoUD suggested cities to take up the entire urban agglomeration area when planning for the future, some cities only considered their municipal limits, thereby leaving out the relevant outskirt areas which are likely to grow faster in the future and adding on to travel demand in the city. A standard four stage travel demand modeling framework was the chosen methodology in practically all cases. Licensed software packages like TransCAD, CUBE or VISUM were used by consultants to develop the travel demand forecasts. However, since they were not developed to represent the traffic conditions in Indian cities, they could not accurately account for the heterogeneous mix of vehicles on the road found in the local context, like auto-rickshaws, for instance. Therefore the travel demand forecasts are likely to be erroneous, even those used by the consultants when preparing the planning documents. With the exception of a few cities, most local government bodies do neither have the required licenses, nor the capacity to test and update the developed models after the final report. With the exception of Delhi, Bangalore and Chennai, most cities followed a 'predict and provide' style planning procedure, where current travel patterns were extrapolated in a twenty-year time horizon and identified the supply measures needed to satisfy this demand. Very little attempt was made to identify demand-side management measures in order to reduce the need for travel, and practically no scenario analysis has been carried out to identify alternative and more sustainable methods. While some of the reports highlighted public and non-motorized transport as key areas for policy interventions, 97 of the 133 urban transport projects eventually funded through the JNNURM scheme (equaling around 65 percent of the total allocated funds for this purpose) were utilized for road widening and construction of flyovers, further strengthening a car-dependent, yet unsustainable, development of their transport system. The CMP's did not include strategies to reduce emissions from transport without compromising the accessibility and mobility needs of various social groups. Furthermore, they were not cross-checked with other policies like the NAPCC. Since most of the mobility plans have been prepared by third-party private consultants, the technical capacity of city officials who had to execute the proposed projects was not being built up in the process. In summary, the plans ended up as a desired list of – mainly road infrastructure related – projects that would meet present and future mobility demand without considering its environmental and social impacts and the original vision to achieve livable and sustainable cities.

To address the methodological drawbacks like the lack of disaggregated set of indicators covering various socio-economic groups and the environmental impacts of the current and recommended transportation system in the previous CMP's, MoUD released a revised set of guidelines in 2014. Three cities have initiated the process of developing their CMP's under the modified guidelines, but were not published at the time of data collection for the current paper.

Despite all criticism, for the first time, data related to the transport sector in Indian cities was collected and measures guiding the development in the future were identified on a wider scale using common guidelines. Around 43 cities developed respective planning documents and submitted them for the approval of MoUD until 2014. This turns them into a valuable data source for conducting research on urban mobility in India as a whole and to discover differences and common challenges for city authorities across the country. The current paper reviews 17 of them complemented by CDP and CTTS documents for some cities where a CMP was not available and presents the key findings emerging from widened perspectives. The public availability of the final reports is limited, as is their documentation in some cases. This poses the challenge to find data points that are available over their entire range. Therefore, we only use those planning documents which contain an adequate amount of data and concentrate on a smaller set of indicators, but recognize the need to expand the database to obtain improved results and additional findings.

3.5.2 CMP Analysis and Findings

We base our analysis on the parameters that specify travel demand, which are: population size (POP), Per-capita Trip Rate (i.e. the number of trips every citizen undertakes daily) and the average trip length (ATL). The unit of measure is total passenger kilometers travelled per day:

$$\text{Travel Demand [pkm]} = POP * PCTR * ATL \tag{11}$$

While population figures are treated as exogenous input to transport demand models, the amount and length of trips are a result of the travel patterns in the study area. State-of-the-art models estimate total demand as a function of people's activities and behavioral choices. We, on the other hand, adopt a different approach: we examine if variables within our generated data set, such as household size (HHS), income (HHI), vehicle ownership (VOS), urban density (POPD) or city size (AREA) have an empirically significant impact on the values specifying demand (ATL, PCTR). This also allows us to check if certain findings, which have already been validated in the context of a single city are true for other cities, as well; in short, are there general lessons to be learned for urban mobility in India that we can derive from the existing CMP documents? The following sections present a detailed analysis of each of the determining variables for travel demand. This is followed by a separate discussion of land use patterns and the implications to transport thereof. A summary of the collected data is provided in Appendix A-1; values for PCTR and ATL hereby include motorized and non-motorized (walk, cycle) transport. Land use distribution refers to AREA, unless stated differently.

Population

Population size is a sensitive parameter to transport demand because it is dimensionally much larger than the others in the equation above (by factor 105-106). The CMPs either reference to the city's Master Plan (e.g. Amritsar) or develop independent estimations for the study purpose. As to every planning exercise, forecasts are subject to uncertainty; however, few of the final CMP documents account for this and do not explicitly consider different scenarios. In our first analysis we, therefore, check the CMP estimates for consistency with available United Nations data [United Nations, 2012]. Census of India has not published separate long-term population projections, which we could add to our review. Comparing the data proves to be difficult by some means, because each study has its own definition of where the "city" actually ends. Many CMP study areas comprise adjacent districts to the municipal core and have different population figures than the World Urbanization Prospects. We, therefore, draw on compound annual growth rates (CAGR), which express relative, not absolute, growth. The comparison reveals interesting gaps (see Figure 23): in 7 cases UN-data suggests higher growth rates, whereas in 9 cities they are lower; 5 cities did not provide any data for the 2030 horizon at all. For Agartala, Chandigarh, Ludhiana, and Nashik, in particular, it seems advisable for planning bodies to check their base assumptions and revise their estimates. Besides, the measures envisioned in the mobility plans are going to be designed for demand scenarios that may never come to effect. Given the high investment in transport infrastructures and the long-term lock-in they create in the shape of the city, the adopted mobility plan may, ultimately, not be very effective. Moreover, we reason that future CMPs should take adequate care while developing projections in order to develop effective plans and infrastructure recommendations.

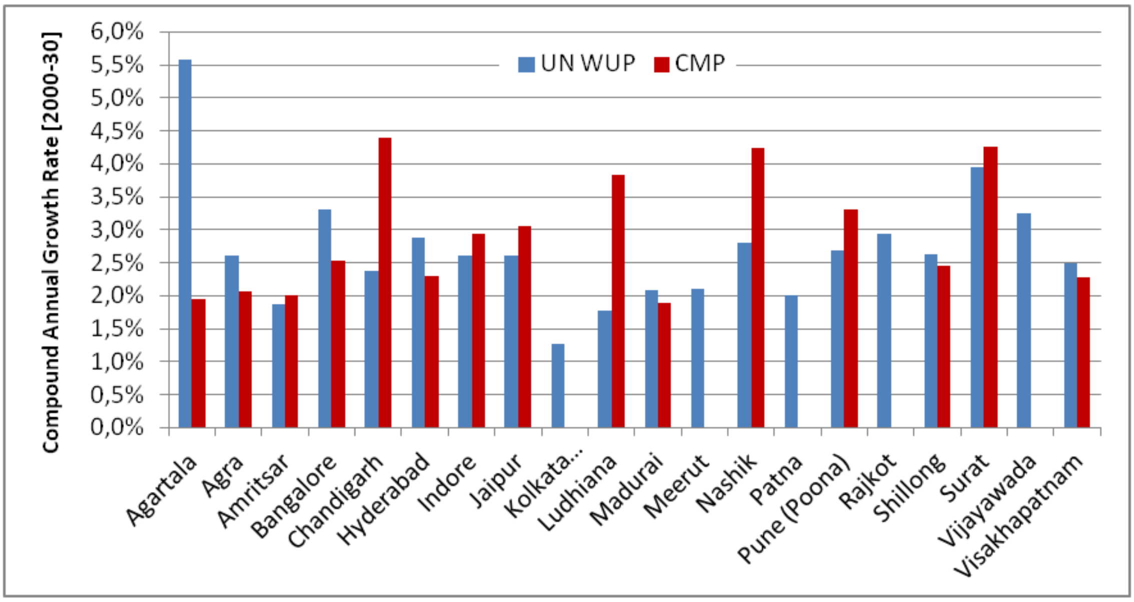


Figure 23: Comparison of United Nations and Indian CMP population estimates [Data: UN, 2013]

Per-capita trip rates

As discussed, for instance by Singh [Singh, 2005], trip rates usually display positive correlation with motorized vehicle ownership. Therefore, we apply a linear regression model to our data, but find no empirical evidence to support this hypothesis (Table 6). In contrast, Gadepalli et al. [2013] found in a case study for Patna that trip rates were very similar across households with varying incomes, despite low income groups owning mostly bicycles, and higher income groups possessing motorized two-wheelers or even cars. Plotting our data seems to support these findings.

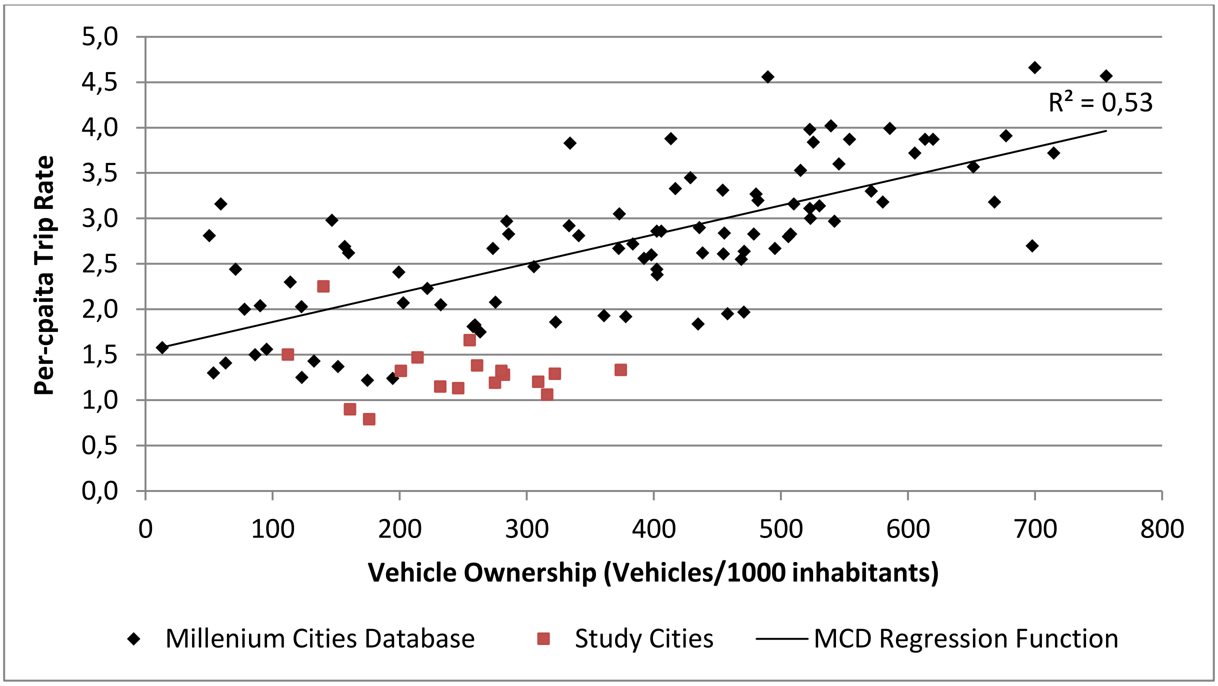


Figure 24: Per-capita trip rates in Indian sample cities compared to foreign cities [Data: Kenworthy and Laube, 2001]

Even for cities at motorization above 200 vehicles per 1000 inhabitants, trip rates do not increase much. If we compare this to other cities in low-income countries [Kenworthy and Laube, 2001], we find that this is an exceptional characteristic of urban mobility in India. Testing for other explanatory variables, as well as using non-linear and multivariate regression models do not produce any statistically significant results, either. We, therefore, conclude that per-capita trip rates are randomly distributed in our dataset.

Average Trip Lengths

Trip lengths are subject to two different phenomena in Indian cities. On the one hand, the majority of trips are short (only up to 4-5 km) even in the large metro cities because of the significant presence of urban poor. Those people tend to stay close to their work place and are captive to walking and cycling, which limits the distance they travel to access various activities [Mohan and Tiwari, 2000]. On the other hand, we can observe low density sprawl at city borders, which result in longer distances for daily commutes to the central business districts, where regular jobs are located [Pucher et al., 2005]. The average trip length indicator reflects which of these two driving forces is dominant in the local context. From international reference data [Kenworthy and Laube, 2001], we assume that sprawling (measured in population density POPD) leads to longer trips. We test, whether this also holds true in our dataset. We opt for a linear logarithmic regression model and find that the residuals are significant (at the 90% confidence level), which verifies our hypothesis and supports the call to maintain compact city structures with mixed land use. Furthermore, it is an argument for better land use control as a measure to hinder undesired urban growth at the outskirts. Alternatively, using the same model with AREA as a predictor variable produces even better results, both in terms of model fit and significance values for the residuals. A possible explanation could be that many planning documents comprise the surroundings to the actual city, which are mostly rural, sparsely populated areas. In certain cases, this leads to much lower density values for the entire study area. A complete summary of our regression analysis for PCTR and ATL is presented in Table 6, including the statistical metrics.

Table 6: Summary of results for (linear) regression analysis of CMP mobility indicators

	Model	X	A			B	Model Fit	
			Coeff.	t-Stat.	p-value	Coeff.	Multi R^2	F-Stat.
CMP Data	PCTR(x) =A*x+B	VOS	-0.00102	-0.884	0.391	1.5562	0.04953	0.7816
		POP	3.70e-09	0.271	0.789	1.263	0.00317	0.0732
		HHS	0.06022	0.799	0.4327	0.9963	0.02698	0.6377
		HHI	3.43e-06	0.317	0.756	1.234	0.00622	0.1002
		AREA	-7.03e-06	-0.227	0.822	1.286	0.0022	0.0515
		POPD	-5.10e-06	-0.465	0.647	1.339	0.00972	0.2158
	ATL(x) = A*x+B	AREA	0.00063	4.92***	0.000183	4.947	0.6178	24.25***
	ATL(x) = A*ln(x) +B	POPD	-0.7896	-2.045°	0.0588	12.637	0.2181	4.184°

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '°' 0.1 ' ' 1

Land Use Distribution

Land use and transport are highly interdependent; therefore an analysis of urban transport systems in India seems incomplete without this spatial perspective. Land use distribution impacts, to a great extent, how far citizens have to travel to access desired activities. Therefore, we investigate the current land use patterns of the sample cities to understand their implications on travel demand.

It was observed that the CMPs were all prepared separately from the City Master Plans, but include their land use data in the final documentation. It is important to note that the area definition for the Master Plan and the CMP differ in most cases because the latter comprises neighboring districts that are relevant to transport demand scenarios, but not within the authority of the city. For the comparative analysis we relate to the final CMP reports, but separately state if they are linked to another reference area (see appendix A-1).

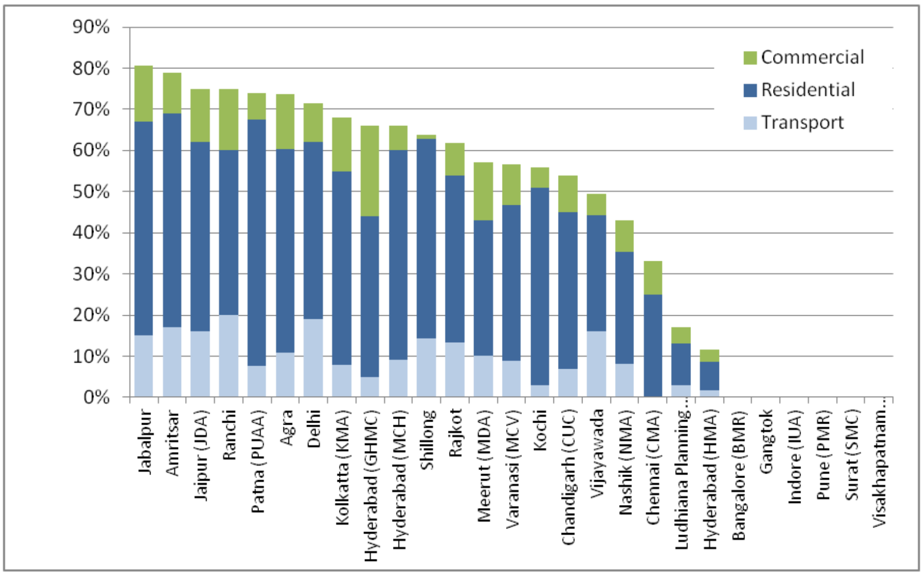


Figure 25: Land use distribution in study areas

Figure 25 suggests that urban space is well developed in a number of sample cities, which gives them limited opportunity to absorb future population growth within their present delineation. Jabalpur, Ranchi or Jaipur are such cities that should reason whether they want to expand horizontally in the surrounding areas or vertically, by augmenting population densities in the municipal core. On the other hand, Chandigarh and Nashik still have enough land to bear with greater population size. Hyderabad is a very good example for a city following the horizontal growth path: the greater municipal core (GHMC) is well developed (67%), whereas the entire metropolitan region (HMA) is pre-dominantly rural. Local authorities plan to develop a polycentric city shape with multiple job and leisure centers spread across the metropolitan area. This strategy is very sensible indeed, but can only be successful if centers and their surroundings follow a high density mixed land use pattern and public transport services are provided adequately. Transport demand is expected to more than double from the base year to 2030. If not enough mass transit capacities are installed until then, congestion and poor air quality will considerably deteriorate livability for citizens.

Another interesting finding is that the share of infrastructure related to transport differs significantly. Cities such as Delhi, Ranchi or Amritsar form the top group, with up to 20% of land assigned to the movement of people and goods. On the other end of the spectrum, Ludhiana or Hyderabad still offer abundant space, providing more flexibility in terms of which transport demand strategies to pursue.

3.5.3 Summary

This review has investigated the key planning documents of selected cities in India and explored in several ways, how they compare to each other in terms of high-level travel demand indicators and land use distribution data. From our analyses, we expect that the development of cities will be different from the predictions outlined in the CMP. This is because the CMP framework does not incorporate the interdependencies between land use and travel demand adequately. We conveyed that larger cities in India have longer average trip lengths than smaller ones. Nevertheless, the Master Plans suggest that sample cities are primarily targeted to develop neighboring districts for further growth, thus, pursuing a horizontal growth path. As a result, we must expect average trip lengths to increase in most of the sample cities, and push people to use motorized transport modes in order to access their daily activities (i.e. work). As a consequence, road traffic along the major commute corridors connecting the residential and commercial districts will surge. If this demand growth is not met with an adequate public transport service, the street network is constantly going to be gridlocked, negatively impacting travel times and environmental quality. The nation’s capital Delhi serves as an expedient examples for other cities in India, to this regard. On the other hand, we identify cities, which exhibit a dense city structure and already have allocated ample public space to transport infrastructure. Such cities are left with little choice other than to utilize the installed road network more efficiently. However, their expected growth rates will presumably outpace those efficiency gains; therefore, it is likely that cities, such as Ranchi or Amritsar will prosper at a slower pace than projected due to their limited ability to accommodate the demand surplus so rapidly.

There exists no silver bullet solution to the urban mobility challenge in India, but our analysis highlighted key policy areas, which have also been addressed in the revised CMP guidelines [MoUD, 2014]. In order to avoid traffic in the first place, integrated land use transport planning is crucial to design a city of short trips, where daily activities can easily be accessed within walking or cycling distance. Complemented by a safe, reliable and comfortable public transport service, effective demand management strategies, such as parking fees, and modern ITS solutions that leverage the exceptional prevalence of smart phones and the know-how of the IT sector, cities will be able to utilize the scarce resource of space in the most efficient way and deliver on their promise envisioned in the CMP’s to provide mobility for all citizens.

3.6 Conclusions

Reviewing state-of-the-art transport modeling techniques leads to the conclusion that present research efforts are mainly directed towards a more detailed and realistic representation of travel patterns in the existing frameworks. With this, it is possible to estimate travel demand more accurately and improve the traceability of the models, as compared to the original four-step algorithm. Activity chains make it possible to link the movement of people (or goods) to their true reasons, which allows for a deeper understanding and derivation of suitable strategies. More sophisticated mode choice models aim to mimic the complex human decision process and help to derive measures that make favorable modes of transport, like walking, cycling or public transport more attractive to use. Finally, advances in computing power have made it possible to use highly disaggregated, microscopic model frameworks for large-scale macroscopic use-cases, enabling a bottom-up calculation of travel demand with detailed information on the agents in the system. All of these research activities call for a significantly higher amount and quality of data for setting up the model and perform simulations. Improved ways of data collection are, therefore, equally important for these advanced methodologies to work. In this context, the wide adoption of smart devices (i.e. smart phones) provides a valuable opportunity to obtain large amounts of data at comparably low cost directly at the source in the future.

Despite their high level of sophistication, state-of-the-art travel demand models presently do not capture the dynamic interaction of mobility with the urban environment very well in their forecasts. Land use transport interaction models attempt to close the gap, but have not been embraced, other than in the specific use-case they were programmed for. Alternatively, System Dynamics was proposed to include temporal effects, but the models have not been widely received by the transportation community so far either. One of the main reasons for this seems to be that there is no sound empirical evidence of the interaction assumptions in the models over a longer period of time. This criticism is justified under the premise of achieving higher accuracy and traceability of a model, but it oversees the merits that a general understanding of transport dynamics is able to provide for planning bodies. So-called “small” models serve this purpose in the System Dynamics research community. They require significantly less input data, but more modeling effort on the interaction level in order to produce useful results. The objective of such models is to translate qualitative assumptions and observations about the system in a reasonably-sized computable mode and analyze its behavior over time, as well as its sensitivity to parameter variation. Such models are set up to explain, for example, supply chain dynamics or innovation diffusion, and commonly embedded in larger SD models, analyzing more specific use cases.

For the case of urban transport in India, the literature review did not surface any model that included a dynamic perspective. The CMPs are exclusively based on the classic four-step model with varying degrees of sophistication in the trend projections. Consequently, we need to develop a proprietary simulation model in order to answer the research questions in this study.

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4 Modeling Urban Transport Dynamics in India

The computer simulation model we develop and explain in detail in this chapter serves the purpose of investigating the dynamic development of travel demand and supply in Indian cities. Corresponding to the objectives of this thesis, three critical boundary conditions guide the model selection and setup process. First, we strive to understand the general implications of economic development and urbanization trends in India. We, therefore, want to be able to cover multiple cities with one model and the underlying assumption that there is a generic paradigm to urban growth, which is valid beyond the sample cities selected for this study. Second, literature review and an extended research visit at the Institute of Urban Transport (India) led to the finding that urban transport data availability – and, more importantly, accessibility – is limited, as we were not able to identify a database or archive of the various models that were developed for preparing a CMP or other transport projects in India. Hence, the model is confined to the data we were able to extract from the final reports. Third, we want to be able to add the dimension of time to the analysis. Given the projected exponential growth in population size and income levels in the investigated time-frame, a dynamic perspective offers the possibility to assess how travel demand will evolve and whether a proposed bundle of measures is sufficient to manage it sustainably.

Macroscopic demand models have been set up in the CMPs, but they cannot be modified to account for dynamic feedbacks. More modern frameworks, such as activity-based or microscopic models, have not been applied in India and would require the collection of new data, consuming substantial time and resources, which was beyond the scope of this research project. Integrated land use transport models, too, have not been generated and the lax land use control in India make this modeling approach questionable with respect to the validity in future scenarios. They, too, would depend on rich data in order to produce meaningful results.

For these reasons, we opt for the System Dynamics (SD) framework, which fulfills both the condition of being able to incorporate dynamic feedback between parameters, as well as offering the flexibility to scale the model to the available amount of data. A comprehensive review of SD literature showed that a “blueprint” model is not available for the purpose of our study. Yet, we draw upon a more general (qualitative) thinking model of urban transport from literature in this field and adopt the system structure to the context of India and our data repository. We propose a “small” System Dynamics simulation model that captures the high-level structure and the dominant feedbacks of urban mobility in India and provides alternative travel demand forecast scenarios to those included in the CMP final reports. It also allows testing a set of general transport strategies to lower the congestion level and identifies the challenges that arise out of a dynamic perspective on the transport sector in the observed time-frame, in particular, the limits to travel demand growth due to the infrastructure supply constraints. The model is calibrated to six study cities representing India’s urban heterogeneity; yet it is designed to be applicable to all cities that have prepared mobility plans according to the guidelines from the Indian Ministry of Urban Development.

Before we describe the model structure and its parameters in detail, we elaborate on the need for dynamic modeling in transport in this chapter and outline the additional insights in which planning bodies are able to convey, thereby improving the strategic planning process.

Moreover, because System Dynamics models use their distinct notation and have a sound theoretical basis, we give a brief introduction into the subject. Starting with the fundamental behavior of dynamic systems, we continue with the basic building blocks for setting up a SD model, namely stocks, flows and feedback loops. We conclude this section by characterizing S-shaped growth, a fundamental system behavior we can observe in various technical and social systems. It reflects the fact that no growth process is infinite (i.e. constrained by the resources it consumes) and, thus, serves as the reference mode for the situation we investigate in this study: exponentially rising travel demand, which is limited by the supplied (road) infrastructure.

Finally, we present the qualitative thinking model of dynamic interactions of (urban) transport from SD literature and discuss its assumptions in more detail, as they build the foundation upon which the equation sets and the feedback structures of our model in this thesis have been developed.

4.1 The Need for Dynamic Modeling

The urban transport system is dynamic in very different ways, depending on the observed time-frame. On an hourly basis, we observe that transport demand is higher in the morning and evening hours, ("peak hours"), which causes congestion. These dynamics occur because most people need to go to work and home in a relatively small time window. On a daily basis, we observe different travel demand on business days and weekends, because most people do not have to work Saturdays and Sundays. In strategic transport planning, the dynamics of interest come into effect on a much longer time horizon (30 years): they derive from changing boundary conditions to the system: urban growth (measured both in population size and area/land use structures) and, particularly in the case of India, rapid private motorization.

Classic transport models, such as the four-stage algorithm used in the CMP, are suitable to assess whether a certain bundle of measures is sufficient to satisfy an expected demand scenario in a future point of time (horizon year), but they do not track the time-path that lead to that demand. In absence of this information, defined strategies may not be sustainable because the long-term dynamics point in a different direction than the horizon year calculations of the planning document. We explain this with a picture of transport planning on the timeline:

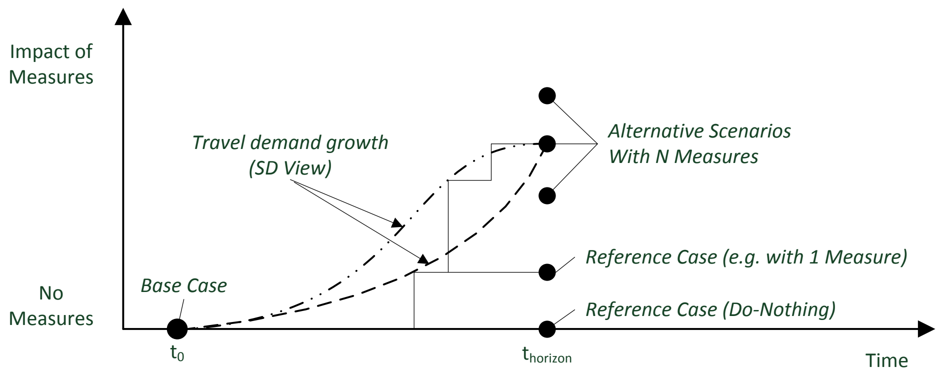


Figure 26: Improved strategic transport planning through System Dynamics modeling

In the traditional four-step approach, primary and secondary data is collected to calibrate the model for the base year. The goal is to provide an accurate image of the status quo (*Base Case*). As a next step, dynamically changing input parameters are projected into the future. Mathematical models are available to calculate, for example, population growth, vehicle ownership or structural data changes (e.g. housing, offices), etc. for the horizon year. On this basis, a *Reference Case* in the horizon year is generated. Depending on the uncertainty in the projections and the available study budget, alternative reference cases might be added.

Different sets of measures (or strategies) are then tested against the reference case to assess their effectiveness to reach the policy objectives. In many studies, a so-called "Do-Nothing" scenario is programmed to show the consequence of no policy intervention at all. The "Business-as-usual" or BAU scenario, on the other hand, includes already decided measures, which have not been considered in the base year calculations, but will be implemented before the horizon year. In the CMP reports, we find both forms of reference cases; larger cities, such as Bangalore or Delhi make use of BAU scenarios due to the ongoing infrastructure projects. Finally, alternative scenarios consisting of various strategy mixes are programmed, of which one is chosen as optimal fit and recommended to be pursued (including an associated project list and budget). Typically, an alternative scenario is proposed, which supports different policy objectives (e.g. a sustainable transport scenario). The four-step approach can, therefore, be viewed quasi-dynamically at best, as it does include time-dependence, but only specifies the system for a defined point in future, rather than for the time span in between. Moreover, the mathematical models for future projections are independent from each other – they do not include any mutual feedback.

But why is it so important to unveil the dynamics of the system? In the logic of the FSM, a scenario that satisfies demand in the horizon year is good, but this is only true for the specific point in time for which it is programmed. As shown in Figure 26, the shape of the demand growth curve determines whether the proposed solution is sustainable or not. We explain this by means of two typical growth modes. In the case of s-shaped growth, the measures are well designed for the horizon year and beyond, but should be introduced more quickly, as most of the demand increase has happened earlier leading to undesired traffic conditions in the transition phase. For exponential growth, on the other hand, the measure set fits the demand curve, but the horizon year solution is not sustainable, as demand increases even more and requires additional supply. Because the doubling rate of exponential functions remains constant, the demand increase actually accelerates beyond the horizon year leading to congested roads very quickly again, although the plans were perfectly fine for that particular year.

The System Dynamics methodology is able to address the mentioned downsides of the four-step model because it focuses exactly on modeling and understanding the critical time-paths of a system. The challenge from a modeling view, is to combine the strengths of the two techniques in a way that consistent and traceable results are produced. One way to achieve this is to use a single model framework, in which the SD layer continuously updates the underlying, four-stage model and handles the feedback loops. This approach is presented, for example, by Swanson [2003] in the *Urban Dynamic Model* (UDM). Beside the amount of data, this approach presents the challenge to correctly specify the dynamic relationships on a disaggregated (district) level, which cannot easily be extracted from standard survey data formats. Alternatively, we can model the temporal and spatial component of urban transport separately and reference the model outputs at different points in time to each other in order to verify results. This approach provides a deeper understanding of system behavior, yet cannot integrate the calculations in a single framework: the SD findings put the output of the four-stage model in the context of the dynamic boundary conditions and helps to understand the long-term implications of travel demand.

In our study, we follow the second approach and formulate the SD model on basis of the CMP data. Demand growth functions and feedback structures are developed independently. As the model framework is scalable to data availability, we present an aggregated model that is applicable to a larger number of cities and not only to one specific study area.

4.2 Principles of System Dynamics

The theoretical foundations of System Dynamics were developed by Jay W. Forrester at the Massachusetts Institute of Technology in the 1950s. Being an electrical engineering graduate, he sought to transfer the fundamentals of control theory to social systems in an attempt to improve the management process of corporations. The application of System Dynamics is closely linked to the emergence of digital computer technology that enabled Forrester and his students to rapidly shift from simple hand-simulation models to the formal computer modeling stage [Radzicki and Taylor, 1997]. The first book in this field was titled *Industrial Dynamics* [Forrester, 1961], followed by the first application of System Dynamics to a non-corporate managerial problem in *Urban Dynamics* [Forrester, 1969]. The title that made the field known to a wider public was *The Limits to Growth* [Meadows et al., 1972], a study of the global economy with the key outcome that its growth is limited due to finite resources. Although well accepted by economists today, the study was strongly criticized at the time, mainly due to the fact that some of the assumptions were not traceable with numerical data. Full validation of SD models remains to be a challenge, often because empirical evidence for relationships is not available. SD modelers mostly verify the system behavior, rather than every equation in the system. This section highlights the fundamental building blocks necessary to construct models that can provide insights on how complex real-world systems behave over time and why they do so. The interested reader is directed to the book of Professor John Sterman [2000], which provides a comprehensive introduction into the field.

4.2.1 Fundamental Behavior of Dynamic Systems

The behavior of any system is dependent of its structure, which consists of feedback loops, stocks and flows and nonlinearities in the interaction of the physical and institutional structure of the system and decision-making agents acting within it. Basic modes of dynamic behavior are detected through the feedback structures which generate them. These modes are growth, caused by positive feedback; goal seeking, created by negative feedback and oscillations created by negative feedback with time-delays. Combinations of these basic structures generate more complex modes, such as S-shaped growth or overshoot and collapse.

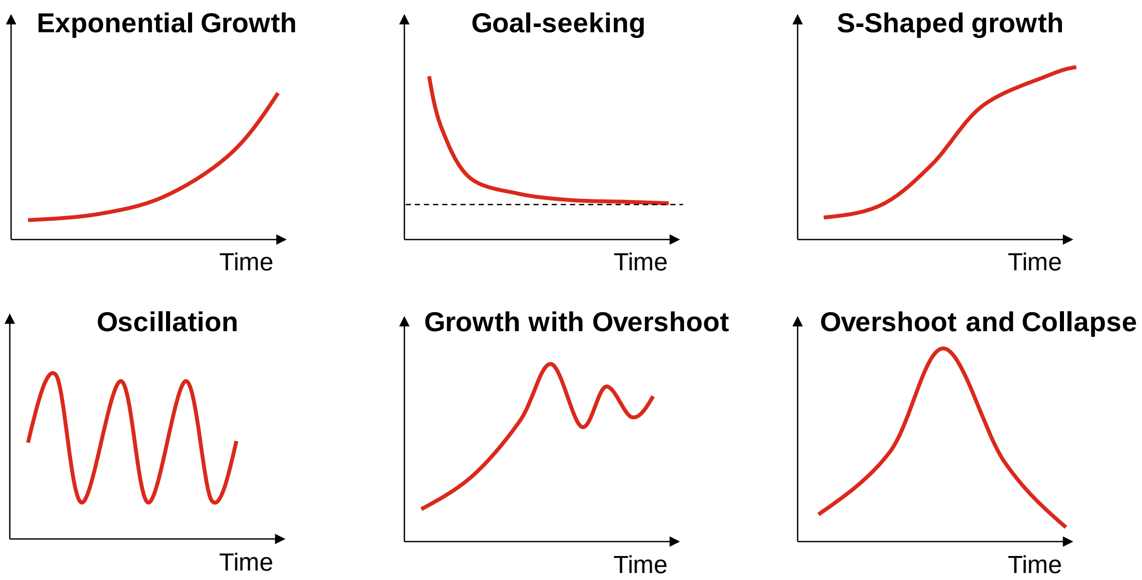


Figure 27: Fundamental modes of dynamic behavior [Sterman, 2000, p.108]

Exponential growth patterns have the property that the larger the quantity, the greater its net increase. As an example, we look at population growth: the larger the population, the greater net birth rate, further enlarging population and eventually leading to even more births[13]. However, positive feedback need not only to generate growth, it can also create self-reinforcing decline. Systems that behave this way are also known as “vicious” or “virtuous” cycles.

The vast majority of dynamic behavior is covered by the patterns outlined above, although there exist two more fundamental modes a system can display: stasis (equilibrium), in which the system remains constant over time, and random variation (i.e. chaos). Constancy either arises because the dynamics impacting the system are too slow in relation to the investigated time frame, or because there are very powerful negative feedback processes making the system extremely resilient towards external disturbances. Chaos, on the other hand, describes a state of randomness in the system. Variations to the state of the system are intrinsic; yet, they do not follow a pattern repeatedly and in a predictable way. The principle that the structure of a system determines its behavior is a useful heuristic for the modeler to identify its feedback loop structure. The particular pattern, also referred to as *time path* [Radzicki and Taylor, 1997], immediately provides information which, of the basic feedback structures, has been dominant in the time covered by the reference data. The system’s *reference mode* is the starting point for every SD modeler. In addition, he must search and include feedback structures which have not become prevalent so far, but could become active as the system evolves.

4.2.2 Stocks and Flows

In System Dynamics modeling, dynamic behavior is sought to occur due to the *Principle of Accumulation* [Forrester, 1961], or more precisely when *flows* accumulate in *stocks*.

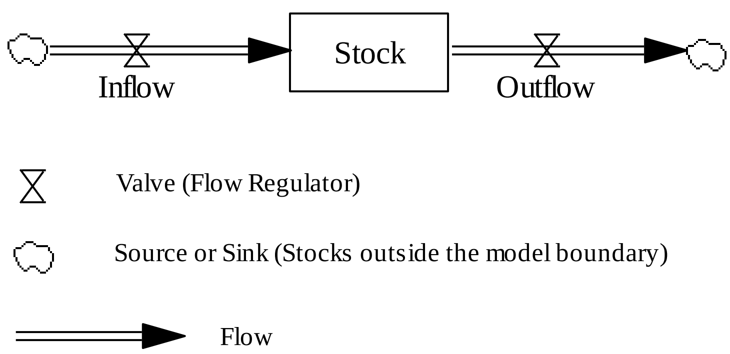


Figure 28: Stock and flow diagramming notation [Sterman, 2000]

Stocks characterize the state of the system and generate the information upon which decisions and actions are based. They give systems inertia, provide them with memory and cause delays (both in terms of time and information) by accumulating the difference between the inflow and the outflow. Because stocks decouple flows, they are the source of disequilibrium dynamics in systems [Sterman, 2000, p.192]. To illustrate this basic concept, we can think of a manufacturing firm’s inventory as stock of goods in its warehouses, which is increased by the production of goods (inflow) and diminished by shipments (and possibly other outflows, such as waste).

[13] A distinct fact about pure exponential growth is that doubling time is constant: the state of the system doubles in a fixed period of time, no matter how large.

The stock and flow notation introduced by Forrester adheres to hydraulics: the flow of water in and out of a reservoir (also referred to as "bathtub" metaphor). The structure represented in Figure 28 can formally be written as:

$$\text{Stock(t)} = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0) \tag{12}$$

with Inflow(s) representing the value of inflow at any time s between the initial time t_0, and time t. Correspondingly, the net rate of change for any stock is given by the first derivative in time:

$$\frac{\text{d(Stock)}}{\text{dt}} = \text{Inflow(t)} - \text{Outflow(t)} \tag{13}$$

To illustrate the difference between stocks and flows we come back to the example of population growth:

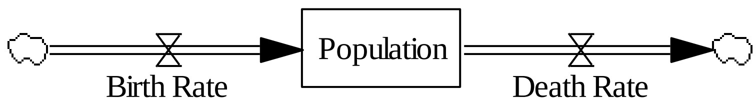


Figure 29: Stock and flow representation of population growth

The population size at the beginning of any year, t_1, is assumed to be 1,000. During this year, 50 children are born and 20 inhabitants die. The flow variables, *Birth rate* and *Death rate,* take the values 50 and 20 in t_1, increasing the stock variable *Population* to 1,030 in the following year (t_2).

The distinction between stock and flow variables is recognized in many disciplines and is not unique to System Dynamics. In mathematics and engineering, stocks are also known as integrals or state variables, flows as rates or derivatives. For the modeler, it is essential to correctly identify the nature of a variable. The so-called "*snapshot test*" (an allegory to photography) helps to identify the key stocks in a system. If all flows come to a stop, the stock variables would remain measurable (e.g. number of employees in a firm or number of goods in a warehouse). Another advantage of this notation is the clear distinction between the physical flows through the network and the information feedbacks that couple the stocks and flows.

4.2.3 Feedback

While stocks and flows are both necessary and sufficient to generate dynamic time paths, feedback is another core concept of system dynamics. It couples stock and flow variables, often nonlinearly, which causes counterintuitive behavior in the system. Such systems are referred to as closed, whereas open systems respond to, but have no influence upon, their inputs. Figure 30 shows a simple generic structure of this typology:

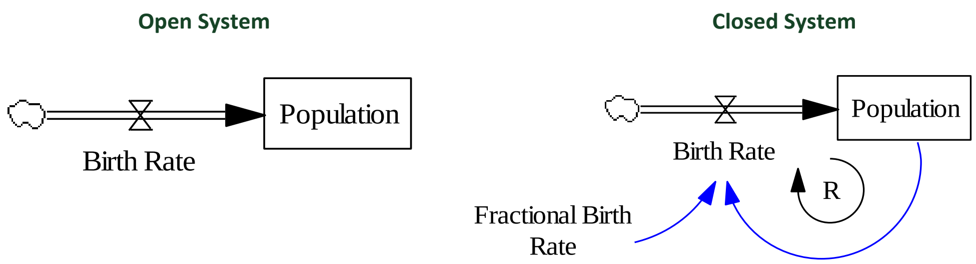


Figure 30: Open vs. closed system taxonomy by means of population growth

It is important to note that the information of the state of a system (or a variable) can be delayed or diluted before it reaches the flow that adjusts to it and, therefore, causes oscillation. Closed systems are controlled either by positive (reinforcing) or negative (balancing) feedback loops. Generally speaking, positive feedback processes destabilize systems and cause them to veer away from the original state; they are responsible for growth or decline of a system. Negative feedback, on the other hand, describes goal-seeking processes stabilizing the system and moving them towards, or keeping them at, a desirable state.

In the field of System Dynamics, so-called *Causal Loop Diagrams* (CLD) are an important tool to represent and visualize the feedback structures of a system.

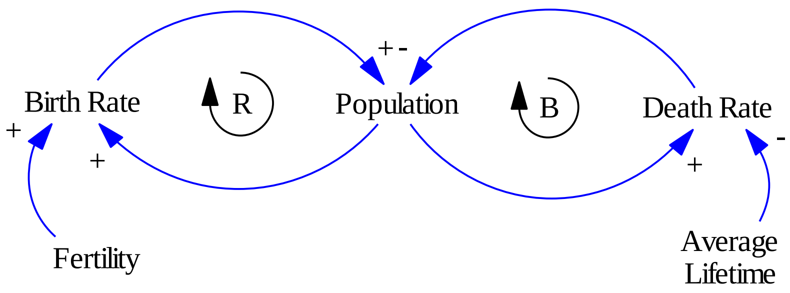


Figure 31: Causal Loop Diagram with a reinforcing and a balancing feedback loop

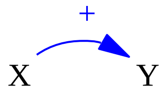
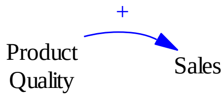
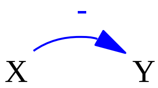
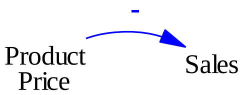
CLD helps to capture the hypotheses of the different stakeholders on the causes of dynamics and to communicate the feedbacks, which are presumably responsible for an identified problem [Sterman, 2000, p.137]. Such a diagram consists of variables connected by arrows denoting the causal relationship between them. Each arrow is assigned either a positive (+) or negative (-) polarity to index the change of the dependent variable when the independent variable changes. Positive links indicate that if the cause variable is increased (decreased), so is the affected variable. A negative link, on the other hand, means that if the cause increases, the effect decreases and vice versa. Loops are marked with an identifier[14] which circulates in the same direction as the loop to which it corresponds.

In the example above (Figure 31), the number of newly born (*birth rate*) increases, either by a larger pool of potential parents (*Population*) or if women, on average, give birth to more babies (*Fertility*), which closes a positive feedback loop (*R*) for population growth. On the other side, more people will die if life expectancy declines, describing a negative correlation (*B*). The system is in a state of equilibrium, if the feedback loops cancel themselves out or, more formally, if birth and death rate are equal. In most developed countries, fertility has dropped below the level required for self-preservation, leading to a shrinking population (without considering immigration effects). Conversely, developing countries usually display significantly higher fertility. In combination with lower fatality due to improved hygiene, the result is the enormous population growth we could observe throughout the last decades.

A summary of the notation for link polarity is given in Table 7:

[14] B=Balancing, R=Reinforcing feedback loop

Table 7: Link Polarity: definitions and examples [Sterman, 2000, p.139]

Symbol	Interpretation	Mathematics	Example
	All else equal, if X increases (decreases), then Y increases (decreases) above (below) what it could have been. In the case of accumulations X adds to Y	$\frac{\partial y}{\partial x} > 0$ In the case of accumulations, $Y = \int_{t_0}^{t} (X + \cdots)ds + Y_{t_0}$	
	All else equal, if X increases (decreases), then Y decreases (increases) below (above) what it could have been. In the case of accumulations X subtracts to Y	$\frac{\partial y}{\partial x} < 0$ In the case of accumulations, $Y = \int_{t_0}^{t} (-X + \cdots)ds + Y_{t_0}$	

Another important element of feedback and Causal Loop Diagramming are delays. They are critical in creating dynamics, give the system inertia and are often responsible for trade-offs between the short- and long-term effects of policies. Delays are pervasive: it takes time to measure and report information, it takes time to make decisions and it takes time for the decisions to impact the system. Proper diagrams mark relevant delays on the graphs that lay out the feedback structure. Two notations exist, of which B) is chosen in this thesis.

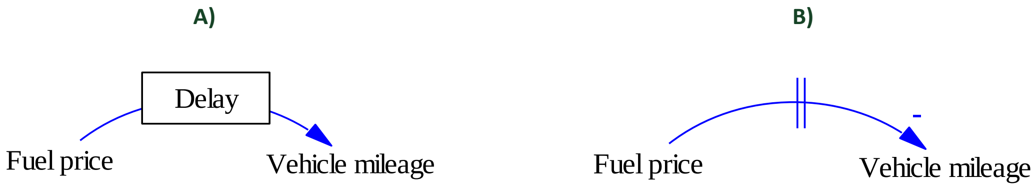


Figure 32: Possible notations for system delays in a Causal Loop Diagram

It is important to note that link polarities describe the structure, not actual behavior, of the system. That is, they chart what would happen if there were a change, however they do not provide any information if that change actually occurs. There are two reasons for this: first, a variable can have more than one input, which may lead to counterintuitive behavior. Second, and more important, CLD cannot distinguish between stocks and flows and, thus, are not able to capture the rate of change. Therefore, a Causal Loop Diagram alone is not sufficient to map the dynamics of a system.

We explain this characteristic using the simple population model specified before. First, we lay out the corresponding stock and flow structure:

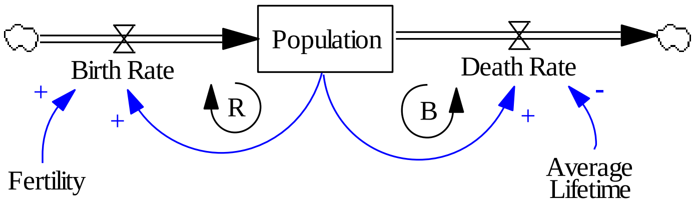


Figure 33: Stock and flow representation of the population model

In the next step, we formulate the mathematical equations that link the variables to each other and represent the modeler's understanding of how the system works. In our example model, population is given by:

$$\text{Population(t)} = \int_{t_0}^{t} [Birth\ Rate(s) - Death\ Rate(s)]ds + Population(t_0) \tag{14}$$

Birth Rate is a function of the population and fertility:

$$\text{Birth Rate (t)} = \text{Population}_{t-1} * \text{Fertility} \tag{15}$$

and *Death Rate* is given by:

$$\text{Death Rate (t)} = \text{Population}_{t-1}/(\text{Average Lifetime}) \tag{16}$$

Fertility (measured in number of children per thousand inhabitants) and *Average Lifetime* are assumed to remain constant for reasons of simplification. We calibrate the base scenario with typical values derived from World Bank data [World Bank, 2015] and investigate alternative scenarios by varying the rate parameters. Table 8 summarizes the parameter set (changes in the scenarios are marked in bold):

Table 8: Input data for model scenarios

		Scenarios					
		Base	S1	S2	S3	S4	S5
Variables	Starting Population (tsd.)	10,000	10,000	10,000	10,000	10,000	10,000
	Fertility (births/1,000 pop.)	0.05	**0.03**	**0.0125**	**0.06**	0.05	**0.005**
	Average Lifetime (yrs)	80	80	80	80	**50**	80
	Simulation Period (yrs)	50	50	50	50	50	50

Plotting the results of the scenarios shows that the system "dynamics" change, although the underlying structure (Causal Loop Diagram) remains the same.

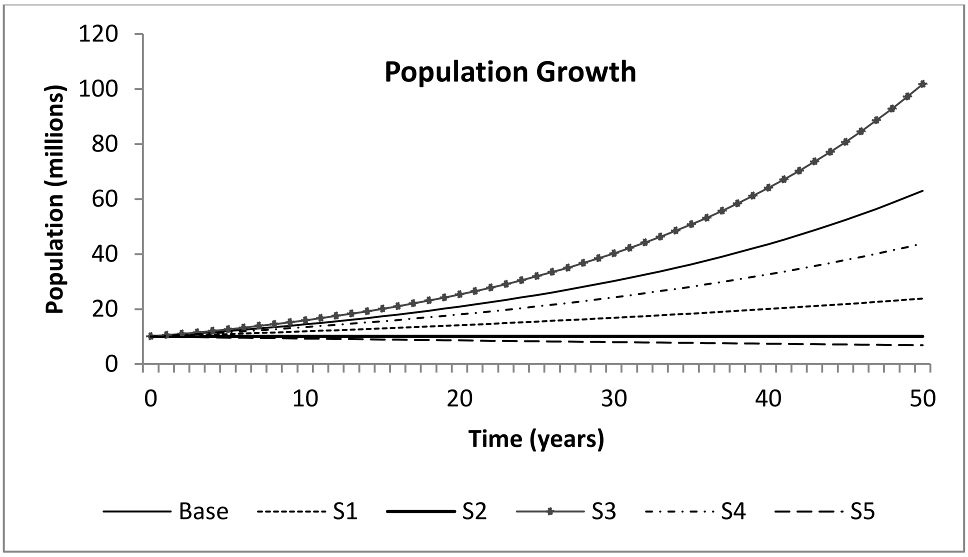


Figure 34: Population dynamics in different scenarios

This is because the feedback loops (determined by the rate variables) are balanced differently, resulting in very different outcomes: exponential population growth (S3), no growth (S2), or even a shrinking population (S5), in case birth rates become too small (due to very low fertility) to compensate for the annual deceased. This basic model can, of course, be expanded by making *Fertility* and *Average Lifetime* time-dependent or adding feedback loops, which would surface further trend patterns.

The simple example shows the importance of a correct system description in terms of stocks and flows, feedbacks and the mathematical equations connecting the variables. All of these steps determine the quality and validity of a System Dynamics model. Particularly in very large models, it is challenging to capture and fully comprehend the impact of feedback loops. Causal Loop Diagrams then serve to lay out the system structure in a way that is easier to grasp and to communicate to the targeted audience.

4.2.4 Dynamics of Growth: S-shaped Growth

Simple modes of behavior are caused by only one basic structure. For example, exponential growth is specified by positive feedback. Other, more complex, patterns of system behavior emerge through the nonlinear interaction of the three basic modes described earlier (positive/negative feedback, negative feedback with delay). Out of these, “S-shaped” growth is particularly relevant, as we can observe that no entity can increase forever. Eventually, one or more constraints halt the growth process. S-shaped growth describes a function that initially is exponential (reinforcing feedback), but then gradually slows until the system reaches an equilibrium level (negative feedback). The shape of the function resembles a stretched “S”, which gives it the name. To understand the underlying structure, it is useful to draw upon the ecological concept of “carrying capacity”, that is the number of organisms of a particular type that any habitat can support and which is determined by the (natural) resources available in the environment and the resource requirements of the population. Any real quantity can be viewed as a population drawing on the resources in its environment. As the capacity of the environment is approached, the adequacy of limiting resources decreases and the fractional net increase rate must decline. The state of the system then grows at a slower pace; until resources are just sufficient to maintain equilibrium.

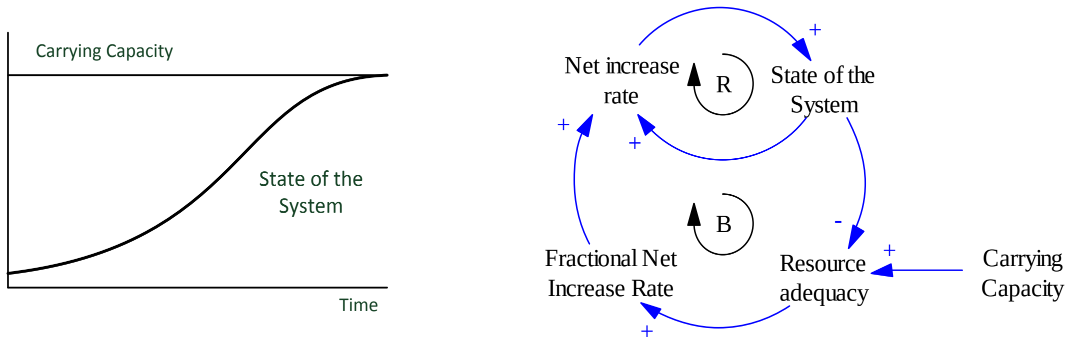


Figure 35: Structure and behavior of S-Shaped growth

For a system to generate S-shape growth, two critical conditions have to be met. First, the negative loops must not show any significant time delay. If this is the case, the system oscillates around the saturation point, rather than approaching it smoothly. Second, the carrying capacity must be fixed. If it is consumed by the growth of the population, the system gradually collapses. When the population is at its peak, so is the rate of decline of the limiting resources. Real-world examples for s-shaped growth are manifold. In the context of this study, vehicle ownership as a function of income level and urbanization follow this pattern (for more details see Chapter 4). However, we do not model urban population growth in detail because the negative feedback structure will only come into effect well beyond the simulated time-frame (India's share of urban population is projected to only be 40% in the horizon year).

Certainly, modeling S-shaped growth is not limited to System Dynamics. There exist a number of functions that can be solved analytically, despite being nonlinear. Among them, the logistic function (or Verhulst function), first published in 1838, is most widely used due to its simplicity and analytic tractability:

$$P(t) = \frac{c}{1 + a * e^{-b*t}} \tag{17}$$

With: P(t) Population
a,b,c Constants >0

The logistic function is a special case of a more general function, because the fractional net increase rate is a (downward sloping) linear function of the state of the system. Other prevalent models, which relax this restrictive assumption are the Richards curve, the Gompertz function and the Weibull model, which is based on the Weibull distribution (for further readings, please refer to [Sterman, 2000, p.263ff]). However, data may not be confined to the assumptions of any of the analytic models. With (numeric) computer simulation, it is possible to specify any nonlinear relationship supported by the given dataset and then explore the system behavior over time.

4.3 Qualitative Model of Urban Transport Dynamics

On a high level, urban transport systems feature a generic structure that can be found in cities across the world, despite each of them preserving their unique characteristics in terms of urban form, available transport modes, mobility cultures, etc. This assertion may seem counterintuitive for visitors to diverse cities such as New York, Graz or Delhi. Yet, although their boundary conditions are unique, they share the mutual challenge to manage urban growth and the resulting travel demand without deteriorating the city's quality of life. The magnitude of the growth process is determined by the speed and scale at which it occurs, but the underlying dynamic system "structure" is, effectively, quite comparable.

A number of SD models were developed to study urban transport, but there is no fully documented reference simulation model we can apply to our study questions. Therefore, we turn to a useful system characterization by Sterman [2000, p.177ff] that points to the relevant stocks and flows and describes the feedback structures veering people away from public transport to using private vehicles. The Causal Loop Diagram sketches the dynamics that led to sub-urbanization and, consequently the steady decline of public transportation in most U.S. cities. Interestingly, many cities in Europe and other parts of the world have experienced, or are currently subject to, very similar dynamics and India is no exception: the country's major cities (e.g. Delhi) expand beyond their original delineation because central districts are already populated very densely. Public transport offerings to these areas are either poor or do not exist at all. People who can afford to purchase private vehicles (pre-dominantly two-wheelers), do so instead, thus, increasing road travel demand. The differences to the U.S. case are that the speed at which those dynamics occur is quicker and the magnitude of demand, significantly larger. In SD terms, the flow rates and the size of the stocks are larger, but the underlying "structure" remains comparable. We, therefore, adopt this general thinking model of urban transport dynamics for the Indian context and translate it to a working computer simulation model.

The Sterman model is developed around the intention to reduce congestion by expanding road infrastructure. From a systems perspective this is an incomplete representation of the system, – the more traffic on the roads, the more roads are being built – which does not include any behavioral feedback. Travel demand and level of service on the network are (positively) interrelated. Empty roads make driving attractive, highly congested roads do not. A common measure for the level of service is travel time, which results out of the vehicle volume and the road or network capacity. There are different models to estimate the travel time loss when capacity is approached on the link level. They are referred to as volume-delay functions (see Chapter 3). In order to maintain travel time on a desired level, one can either increase capacity or limit the traffic on the roads. By increasing capacity, not only road construction is included, but also improving the design of intersections, adding lanes, etc. Figure 36 illustrates this capacity expansion loop (B1). After the new capacity is added, travel time drops, relieving the pressure to reduce congestion. In the CMP reports, we find that this strategy is commonly applied and, so far, it seems adequate. Many city authorities and transport planners assume that road traffic volume grows as population grows and the local economy develops. They view their task to provide enough infrastructures to keep travel times at acceptable levels and focus their efforts on this feedback loop. However, the key point is that traffic volume is not exogenous to the system. To formulate the causal structure correctly, it is useful to decompose its drivers:

$$\begin{gathered} Traffic\ Volume\ = Vehicles * Average\ Trips\ per\ day * Average\ Trip\ Length \\ [Vehicle\ km/day] = [Vehicles] * [Trips/day] * [km/Trip] \end{gathered} \tag{18}$$

Traffic volume (measured in vehicle kilometers per day) equals the number of cars in the study area multiplied by the number of kilometers travelled each day, which again is a product of the daily number of trips and their average length. The last two variables of the equation describe vehicle usage, which is not constant. It depends on the level of congestion, which in turn, ascertains the attractiveness of driving. If getting around the city by private vehicles is easy because the roads are empty and there is no cost (e.g. for parking), people will favor driving.

Moreover, the number of vehicles can further be broken down to the size of the population multiplied by vehicles per person (commonly defined as motorization rate and measured in vehicles per 1000 inhabitants). Again, we observe a positive correlation between vehicle ownership and usage, due to the associated economics: cars, in particular have high fixed cost (purchase, insurance, tax), which are only accepted if the car can be driven on a regular basis (apart from some exceptions, such as car collectors). Buying a car is therefore dependent on the attractiveness of driving. This is not fully true in the Indian context, as car ownership also serves other purposes, such as social status, but in terms of mode choice, there is empirical evidence that the basic assumption of who owns a vehicle will use it, holds true [Srinivasan et al., 2007]. Adding these relationships to the model closes three negative feedback loops that all increase congestion whenever road capacity is expanded. It is important to note that all of them are behavioral feedbacks that come into effect with delay. Short term, travel times drop because the number of cars has not changed and neither have people's habits. But as they notice the greater convenience as a result of reduced congestion, they will take more trips (B2), or they might choose to perform their activities further away (B3). Over time, if people can afford to, they will eventually buy their own vehicle, and switch away from public transport (B4). Of course, mode choice is also dependent of other factors (e.g. comfort), but travel time and cost continue to dominate people's decisions in this context. Unlike developed countries, most public transit riders in India are captive; as soon as they can afford to, they will switch to private vehicles which are viewed to be more convenient.

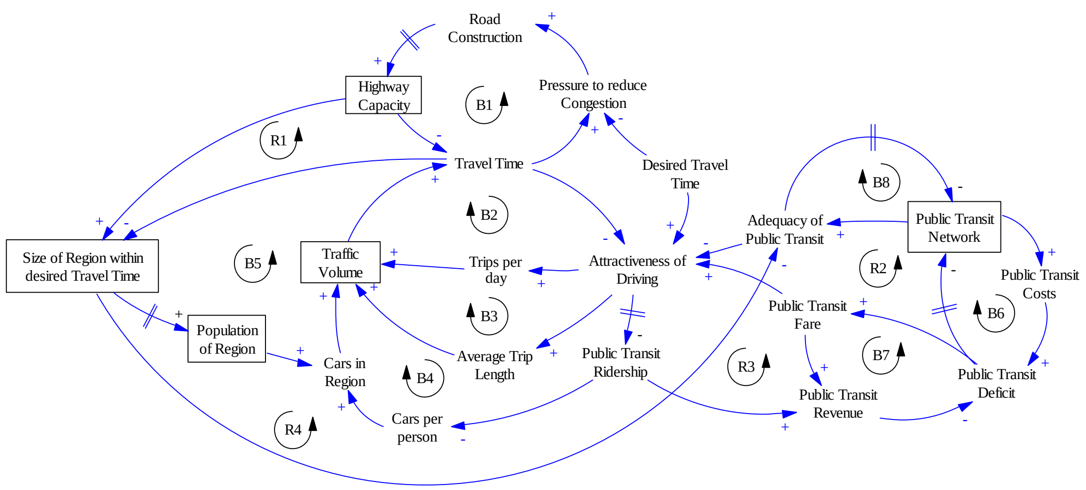


Figure 36: Urban Transport Dynamics Causal Loop Diagram [Sterman, 2000, p182]

To this point, our descriptions assume that cities are closed systems, which, in reality, is clearly not the case, because they are embedded in the surrounding districts. New freeways and ring roads improve the accessibility of formerly remote areas, hence, expanding the region which is in reach to the city center in the desired travel time. Congestion, in turn, reduces the radius. This effect closes two more feedback loops. The first is known as urban sprawl (B5); people move out of the noisy city center into the suburbs, and, with it, the vehicle population grows. Traffic volume grows further and travel times rise until the congestion level has reached a point where the attractiveness of living outside the city does not outweigh the long daily commute times. This feedback has long delays because moving an apartment or house is not easily done. These delays can cause congestion to overshoot the desirable level and present powerful barriers to changes in the system.

But road construction usually does not end at this point. To foster economic development and trade, inter-city connections are being built, providing rural areas with enhanced access to urban services (R1). During the entire process, the number of vehicles on the road augments with the familiar impacts on congestion, environmental pollution and quality of life.

We now turn to the effects of road infrastructure expansion on public transport. Standard economic theory suggests that the relative decrease of attractiveness lets people turn to alternative goods or services. But, we do not observe significantly more transit riders when roads are congested. Conversely, lower travel times due to more road capacity make the use of private vehicles more attractive, with the consequence of less riders and revenues for public transport. However, the economics do not play well for transit operators: costs do not drop accordingly because most of them are fixed. The only way for the transit authority to cut its deficit is to reduce service and quality by reducing number of routes or frequency of service (B6). Public transport becomes even less attractive and the deficit greater. A self-reinforcing feedback loop (R2) that continuously erodes mass transportation is the consequence. Raising the fares as a countermeasure is not helpful either, because it also operates as a reinforcing loop (R3) higher ticket prices increase the relative attractiveness of driving and people shift to private vehicles. Consequently, ridership falls and fares need to be raised even more. Due to their cost structure, public transport modes are highly vulnerable to these reinforcing feedback loops. In many cities, tax revenues are used to offset the deficits of service operation. However, this only delays and cushions the effects of the feedback loops, but does not effectively mitigate them. In an effort to compensate the vicious cycles, authorities try to pro-actively expand mass transportation capacity, but limited funds and long planning and construction phases make this strategy challenging to pursue. There is a final feedback loop worth adding: as sub-urbanization continues and urban density lowers, public transport becomes less and less useful in these outer areas, which again promotes the use of private modes and, thus, vehicle ownership. It is another vicious circle (R4) which undermines public transit ridership, particularly in the lower density outskirts of a city.

Sterman translates the familiar elements of the state-of-the-art approach (road network capacity, mode choice, etc.) into a way SD modelers can capture and describe systems. The Causal Loop Diagram representation focuses on the dynamic interaction between the key elements of the transport system, but does not provide a more detailed model of the elements themselves. Typical for SD, certain parameters are aggregated (e.g. road capacity) for reasons of simplification, which brings forward challenges in formulating mathematical equations for a computer simulation model. Table 9 presents both views on the system elements.

Table 9: Four-step travel demand model elements in System Dynamics framework

	4-step Travel Demand Model Element	Sterman Model Element	Differences to State-of-the-art model elements
Trip Generation & Distribution	Trips per day (mobility)	*Trips per day*	No spatial distribution of the trips explicitly mentioned in the model description
	Average Trip Length	*Average Trip Length*	Trip length distribution not particularly emphasized
	Trip Purpose	*n.A.*	Not modeled
	Homogeneous Groups of travelers	*n.A.*	Can be implemented, but not directly mentioned in the model description
Modal Split	Vehicle Ownership	*Cars per Person*	Ownership not on household level
	Travel Cost	*(Public Transit Costs)*	Costs are included, but refer to the general fare structure of public transit, rather than trip costs, in particular
	Travel Time	*Travel Time*	Travel time as an average value
	Utility (function)	*Attractiveness of Driving*	Attractiveness of driving is very similar to the concept of "utility", which quantifies the mode preference.
Trip Assignment	Road Network	*Highway capacity*	Verbal description refers to the network as such; spatial modeling not feasible in SD framework
	Public Transport Network	*Public Transit Network*	Verbal description refers to the network as a whole; spatial representation not feasible in SD framework
	Pedestrian/Bike Network	*n.A.*	Not mentioned
Course of Time	Multiple scenarios are computed for a specific future point in time (forecasting of key system parameters)	*Dynamic interaction of system parameters over the simulated time period in different scenarios*	In System Dynamics, the model evolves iteratively based on the feedback structure (reinforcing/balancing loops); In contrast, state-of-the-art approaches use analytical models to forecast, but do not include dynamic interaction in their framework

Although the spatial aspect is included in the feedback structure through trip lengths and the size of the region within desired travel time, the dynamic model does not capture what is typically referred to as *Origins* and *Destinations*, which help urban planners to understand where people come from and to which parts of the city they go. On the other hand, the model closes relevant feedbacks in mode choice that indicate the short and long term implications of high-level policies.

The model, of course, is still incomplete and could include more feedback loops. For example, the consequences of urban sprawl to average trip lengths and change of mobility patterns thereof. What is more, regulations influencing attractiveness of driving or travel demand management measures, such as parking, are not considered. Yet, the model provides a suitable framework to analyze transport demand and supply dilemma urban authorities in India are confronted with.

4.4 The Dynamic Urban Transport Model for India (*DUTM-i*)

Building on the qualitative model presented in the previous section, we adapt the system parameters and identified feedback structures to our study case and develop a functional computer simulation model, the *Dynamic Urban Transport Model for India* (DUTM-i). A key challenge in this process is to formulate and validate the equation sets, which translate the verbal system description in a computable code. To solve this, we take multiple avenues. First, we adhere to previously published System Dynamics models and related literature to specify, for instance, growth processes or time lags in the system. Transport-related elements, such as vehicle ownership or congestion, are specified with established models from transportation research, where possible. In order to formulate the India-specific system characteristics, we apply the results of the CMP data analysis (Chapter 3), where we were able to identify functional relationships between vehicle ownership and trip rates, as well as average trip lengths and urban area.

The DUTM-i is programmed using the *VENSIM 6.0* software package, which has been specifically designed for system dynamics modeling and is commonly used in the academic community. For the interested reader, the VENSIM source code of the DUTM-i is provided in Appendix A-7. In its open loop representation, the DUTM-i simulates the scenario of unlimited travel demand growth. We then close three different feedback loops to contain road travel demand and reduce congestion, as we ascertain that growth is not infinite. When applying the model to study cities, we simulate the base scenario for each city first, and check whether undesirable levels of congestion are reached within the selected time-frame. We then assess the balancing feedback in terms of their long-term effectiveness and conduct sensitivity analysis to show how robust they are. Through this, we aim to deepen the system understanding and equip involved stakeholders with an easy-to-use tool to communicate the findings, even to non- transport professionals.

4.4.1 Model Structure and Causal Loop Diagram

A distinct characteristic of urban mobility in India is that most travelers are captive. The reason for this is the modest comfort and safety level of public buses, auto-rickshaws, etc., as well as the fact that those modes do not offer any travel time advantages because they are usually road-based. Two-wheelers are, in fact, the quickest mean of roaming the city, due to their size and maneuverability. In cities where metro systems exist, however, travel times along major corridors were observed to be significantly shorter [Advani and Tiwari, 2005]. Captive riders alter the model structure proposed by Sterman because being able to purchase a private vehicle trumps relative attractiveness of driving it as a decisive element for mode choice. It links the growth of road transport demand to the economic development (and consequently the disposable income levels) in Indian cities rather than to the overall attractiveness of driving compared to public transit.

Secondly, a significant share of formal and informal public transport services in India is run by private operators. This has important implications for the qualitative model, because there are much shorter delay times between ridership loss and lower coverage of the transit network. Buses will not continue to serve unprofitable routes, and fares are calculated based on supply and demand (i.e. expensive for remote areas). In other words, there is no deficit to be closed, as private operators simply run out of business if they do not earn profits. In the national action plan, Government of India has recognized this problem and is supporting so-called “City bus” initiatives that put all operations under a central administration to unify fare structure and routing. In the DUTM-I, public transport is treated as a residual value that captures the changes in mass transit demand, due to the modeled behavioral feedback.

Finally, population size is treated as an exogenous scenario variable because urbanization in India is driven by people's aspirations for higher prosperity, rather than improving accessibility for remote rural areas. Cities are confronted with a high influx of people that do not commute to their home villages on a daily basis and require accommodation in the city. It is reasonable to assume that the feedback loop might play a role beyond the simulated time horizon, but has not been considered here. The final model structure in form of a Causal Loop Diagram therefore draws as follows:

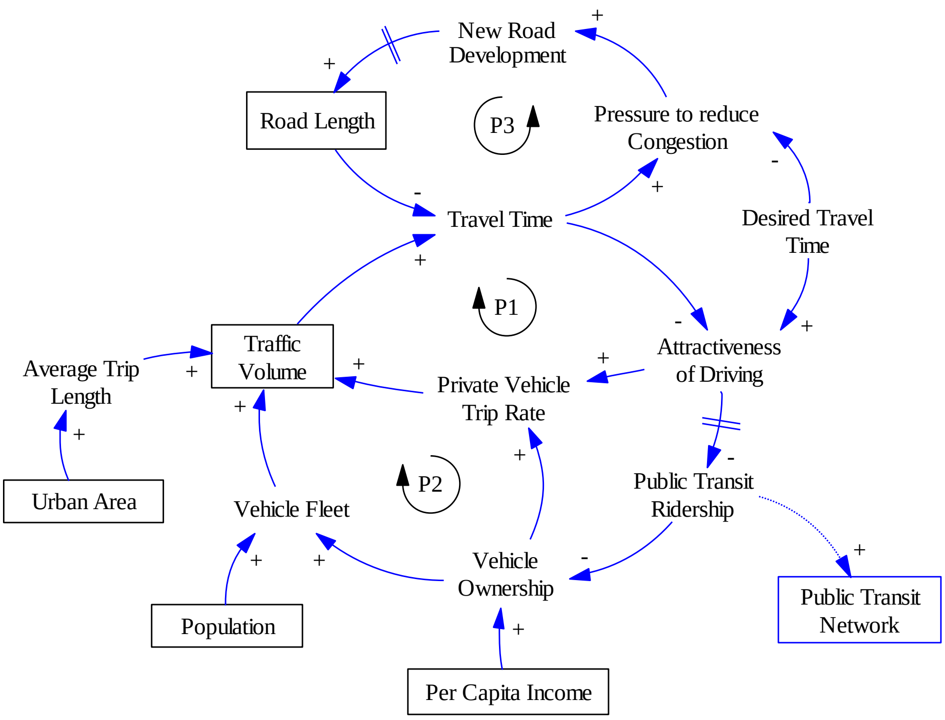


Figure 37: DUTM-i Causal Loop Diagram (with feedback)

As shown in Figure 37, three drivers for travel demand growth (urban area, population size and per capita income) are modeled exogenous to the feedback structure. The DUTM-i treats population size and per capita income as scenario variables, because they are largely dependent on influencing factors outside the transport system (i.e. general economic environment, housing conditions in the city, etc.). The extension of urban area has been defined in the City Plans for the investigated time horizon and is, therefore, regarded as a fixed boundary condition in this study. All three variables are major drivers for expected travel demand growth in Indian cities. Per capita income is directly related to the motorization level, which – multiplied by population size – constitutes the size of the vehicle fleet roaming the city. In mathematical terms, both variables increase exponentially over time, leading to high growth dynamics in the system. From the CMP Analysis, we further found that people travel more in cities with higher vehicle ownership and take longer trips as urban density declines confirming the assertions made in the original Sterman model.

The balancing feedback loops (P1-P3) in the model are triggered by travel time, which results out of average daily traffic volume and network capacity. This is consistent with model building in the CMP's, which rarely include other influencing factors, such as the trade-off in terms of trip cost, in their estimations. If a specific traffic volume on the network level is exceeded, travel time increases significantly and becomes undesirable for a growing number of citizens. Rather than spending most of their time in congestion, they will look for alternative modes of transportation, which reduces the private vehicle trip rate and closes the first, and most powerful, feedback loop (P1) in the system. As congestion worsens, urban authorities are more likely to introduce policy schemes targeted at making driving and car ownership more expensive and, therefore, less attractive (e.g. parking charges, vehicle registration tax, etc.), which closes feedback loop (P2). The example of Singapore shows that strict regulation of vehicle registration licenses can be very effective to contain private vehicle travel demand. Finally, travel time can also be lowered by increasing the network capacity, which includes both extending its total length and optimizing the throughput on the existing roads. This closes feedback loop (P3) and is the preferred way of accommodating the expected travel demand growth, according to the plans that were laid out in the CMPs.

Because public transport is treated as a residual value reflecting excess demand, no feedback loop is closed. Instead it is a relevant output to the model, estimating the required transit capacity over the entire course of the simulation. Table 10 provides a comparison between principal feedbacks found in the DUTM-i and Sterman's system structure:

Table 10: Feedbacks increasing traffic volume in the Sterman model and the DUTM-i

	Feedbacks in Sterman [2000]	Representation in DUTM-i	
Balancing Loops	*"Capacity Expansion"* (B1)	Yes	Implemented as policy loop P3 in the DUTM-i
	"Discretionary trips" (B2)	Yes	positive relationship between *Vehicle ownership* and *Motorized Trip Rate*
	"Extra Miles" (B3)	Yes	Positive relationship *Urban Density – Average Trip Length*
	"Take the Bus" (B4)	No	No mode choice sub-model implemented
	"Move to the Suburbs" (B5)	Yes	Positive relationship *Urban Density – Average Trip Length*
	" Cost Cutting" (B6)	No	No mass transit feedbacks implemented (captiveness of Indian riders). Fare structures are not unified and vary by routes, which are often operated by private sub-contractors; therefore unprofitable routes will not be served.
	"Fare Increase" (B7)		
	"Mass Transit Capacity Expansion" (B8)	Yes	Residual value in the DUTM-i, which is driven by policy loops reducing road traffic volume
Reinforcing Loops	*"Open the Hinterlands"* (R1)	No	Rural population in India moves into the city and does not commute home on a daily basis
	"Route Expansion" (R2)	No	No mass transit feedbacks implemented (captiveness of Indian riders). Private road transport demand is mainly driven by rising incomes that make motorized vehicles (two-wheelers, cars) affordable to the masses.
	"Choke off Ridership" (R3)		
	"Can't get there by bus" (R4)		

4.4.2 Set of Variables

The causal loop diagram captures the general cause and effect relations in the system. For a functional System Dynamics simulation model, we need to specify the stocks and flows in the system. The DUTM-i is composed of seven stocks; five relate to transport demand and two determine the available infrastructure supply.

"Per Capita Income" fuels *"Vehicle Ownership"* growth and multiplied by "*Population*" constitutes the total number of cars and two-wheelers roaming the city. The availability of private means of travel determines their usage and, consequently, the total road travel demand expressed as "*Daily road*

passenger km". As a residual value, "*Daily Public Passenger km*" comprises all trips that are being performed by bus, metro or other (intermediary) public transport systems, either because the users are captive to transit or due to significant travel time savings over private vehicles.

On the supply side, "*Road Length*" determines the capacity of the road network and "*Area*" of the available space. The size of the network refers to the CMP primary surveys: their inventory does not capture all links of the city, but it includes rich secondary data that makes it possible to estimate their capacity more accurately. It is a simplification (there exist a greater number of formal and informal roads that could possibly be used for driving), but also state-of-the-art transport models usually do not include the total network to balance model costs and validity. Moreover, some kind of road hierarchy typically exists and traffic from feeder streets is consolidated on the higher capacity connector routes. In the case of the DUTM-I, considering all roads would overestimate the network capacity and introduce a systematic model bias.

Table 11: Stock variables in the DUTM-i

Demand	Supply	Parameters driving growth of the stock
Per Capita Income		General economic upturn, expressed through fractional growth rates of the urban economy
Population		Urbanization (migration into the city) is the main reason for population increase in Indian cities
Vehicle Ownership		Vehicle ownership follows s-shaped growth with income level as key driver for growth [Dargay et al., 2007]
Daily Road Passenger km		Total road travel demand is increased by growing number of activities by citizens (motorized trip rate), the longer distances they travel and the overall growing population
Daily Public Passenger km		Transit demand is a residual value, and increases, if public transport offers significant travel time savings over private vehicles (mode shift)
	Road Length	Road network capacity can be increased by construction of new roads, adding new lanes or improving flow properties through better signaling, lane markings, etc.
	Area	Area is expanded through long-term land-use planning; for most study cities the area remains constant

The aggregate parameter *Road length* also omits the spatial distribution of traffic flows and, consequently, local congestion phenomena: traffic might seem acceptable on the network level, but specific roads within are already choked. Implicitly, we presume that riders divert to alternative routes, but this would lead to travel time losses which are not captured in the DUTM-i. We factor this effect in by setting the acceptable volume/capacity ratio to 0.8 – the threshold value at which the feedback loops become effective. One of the main reasons for this simplification is the limited data availability for a larger number of Indian cities. Even though road networks can be retrieved from alternative sources, the data to estimate Origin-Destination matrices and load the network were not found readily accessible. The aggregate approach of the DUTM-i is an approximation to the real-world conditions, but triggers the same feedback loops that typically occur, when capacity limits are approached or exceeded.

Another important exogenous supply stock is the area, where we adhere to the City Master Plans (as do the CMP's). Most cities have them available for the simulated time horizon 2030 including the land use plans. However, it is challenging to select the suitable size, as this depends on the study questions to be answered. In Bangalore, for example, the municipal core is already densely populated; growth will primarily take place in the areas around today's city limits. Applying the DUTM-i only on the municipal area would artificially limit the expansion potential of the city. Therefore, we pick the larger Bangalore Metropolitan Area, which also has effects on travel demand through longer average trip distances. For each of the study cities in this thesis, the area definitions are explained in more detail in the description of the base scenario.

All of the mentioned stocks are subject to flows. Because we focus on growth processes in this thesis, stock variables are subject to inflows only. In other words, we do not model a shrinking city or a reduction of vehicle ownership and travel demand in the investigated scenarios because we do not believe that this is a likely development for Indian cities in the simulated timeframe.

The fractional population growth rate is treated as an exogenous parameter to the system. From a SD perspective, one could argue that the attractiveness of a city is linked to the efficiency of its transport system and vice versa, which would imply a feedback between congestion and the fractional growth rate. We did not consider this link for two reasons: first, we wanted to make the results comparable to the original projections found in the CMP. Second, and more importantly, the migration into the selected study cities has reasons that are outside the transport system and, thus, beyond the model scope. Hence, the fractional growth rates reproduce the population size projections found in the CMP model and can be altered to explore alternative scenarios.

Per capita income growth was estimated with data provided by the International Monetary Fund (IMF) referring to the economic growth perspectives of India in the future. For all scenarios in this thesis, the fractional growth rate was held constant at 4% per year (net of inflation). This assumption is conservative, given the expectations that India might display double-digit economic growth rates in the future, but accounts for the fact that economic growth does not fully translate into income growth. As is the case for the fractional population growth rate, this variable is a simulation parameter to explore alternative scenarios to the ones presented in this study.

For the supply-related stocks, the DUTM-i does not feature fractional growth rates. The flow variable "*New road Development*" includes the road infrastructure projects currently under construction and "*New Land Development*" refers to expanding the city beyond its current delineation, if proposed for example, in the Master Plan.

Growth of "*Vehicle Ownership*" is determined by the reference model developed by Dargay and Gately [1999], [Dargay et al. 2007], which is explained in more detail in the next section, as well as the sub-models that yield road and public transport demand increase. With this, all stocks and flows are specified.

Auxiliary variables are used to de-compose equation sets and link the stock and flow variable to each other. For example, *Expected Daily Road Passenger km* (DRPKM) is used to introduce an information delay between the formal (calculated) travel demand increase and the perceived demand, which triggers feedback (e.g. mode shift). Another function of auxiliaries is to introduce perceived thresholds, such as *Desired Journey Speed* (JS), which expresses the minimum acceptable average road speed on the network and initiates feedback reducing road transport demand, if the velocity falls below the critical level. In transportation science, this is often referred to as the "time budget", which denotes the accepted time for a taken trip. Research in mode choice shows that the trip time may only be exceeded in certain boundaries before the people are more likely to shift to alternative modes.

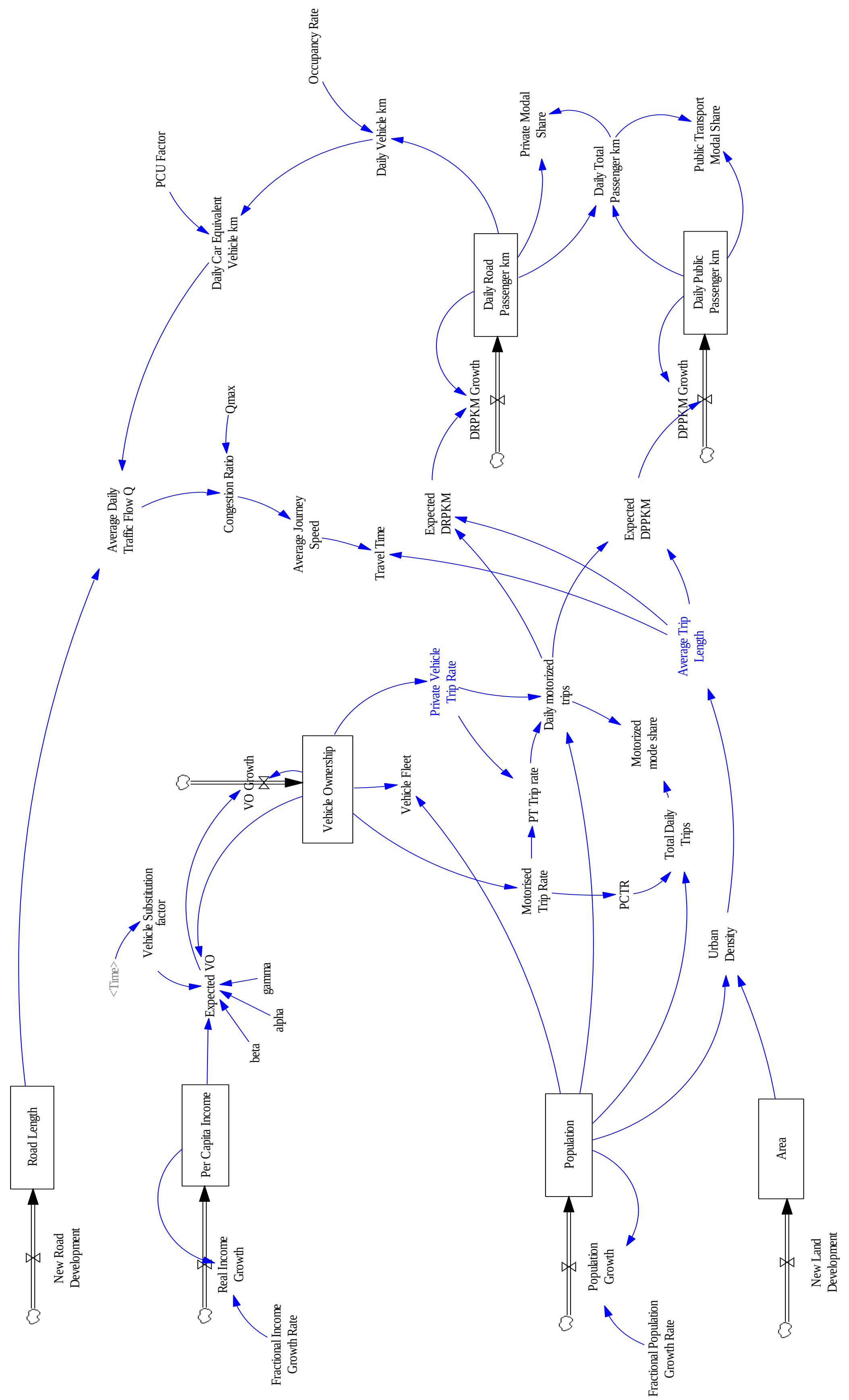


Figure 38: DUTM-i model variables and structure (without feedback)

The "setup variables" define the time settings of the simulation, which starts in 2001 and runs until 2031, with time steps of a year.

Table 12: Temporal parameters of the DUTM-i

Name	Unit	Type
FINAL TIME	30	SETUP
INITIAL TIME	0	SETUP
TIME STEP	1 (year)	SETUP
Time	Years	SETUP

Moreover, the DUTM-i is designed as a scalable model with respect to available transport modes. In order to make results comparable, this number was kept constant in the study city simulation runs. Nevertheless, it can be expanded by alternative modes. In the VENSIM software, so-called "subscripts" transform scalar variables to arrays. The subscript *"Transport Mode"* describes an array containing three values[15] (cars, two-wheelers and public transit). Variables that are subject to this array are marked with *"[ ]"*.

The VENSIM software framework allows to scale the DUTM-i in other dimensions (for example, in homogeneous groups of travelers), too. In the model design phase, we experimented with segmentation of the population and urban areas, which is commonly found in state-of-the-art models; unfortunately, we did not find the required input data for a more disaggregated representation of the selected study cities. We therefore, could not implement these features in this thesis.

The full list of model variables including their dimensional values is documented and referenced in the appendix (A-2).

4.4.3 Description of Sub-Models

In the previous sections, we outlined the structure of the model by means of a Causal Loop Diagram and specified the different types of variables found in the model. We now turn to the description of the mathematical equations that link the variables to each other. As exercised in many SD models, we integrate suitable reference models found in the literature review into the DUTM-i in order to reduce the systematic error of the model setup.

The sub-models, presented in more detail below, cover the key qualitative assumptions of this thesis: the relationship between income level and vehicle ownership and, consequently, road travel demand on the one hand, and estimation of (aggregate) network capacity on the other. A sound estimation of both supply and demand is necessary, because their equilibrium determines the level of congestion, which triggers policy interventions and behavioral feedback if it reaches unacceptable levels.

Vehicle Ownership model

Historically, economic development has been strongly related with an increase in the demand for transportation, especially road-based. This relationship can also be observed in developing and emerging countries today. Motorization (measured in vehicles per 1000 inhabitants) follows an S-shaped function of per-capita income. In System Dynamics terms, the function can be decomposed into a reinforcing and balancing feedback loop. When average per-capita incomes have surpassed a critical threshold level, vehicles become affordable for the masses and the vehicle market expands. As

[15] In an alternative scenario presented in more detail in Chapter 6, we add another vehicle type ("Quadricycles") to the Transport mode array to explore its congestion (mitigation) effectiveness.

a person usually does not own more than one vehicle and the fact that certain age groups are restricted from driving, the vehicle ownership rates saturate at a certain level.

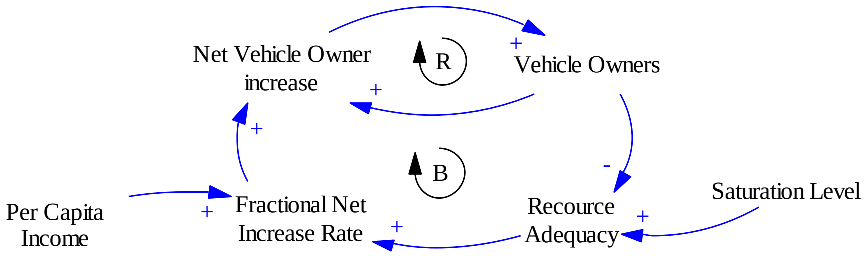


Figure 39: Vehicle ownership dynamics (Causal Loop Diagram)

Historical data shows that the maximum level of vehicles per capita is very different for countries with similar income levels. This implies that the characteristics of the transport system have influence on how dependent it is on automobiles (see [Kuhnimhof et al. 2014]). To model s-shape growth, a set of mathematical functions exist, with logistic and log-normal functions being among the most widespread. To account for the differences in saturation levels, analyses typically assume lower values for developing countries than for developed countries in their models (e.g.: [IEA, 2004]). In their studies, Dargay and Gately [1999], [Dargay et al., 2007] proposed that a Gompertz function best approximates the relationship between the parameters:

$$V_t = \gamma\theta e^{\alpha e^{\beta GDP_t}} + (1-\theta)V_{t-1} \quad (19)$$

With:

V	Vehicle Ownership [vehicles per thousand inhabitants]
γ	Saturation Level
θ	Speed of Adjustment (of vehicle ownership)
α, β	Curvature Parameters
GDP	Gross Domestic Product per capita (measure for income level)

In the improved model, the original assumption that only coefficients, β_i, were country-specific, while all the other parameters were valid globally, was relaxed. Saturation levels are now calculated separately and benchmarked against the level estimated for the USA, which is denoted γ_{MAX}, with countries that are more urbanized and more densely populated saturating at lower levels. The second modification to the original model is the asymmetric response of ownership to income changes, as discovered in the sample. Thus, the θ values for rising and falling income are estimated separately from the sample.

The Dargay and Gately model is viewed as state-of-the art in terms of estimating vehicle ownership growth. Therefore, in the DUTM-I, we integrate the Gompertz function to drive vehicle demand in the simulated timeframe. The parameters alpha and beta (which determine the function's) curvature are estimated based on the available time-series data for vehicle registrations and average per-capita income in the study cities. Saturation level gamma was set to 683 vehicles per 1000 inhabitants, as estimated for India as a country [Dargay et al., 2007, p.14]. It is important to note that income is measured in Gross Domestic Product (GDP) per capita with Purchasing Power Parities (PPP). In economics, this unit of measure yields real income growth, net of inflation and currency exchange rate effects, providing more stable future projections. However, it poses a challenge for implementation in the model, because Gross Regional Product (GRP) data for the study cities does not exist. Instead, we use available average household income data, which has been collected in surveys for the CMP's and the National Census. As we also know the average household size, we can therefore estimate per-capita income, provided in Indian Rupees, for the year the data was collected. To convert Indian Rupees to the currency unit used in the Dargay et al. model (2005 US Dollar PPP), we refer to OECD data [OECD, 2015] and back cast growth rates into the starting year of the simulation (2001). The conversion table is provided in the Appendix (A-3). By this we achieve an acceptable approximation of real income and vehicle ownership for each city separately. We validate our assumptions for every city based on the available data points. Dargay et al. [2007] only consider vehicles with at least four wheels. However, motorcycles and scooters are an integral part of the Indian transport system. To account for this, we model the motorized two-wheeler fleet with the underlying assumption that people gradually upgrade their mode of transportation when they have higher disposable incomes. People shift from bicycles to motorcycles and eventually to cars, as soon as they can afford to do so. Data supporting this assumption can be found in both historical context and CMP household survey data. For calibration, we compare to available vehicle registration data [MoRTH, 2012a], and extrapolate future growth on a per-city basis.

Travel Demand Estimation

For the preparation of a CMP, each city set up such a four-step travel demand model for the base year and defined scenarios in the horizon year. As explained earlier, the DUTM-i calculates overall daily travel demand, rather than disaggregated values on the network level. This is mainly because data to build up a viable model for all study cities is almost exclusively in the hand of third party consultants in India and therefore, not accessible for research purposes. We are aware that we hereby dismiss information; however, we avoid importing significant data errors into our model: uncertain land use planning in the future and lax control practices present a challenge to obtain reliable and stable forecasts in the simulated time frame.

Daily travel demand (measured in daily road passenger km) is therefore the product from following key variables that change dynamically: (average) daily trip length, amount of trips per day and size of population. Taking into consideration the research questions to be answered, we explicitly model road transport only, denoted as:

$$\text{Travel Demand}_t = \text{MTR}_t * \text{ATL}_t * \text{POP}_t \quad (20)$$

With: MTR Motorized Trip Rate [Trips per capita per day]
ATL Average Trip Length [km per trip]
POP Population within study area [people]

The total demand is further decomposed by mode, namely passenger cars, motorized two-wheelers and public transport (including intermediary transport modes, such as auto-rickshaws, minibuses, etc.). Non-motorized transport is calculated in terms of daily trips, as a residual value of per capita trip rate (PCTR) and motorized trip rate (MTR), and utilized to calibrate the model against the reference demand estimations from the CMP model in the base scenario.

The start values for the variables are set according to the information found in the CMP documentations in the base year. For modeling the time path of each variable we come back to the results from the cross-city analysis (Table 6). We make use of the general trend functions discovered in our dataset to forecast the dynamic changes of the decisive factors for total demand.

Average trip lengths follow a negative logarithmic function in relation of population density:

$$\mathrm{ATL_t} = \mathrm{A} - 0.789 * \mathrm{LN}\ (\mathrm{Urban\ Density_t}) \tag{21}$$

Motorized trip rate increases moderately with growing population:

$$\mathrm{MTR_t} = \mathrm{B} + 0.56 * \mathrm{LN}\ (\mathrm{Vehicle\ Ownership_t}) \tag{22}$$

Parameters A and B are calibrated against the year the CMP was prepared for. Estimating trends for mode split is difficult from an aggregate view, because typically consumer decisions are modeled using utility functions, which consider a set of factors. From the base data set, we are able to figure the amount of trips performed per vehicle type (in Indore, for example, 1.24 trips per car and 1.19 per two-wheeler). We assume that this ratio remains constant for the base scenario. In the CMP four-step models, too, travel time is dominant for mode choice. Only some cities (e.g. Bangalore) include travel cost. Unfortunately, parameters cannot be applied to the DUTM-i, as they are not generally valid, but estimated for the specific use-case.

Therefore, we choose to specify "*Trips per Vehicle*" as a scenario variable, with the implicit assumption that owners are very likely to use their vehicles in a similar way. Despite the strong constraint of constant trips per vehicle, the base scenario shows very good fitness values for 2031, compared to the CMP estimations. Public transport demand was not explicitly modeled and is a residual value of subtracting two-wheeler and car trips from the overall motorized trip rate. In the alternative scenarios, demand shifts from private to public transport with the implicit assumption that people will not opt to walk or cycle. In Europe, we see that this presumption does not hold true. In cities like Copenhagen, for instance, riding a bike to work is not only considered a means of healthy and sustainable lifestyle, but really offers the advantage to avoid long and stressful daily commutes. Mobility research in India suggests that a shift from private vehicles back to non-motorized modes, however, is not likely to take place in the observed time-frame because they are considered unsafe and inconvenient. In our simulations, we focus on the implications to public transport demand in case of mode shift, because this requires adequate planning in Indian municipalities in the future. Population figures directly refer to the CMP data with neither a proprietary model nor assessment of alternative growth scenarios.

Congestion Model

Congestion occurs, when travel demand exceeds the design capacity of a given link or network. The objective of transport planning is to mitigate congestion as much as possible and to ensure a high level of service in the network. To achieve this, measures can be taken both to reduce demand and to increase supply, and more recently, the capacity of existing road infrastructure via Intelligent Transport Systems (ITS). In state-of-the-art macroscopic transport models, sophisticated algorithms are deployed to calculate optimal utilization of the available transport network and to investigate alternative scenarios (e.g. construction of an urban ring road). In order for the optimization to produce good results, detailed information on network properties, such as link capacity or average link speeds, is required. Microscopic effects, such as intersections, are factored in with parameters to reduce layout capacity.

The DUTM-i takes on the same thinking model to simulate congestion effects, but as demand is modeled as an aggregated variable, the road network capacity must be treated as such, too. This entails the key challenge to rate the capacity value correctly because there is limited research to draw upon, especially for Indian road conditions. To estimate network capacity, we refer to research undertaken at the University of California, Berkeley and the Swiss Federal Institute of Technology, Lausanne on modeling congestion effects in aggregate, macroscopic models. Geroliminis and Daganzo

[2008] present empirical findings that *"a macroscopic fundamental diagram (MFD) linking space-mean flow, density and speed exists on a large urban area […]"*. They suggest that *"conditional on accumulation large networks behave predictably and independently of their origin destination tables."* Their simulations show that the maximum capacity (in terms of vehicles per hour) was reached around 500 on the network level, compared to the theoretically 2000 vehicles per hour defined in the Highway Capacity Manual [Transportation Research Board, 2010] for single links without intersections[16].

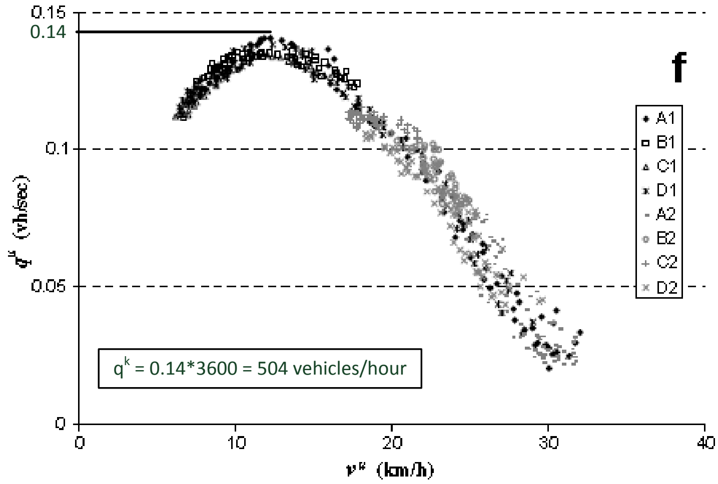


Figure 40: Derivation of maximum capacity from experimental findings on existence of urban-scale MFD in Yokohama [Geroliminis and Daganzo, 2008]

Mühlich et al. [2015] analyzed traffic performance on various idealized hierarchical urban street networks using micro-simulation. The MFD was used to compare the performance of different arterial structures. We consider these findings to adjust the network capacity to different city shapes found in our study cities. The results suggest that networks only consisting of local streets are better than those where both local and arterial streets are mixed and have no ring roads. Grid layouts perform significantly worse than the other investigated network types unless they are hierarchical, which is the case in one study city (Chandigarh).

Finally, we turn to the question, whether those research results are transferrable to the Indian case. The Indian guidelines use the same theoretical capacity values found in Europe or the US, for urban roads. The adjustment to local traffic conditions is achieved by introducing passenger car unit (PCU) factors, which normalize different modes of transport to the equivalent of a passenger car. Indian Roads Congress (IRC) [1990] provides the following PCU values for typical means of transport in India:

[16] In practice, the theoretical values of the manual are generally lowered to around 1000 vehicles/hour for urban two-lane roads.

Table 13: PCU conversion values [Indian Roads Congress, 1990]

Vehicle Type	Equivalent PCU Factors	
	Percentage composition of vehicle type in traffic stream	
	5%	**10% and above**
Fast vehicles		
1. Two-Wheelers	0.5	0.75
2. Car/Jeep/Van	1.0	1.0
3. Auto-rickshaw	1.2	2.0
4. Light Commercial Vehicle	1.4	2.0
5. Truck or Bus	2.2	3.7
6. Agricultural Tractor Trailer	4.0	5.0
Slow Vehicles		
7. Cycle	0.4	0.5
8. Cycle Rickshaw	1.5	2.0
9. Tonga (Horse drawn vehicle)	1.5	2.0
10. Hand Cart	2.0	3.0

The guideline values are calculated on the assumption that there is no big speed difference between the different modes in the urban environment. However, Arasan and Krishnamurthy [2008] found that the PCU value of a vehicle type varies significantly with traffic volume, both on urban and rural roads. If traffic volume is low, the speed difference between, for example, an auto rickshaw and a car, is relatively high. In this case the PCU value for auto rickshaws is high as well, because they lower the road capacity (measured in vehicles per hour). As traffic volume and, consequently, density grows, the speed difference between slow moving modes and cars diminishes and the PCU values decrease until the smaller footprint of modes, such as auto rickshaws, eventually increase the road capacity . What is more, in highly congested road networks certain modes (e.g. motorcycles) allow for easier maneuverability, which reduce the PCU value even more. In other research papers and reports, PCU values were also found to vary according the traffic composition and the road design itself.

For the DUTM-I, we refer to the values provided by IRC for two reasons: first, the feedback loops we study come into action at a certain congestion level, where we assume little speed difference to occur and only the spatial aspect to remain, which is reflected in the IRC guideline. Second, the level of analysis is on the entire network, which makes it difficult to include road-specific properties in the PCU estimation. In a conservative approach to estimate the capacity, we opt for the smaller PCU values from Table 13 per mode found in the DUTM-i, because we do not want to artificially underestimate road capacity in the model.

Because the PCU values adjust the theoretical values from the manual to the real traffic conditions, we are able to convey the results of Geroliminis and Daganzo [2008] and Mühlich et al. [2015] to our model as a viable approximation. Due to the limited representation of the real network, we relax the maximum capacity to 600 vehicles per hour in the base scenarios of most study cities, as this also matches the CMP results against which we calibrate the model. In addition, we perform sensitivity analysis to rate the error in the simulation model.

The output of the travel demand sub-model is measured in passenger kilometers per day, whereas the link capacity is denoted in vehicles per hour. In order to obtain a correct volume-capacity ratio, both variables are normalized to the unit of Daily Car Equivalent Vehicle km:

$$\frac{\text{Passenger km per day}}{\text{Occupancy Rate}} * \text{PCU Factor} = \text{Daily Car Equivalent Vehicle km} \tag{23}$$

$$\text{Vehicle capacity per hour per lane} * 10 \text{ hours per day} * \text{Number of lanes} \\ * \text{Road network km} = \text{Daily Car Equivalent Vehicle km} \tag{24}$$

Occupancy rates are documented for every city separately, based on the primary road surveys in the CMP's.

With respect to capacity we first have to transform average daily capacity. We follow the approach in state-of-the-art transport modeling, which assumes that average daily capacity is equivalent to 10 hours of layout capacity.

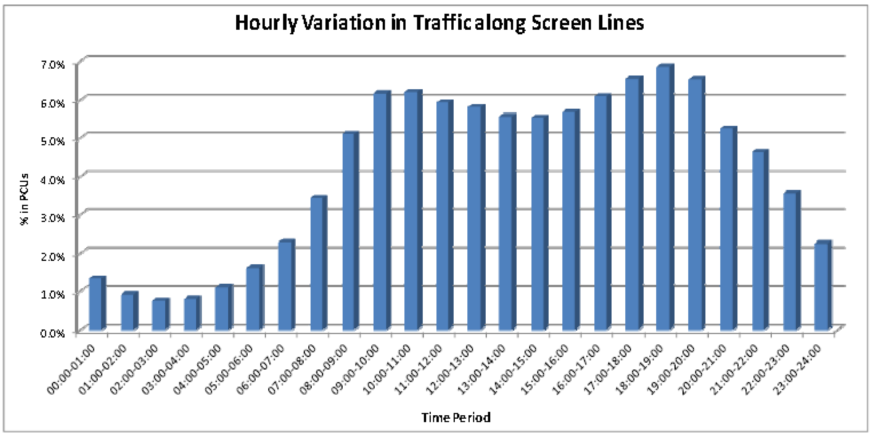


Figure 41: Hourly variation of traffic in PCU's in Hyderabad (screen lines) [LEA Associates, 2012]

As the theoretical capacity is usually defined on a per-lane basis, we multiply with the average number of them in the network to get the entire road capacity. This data is available from the conducted road surveys in the CMP, as is the utilized length of the road network, which does not necessarily represent the entire network as explained earlier. We trust that, in the course of preparing the CMP, there was an educated decision on what parts of the network to include and to omit. As we also compare our simulated travel demand data with CMP reference data, we do not introduce an error source by using this data, but are aware that the real network capacity might be greater due to diversion effects in the case of congestion.

The result of the mathematical transformation is the "*Congestion Ratio*", which indicated the degree to which the capacity is utilized at every given time step. Our network approach dismisses local congestion that typically arises before the entire system is gridlocked. To account for this, we assume that already above 80% utilization, there will be a significant impact to average travel speeds, and thus, becomes the tipping point for strong balancing feedback loops that come into effect, accordingly. The CMP reports support this assumption by using the same threshold value for level of service on street level. In the last step, we have to quantify the effects of congestion on average journey speeds. As the existence of a MFD was assumed, we model travel time increases in the same way, as on the link level. We apply the following convex capacity restraint function:

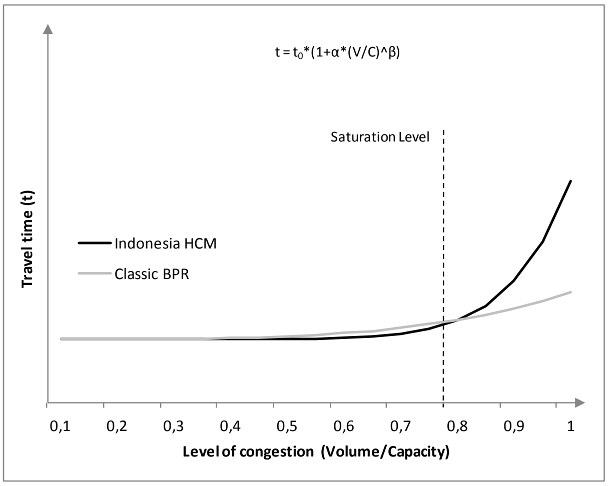


Figure 42: Volume-delay function (generic form)

The parameters alpha, beta is fixed, unless otherwise stated, for all cities and taken from the Indonesian Highway Capacity Manual [Directorate General of Highways, 2013]. This is because there are currently no standard Volume-delay function parameters for India. They are under development and expected to be available in the next years. As Indonesia also displays a high share of motorcycle riders and is considered an emerging country in Asia, we opted for this reference, rather than values from European or American study sources.

4.4.4 Feedback Structures

The base scenario simulates unlimited growth of vehicle ownership and travel demand. Provided that, on average, only 5-10 percent of the population owns a car, this seems a reasonable view on the future of urban transportation. However, the boundary conditions, such as available road space, air quality, etc. limit the amount of vehicles that can be carried in the system. In SD terminology, this means that strong balancing feedback loops will seize control to hinder further demand growth. In the past, these constraints merely played a role as soon as the market was well developed, and in some cases, they never became relevant at all. Indian cities, however, are among the most densely populated in the world, which means that the dynamic feedback loops are going to emerge sooner and will become prevalent in the simulated time-frame. In our simulation we model, three feedback loops reduce congestion:

1. Reduce road vehicle usage (mode shift) – P1
2. Reduce vehicle ownership (registration control) – P2
3. Satisfy demand with more infrastructure – P3

In the DUTM-i, we are not able to perform studies of single measures comprised in the feedback (e.g. impact of a new Bus Rapid Transit corridor), but aim to size their implications to the transport system and, in particular, the consequences of mode shift to public transport.

To visualize the first feedback loop we use a Causal Loop Diagram.

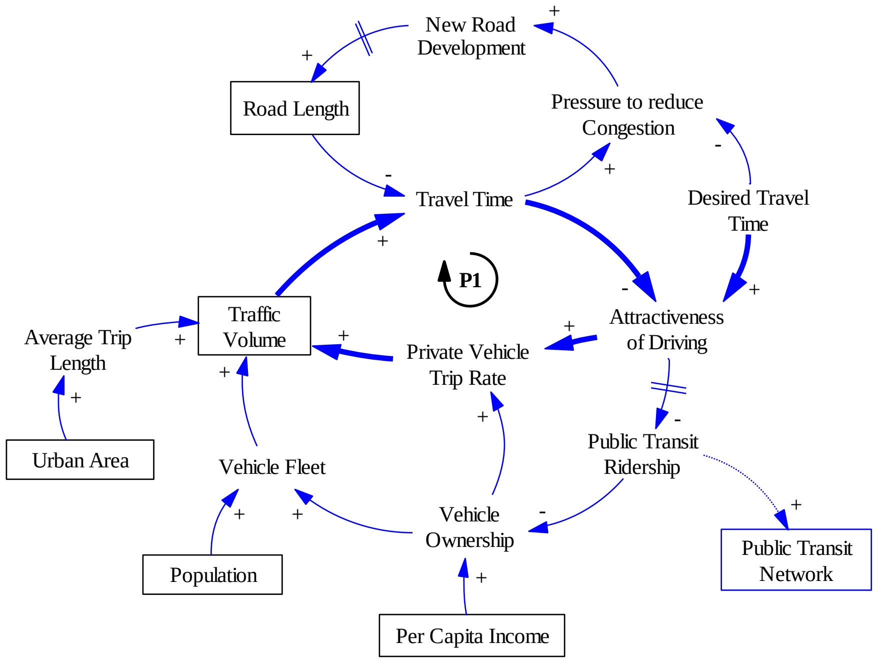


Figure 43: Feedback P1 – Contain Travel Demand

In system dynamics, there is the need to define a carrying capacity that triggers the balancing feedback. In the case of P1, we use congestion ratio as an indication pushing people to think about alternatives to private vehicle ridership. As outlined above, we assume 0.8 to be a level, where significant travel time increase will start to become a daily routine on major corridors (see Figure 42). When this is the case, citizens have different options to impede spending hours to get to work or participate in other activities. They could move closer to the destination of their planned activity. Due to the great cost and effort associated to this, people are usually reluctant to change their home location and accept the trade-off that it takes more time to commute. In addition, non-transport factors, such as the quality of life in the neighborhood, etc. strongly influence this decision. Alternatively, citizens can adapt the location of their activities. Here, we have to distinguish between different kinds of activities: leisure trips (e.g. shopping, gym) are easily substituted and adjusted in terms of how long it takes to get there in the activity chains. Others, such as education, are more difficult to substitute and, will therefore not be changed in the short-term. Third, and in most cases the easiest way, is to shift to alternative modes, provided that it is reliable, safe and significantly quicker. In absence of a spatial dimension, feedback loop P1 focuses on this mode shift to avoid long travel times on the road. The variable *Trips per vehicle* –regulates the degree to which private vehicles are utilized on a per capita basis. A pre-condition for such a change in user behavior is that mass transit is decoupled from road traffic, either by being rail-bound or by having dedicated facilities, such as bus lanes or high-speed corridors available. Shift to public transport can be further promoted by accompanying regulatory incentives (e.g.: collecting parking fees, city tolling, entry restrictions for private vehicles, etc.). Those schemes are typically summarized under the term Transport Demand Management.

We specify *Trips per vehicle* as Stock variable, which can be augmented or decreased, depending on the congestion ratio.

$$\text{Trips per Vehicle}_t = \text{TpV increase}_t - \text{TpV decrease}_t \tag{25}$$

For the feedback P1, only *TpV decrease* is relevant, which is determined by the *Fractional TpV decrease rate* and can be interpreted as gradually diminishing use of private vehicles caused by congestion.

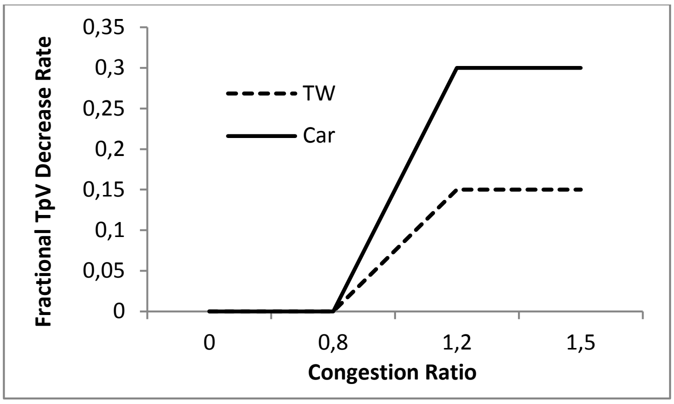


Figure 44: Function for trips per vehicle fractional decrease rate

Formally, this yields the following equation:

$$\mathrm{TpV}\ (\mathrm{t}) = \int_{\mathrm{t}_0}^{\mathrm{t}} \mathrm{TpV}(\mathrm{t}_0) - \mathrm{TpV\ decrease}\ (\mathrm{CR}\ (\mathrm{s}), \mathrm{s})\mathrm{ds} \qquad (26)$$

With: TpV Trips per Vehicle
CR Congestion Ratio

The second possibility to contain road transport demand is to reduce the vehicle fleet size:

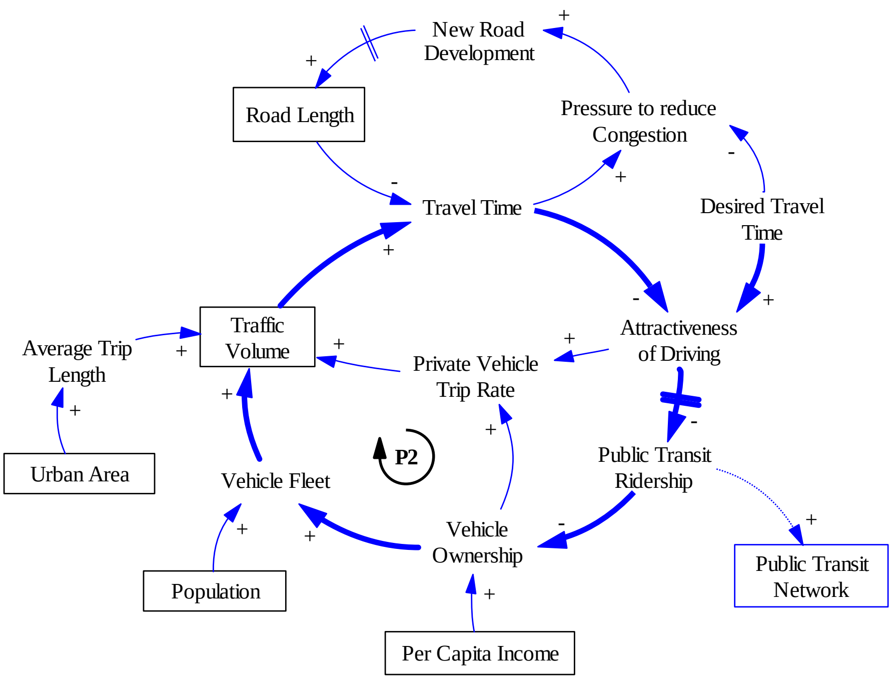


Figure 45: Feedback P2 – Reduce Vehicle Ownership

Here, we distinguish between two different ways of feedback. In structure 2a, we model behavioral change of consumers and assume that the ownership growth decelerates, if the purchased vehicle cannot be used on a regular basis. Despite the observation that especially passenger cars serve as a status symbol in India, the total cost of ownership is likely to be considered too high for many people. We model this through gradually reducing vehicle ownership growth rate (by mode), above the desired threshold level of congestion:

$$\text{VO Growth} = \frac{\text{Expected VO} - \text{Vehicle Ownership}}{2} * \text{Private VO Fractional Decrease Rate} \quad (27)$$

The first term of the product is a mathematical representation of the delays in the system (in this case 2 years) to adjust to the ownership level determined by the VO growth function. Similar to P1, *Private VO Fractional Decrease Rate* is modeled as a linearly decreasing function of congestion ratio, representing a diminishing share of potential new vehicle buyers actually opting to do so:

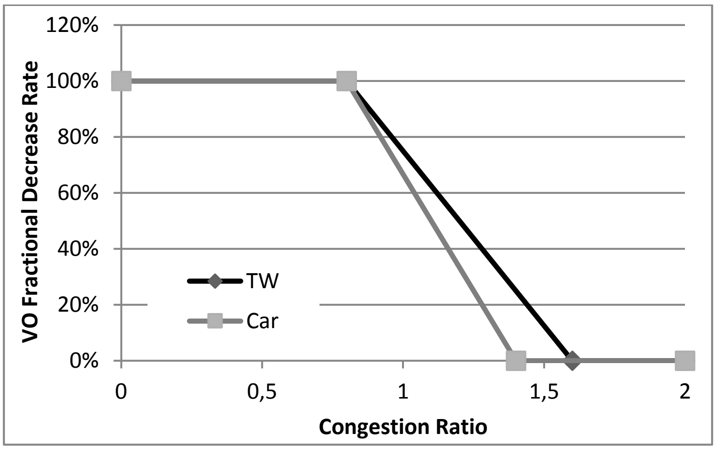


Figure 46: Function for private vehicle ownership fractional decrease rate

It is important to note that the function only impacts the parameter *vehicle ownership*. If the population continues to grow, the vehicle fleet (i.e. the number of vehicles) does so at the same rate. This is an interesting finding, as shown by the results of the study cities.

Another way of restricting the amount of vehicles on the road is a vehicle quota system (Strategy 2c). This way of regulating road traffic was first introduced in Singapore and previously in larger Chinese cities, such as Beijing and Shanghai. The allocation of the vehicle registration rights can either be based on market mechanisms with price per registration depending on supply and demand or randomly given to car buyers (lottery system). In the first case, obtaining a car license can become very expensive and be regarded a luxury good. Singapore and Shanghai pursue this scheme. It is not an equitable policy approach because it links vehicle ownership to income. Therefore, Beijing opted for randomization and issues number plates in a car lottery, where everyone may participate. The system has its downsides in terms of equality, too, because it does not allocate the vehicles to those who need it most, but to a certain number people who were lucky winners. Yet, in contrast to the European and North American strategies, which aim to make vehicle ownership unattractive through other means of pricing (e.g. taxation, residential parking fees, etc.) this policy has proven to be very effective in a very short amount of time – a key advantage in a highly dynamic system environment.

The vehicle quota can either be oriented at the capacity of the road network or subject to a political decision. In China, it is usually found in the five-year plans of the municipality [Beijing Municipal Government, 2013]. In our simulation model, we adopt this strategy and propose a quota based on the amount of vehicles that were newly registered in the year the desired level of congestion was passed. From a modeler perspective, the quota is a parameter that can be adjusted by the user to explore alternative scenarios. Feedback 2c introduces an alternative inflow to vehicle ownership based on the defined vehicle quota. The original growth model does not contribute anymore, as the regulation now determines the amount of new vehicles. Like in China, we assume this kind of quota to be targeted exclusively towards passenger cars. This leads to interesting dynamics in the system, as shown in the case of Bangalore.

A variation of this policy is to introduce a road capacity based approach (Feedback 2b). In such a policy scenario, the vehicle fleet would be adjusted to the available network capacity. If the population of the city remains to grow, this implies that the vehicle fleet has to shrink at the same rate. Although theoretically possible from a modeling perspective, this policy would be very difficult to enforce, especially in a democratic country like India. Therefore, we do not investigate scenarios based on this feedback loop.

The third strategy we investigate is adapting supply to (increased) demand. As discussed earlier, this option is short-sighted, as it omits the fact that better road infrastructure makes driving more attractive and induces even higher ownership growth rates. Nevertheless, analysis of the CMP documents showed that most cities are planning to expand their road network. Through feedback loop P3 we can assess whether the projects envisioned in the CMP's are likely to be sufficient. If not, we are able to estimate the required capacity increase instead and check if it is realistic to implement.

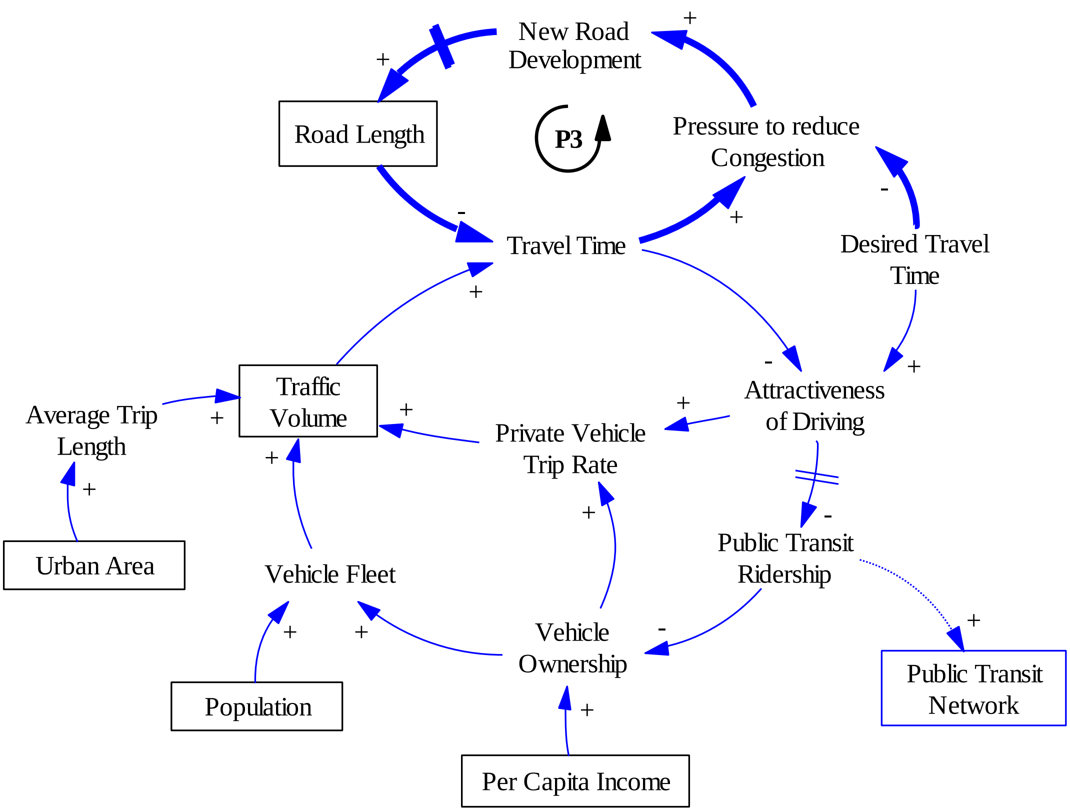


Figure 47: Feedback P3 – Expand road infrastructure

4.5 Summary

The DUTM-i is designed as a flexible and open framework to analyze the dynamic behavior of urban transport systems. In the open loop representation, road travel demand can grow infinitely because the attractiveness of driving by car is not influenced by travel time. Such a system description implies that people do not care how long their journey lasts. A number of studies in transportation research have shown that this is not true, and that people have an acceptable duration attached to any particular trip they perform, which, however, is not uniform. Yet, if the implicit expectation regarding travel time is not met, people are likely to opt for alternative modes that offer faster connectivity. The first feedback structure (P1) closes this important feedback in the DUTM-i. As private cars and motorcycles share the same road space, people in the model turn to public transportation, which is assumed to either be rail bound (e.g. metro systems) or run on dedicated lanes (e.g. bus rapid transit) and, consequently, separated from vehicular traffic. Mode shift is a very powerful balancing feedback loop and promoted by urban planners all over the world. A second option is to reduce the number of vehicles by limiting the access to private cars or making ownership expensive. In this context, the car lottery scheme deployed in Chinese cities serves as a prominent example, but also in New York, high parking fees have led to significantly lower ownership levels in downtown Manhattan than compared to New Jersey. Feedback P2 models this balancing effect in the DUTM-i. Typically, this feedback is weaker than mode shift, because many people opt to own a vehicle, although they do not use it for their daily trips. Some research studies suggest, however, that this behavior may change for urban areas in the future and that sharing services will become increasingly popular. In the context of India, the assumption that vehicle ownership does not reduce at the same rate as people shift to alternative modes in the case of significantly higher travel times is likely to hold true, as owning a car is still viewed as a status symbol and not merely a means of transportation. The third option to reduce congestion and travel time implemented in our model is to enhance the road infrastructure (P3). This is widely adopted by urban planning bodies; however, for exponential growth scenarios, like in India, this measure is not sufficient to solve the urban transportation challenge. In contrary, it offers short term improvements, which motivates travelers to drive even more, leading to higher levels of congestion in the long run.

In the next chapter we apply the DUTM-i to a set of study cities, which have been selected to best represent the heterogeneity of cities across India. Population and income growth functions remain unchanged per city, in order to validate the base scenario against the CMP results and to isolate the feedback effects in the system. We initially run the (open-loop) base scenario to investigate whether the congestion ratio on the network level exceeds a desirable level (0.8) in the simulated time horizon (2001-2031). If this is the case, we test the three balancing loops separately, to identify their impact to the system and verify if the model produces viable results in these extreme scenarios. Finally, we apply all feedbacks simultaneously, which is a more realistic approximation of system behavior. In this trend scenario, the desirable level of congestion is met by expanding roads and, more importantly, public transport infrastructure and containing vehicle ownership at a moderate level. From this scenario, we can derive the estimated travel demand for two-wheelers, cars and public transportation modes not only for the horizon year in each city, but we also provide information on the dynamic timeline. Furthermore, it is possible to extract transport indicators, such as average trip length and travel time for each time step. In a qualitative analysis, we compare these findings with the suggested policy scenarios in the CMP reports to assess whether the measures listed therein will be sufficient and available in time to meet the expected demand. Finally, we conduct a cross-city comparison to identify common challenges and differences for urban transport in India.

5 DUTM-i Application

5.1 Selection of Study Cities

Data extracted from the CMP reports covers 45 cities with different levels of detail. Out of these, 25 contain sufficient amount of information to perform quantitative analysis. As we require good data availability for calibration, we choose the model cities out of this sub-set. We also seek a distribution, both in terms of city size and geographical location, to reflect the differences and be representative of the urban landscape in India. An overview of the selected study cities is given in Table 14:

Table 14: DUTM-i Study Cities: Location and Population Size

City	Province	Population 2011[17]
Bangalore	Karnataka	8,499,399
Chandigarh	Punjab/Haryana	1,025,682
New Delhi	Delhi NCT	16,314,838
Hyderabad	Telangana	7,749,334
Indore	Madhya Pradesh	2,167,447
Jaipur	Rajasthan	3,046,163

For these cities, a base scenario is programmed that reflects the Do-Nothing or Business-as-usual scenario in the respective CMP and only accounts for land and road infrastructure projects, which have already been commissioned. For example, the urban area under development in Indore was extended in the latest Master Plan, which was approved in the simulated time-frame. In this chapter, we briefly present background information on the selected cities and their specific transport challenges. We then elaborate on the development in the simulated time-frame and the identified key challenges in the base scenario, as well as on different feedback scenarios. Finally, the trend scenario, based on a combination of feedback loops, presents a viable, alternative growth path for the study cities.

The actual computer simulation runs beyond the investigated time-frame (30 years) and gives important information to the modeler, if the general structure produces sensible results. Being primarily a verification test for the DUTM-i, we can also use it to display how feedback fully unfolds in the system. As a mean to get a better grasp of this central concept of the DUTM-i, we present the comparison between the base and the alternative scenarios on an extended timeline (until 2041). Hereby, the principal growth driver fractional population and income growth remains constant. Scenario analysis is confined to the period until 2031, because the CMP reports do not provide any information beyond this year, population estimates in particular, which we could use as reference data.

[17] As of Census of India 2011 [GoI, 2011]

5.2 Bangalore

5.2.1 Bangalore City Profile

Bangalore is the fifth largest metropolitan city in India and capital of the southern province Karnataka. It has undergone considerable growth in the last decades and earned a reputation as a premier destination for high-tech industries, particularly aerospace, IT and biotechnology. The Bangalore Metropolitan Region's radial structure is made up of an urban core, which is surrounded by smaller towns and rural areas. It covers 8,005 km² in total, and houses a population of 8.4 million as per census 2001 with a decadal growth rate of 30%. Due to its location in the southern part of the Indian sub-continent, climate is sub-tropical with temperatures averaging between 19 and 29°C throughout the year [Wilbur Smith Associates, 2010].

The road network extends to approximately 6,000 km. Bangalore is well connected to other major cities and towns within and beyond its boundaries through two National Expressways and three National Highways, as well as 12 State Highways. The radial road network converges into the core containing both center-periphery and through traffic. The rapid urban population growth has resulted in an increasing gap between the transport demand and supply. As a result, the city center is highly congested and the air is polluted. Despite measures taken by the Bangalore Development Authority, the network is underdeveloped in terms of size, structure continuity and connectivity. The layout dates back to the 1940's when the city had a population of less than half a million. The roads and intersections are operating at or above capacity. As a consequence of junction delays, journey speeds have dropped significantly, down to less than 10 km/h on some key roads in peak hours and prompt traffic police to disable signaling and to manage the traffic manually. Given the strong economic position, Bangalore is projected to become a so-called "Megacity" – magnifying the challenge to manage the complexity of urban transport.

The total number of registered vehicles in 2009 was 3.3 million with a share of 71% two-wheelers, followed by 17% cars and jeeps. Within the region, "Bangalore Urban" has the majority of the vehicle fleet with 96% of total registrations. Hence, most of the transport related issues refer to this district.

Urban vehicular transport in Bangalore is essentially road-based, since the national rail lines were neither designed, nor operated for urban and regional traffic. Motorcycles and three-wheeled auto-rickshaws are the backbone of the transport system. Conventional public transport services are provided by the Bangalore Metropolitan Transport Corporation (BMTC), which operates a fleet of 5,500 buses and is considered one of the better run bus transport systems in the country. Since 2011, the first metro line has gone into operation, which will expand to a network of 114 km in 2023. In addition to this, private mini buses or maxi cabs provide transportation services for companies and citizens.

The per capita trip rate derived from household surveys in Bangalore Metropolitan Region (BMR) is found to be 1.28 for all trips and 0.81 for motorized trips alone. The modal split is actually very favorable to walk (34%) and public transport (30%); around a quarter of trips are performed with private vehicles. In terms of average trip lengths, it can be observed that bus, cars and two-wheelers substitute another well in the range of 8-10 km, whereas auto rickshaws are dominantly used for the shorter inner-city trips (up to 6 km).

5.2.2 Base Scenario

In the base scenario, we follow the CTTS assumptions and expect the population to grow from 8.4 million to 18 million in the horizon year at an annual rate of 2.6%. For the simulation, we refer to the urban area, which covers only 27% of the total land. As there is sufficient space for the city to expand beyond its boundaries, we assume the enlargement to only slightly lag population growth. Consequently, urban density increases at comparatively low levels from 3,830 inhabitants per km² in the base year to 4,570 in 2031. In the CMP analysis we found a negative exponential correlation between density and average daily trip lengths. This function yields a reduction of only 0.1 km until the horizon year for all simulated modes. The total road network is not increased, but average daily capacity per road km improved from 12,500 to 15,000 PCU by construction of fly-overs and grade separators. Private incomes are projected to rise 4% net of inflation, which is a conservative assumption, given a compound annual growth rate (CAGR) of 10% in the previous decade (1991-2001), but allows for periods of slowed growth within the simulation time frame. Household size is assumed to remain constant at 4.2.

With respect to travel demand forecasts, the CTTS projects a motorized trip rate (MTR) of 0.93 for the horizon year 2030. Our model, derived from CMP regression analysis estimates a higher value of 1.09. Overall per capita trip rate (incl. NMT) is expected to be 1.49, which equals a total of 26.3 million daily trips assigned to the network. The vehicle ownership growth model yields 469 vehicles per 1000 inhabitants for the horizon year. This translates to a fleet of 8.5 million vehicles, out of which 60% are passenger cars. The total daily car equivalent vehicle kilometers sum up to 30.3 million for the study area, an increase of 21.6 million kilometers compared to the CTTS reference year (2010). The share of public transport in the modal split reduces from 62% to 53% over the entire simulation period. However, absolute trips performed by bus and metro are projected to rise to 10.6 million, which is more than four times the number of base year trips (2.31 million). The travel demand growth dynamics in Bangalore lead to severe traffic problems on the overall transport network by 2018; in this do-nothing scenario congestion, ratio rises to 1.4 in 2030, leading to significant travel time losses throughout the network. Private vehicle usage is too high for the provided road infrastructure; therefore, Bangalore has to adopt strategies addressing both transport demand and supply. In the following scenario analyses, we look at the effectiveness of the identified feedback structures, separately.

5.2.3 Alternative Scenarios

- *Scenario P1 – Mode Shift*

The first scenario looks at the required mode shift to maintain a congestion ratio of 0.8, which is considered the maximum value to provide a good level of service. In our simulation, we model this by reducing the number of trips performed by cars and two-wheelers per day. The mental model follows a common observation that people either avoid unnecessary trips or opt for alternative, faster modes of transportation if they face travel time losses. Not all people are able or willing to do so, but their number gradually grows as traffic conditions get worse.

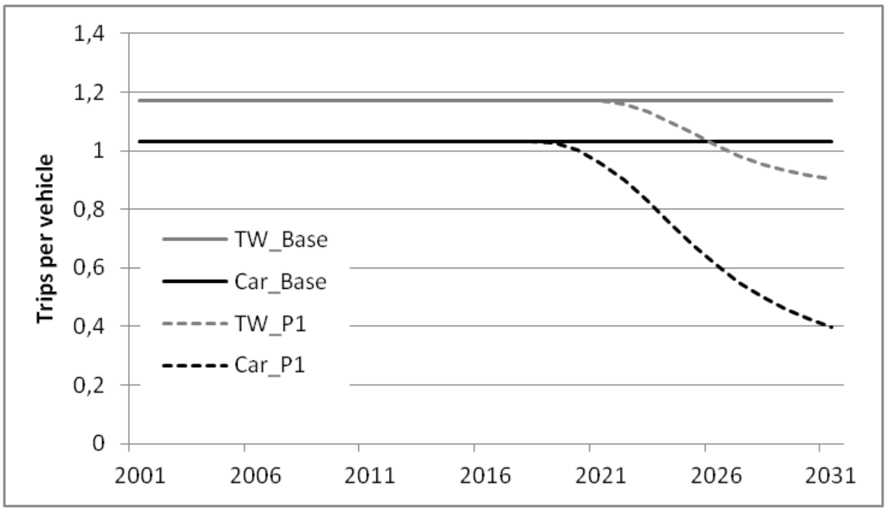


Figure 48: Bangalore trips per vehicle base vs. mode shift scenario

We assume a stronger decline rate for passenger cars, as motorcycles can be a quick way to get around, even in congested streets. In scenario P1a, we increase the maximum decrease rate for two-wheelers to 0.2 and to 0.5 for cars. This leads to the expected effect of a more rapid decline of trips per car, which, in return, allows a higher use of two-wheelers on the road (1.01 in scenario P1a in 2031, compared to 0.93 in scenario P1).

The congestion ratio in Scenario P1 has a maximum of 0.9 in 2025, and then constantly declines to 0.8 in the next ten years. It, thus, represents a very effective scenario, but implicitly presumes that there is enough public transport capacity to absorb the additional demand. Total daily public passenger kilometers increase nearly threefold to 130 million compared to the CTTS reference year (2010) and by 32 million compared to the base scenario in the horizon year 2031. As Bangalore CTTS provides detailed information on the transport strategy, we find the total capacity of the suggested transit network in 2031 to be approximately 168 million passenger kilometers for a 10-hour operation [Wilbur Smith Associates, 2010, p105]. However, even with sufficient services in operation, car owners are unlikely to reduce utilization of their vehicles without strict regulation, such as congestion pricing, parking fees, or city entry restrictions. This legislation “push” is addressed in the CTTS, too, which proposes to introduce all of the measures mentioned above and even a petrol confinement to encourage motorists to shift to public transport. In our scenario, the mode shift would lead to a 74% share of public transport, compared to 70% targeted in Bangalore in 2030 and validates that the DUTM-i model produces realistic results.

- *Scenario P2 – Vehicle Ownership reduction*

In the second policy scenario, we investigate the effectiveness of reduced vehicle ownership to mitigate congestion. The first feedback structure (P2a) simulates that inhabitants buy less cars, if they cannot use it on a regular basis. For Bangalore, we use the ramp function (see Figure 46) to model a decreasing ownership growth rate when congestion worsens.

With car ownership growth diminishing above congestion ratio 1.4 (1.6 for two-wheelers), motorization level reaches a maximum at 450 vehicles per thousand inhabitants (with 52% of the fleet constituted by cars). Although the modeled effect of reduced vehicle purchases results in lower congestion than the base scenario, it does not solve the traffic problem for the city, as this would require a much larger number of vehicles to be taken off the road.

In a second feedback structure, we assess the impact of vehicle quotas (Scenario P2c), which could be imposed by city authorities. We adhere to the Beijing model that defines contingencies for a five-year period and allocates license plates based on a random draw. The quota is calculated based on the new vehicles added to the fleet in the year prior to the tipping point of congestion ratio 0.8. In the case of Bangalore, this yields a registration cap of 100,000 new cars in 2021 which is gradually reduced to 75,000 vehicles in the following five years. The quota is applied to passenger cars only – two-wheelers remain untouched. Consequently, people in our model will switch back to motorcycles – a mechanism that has been observed in Chinese cities as well [Weinert et al., 2007]. In terms of size, the total car fleet in 2031 is reduced by 2.4 million compared to the base scenario, whereas the two-wheeler fleet increases by 1.7 million. Similar to scenario P2a, the quota slows down the pace of worsening congestion, but it does not result in the desired mitigation effect as a single policy measure without accompanying incentives to promote mode shift.

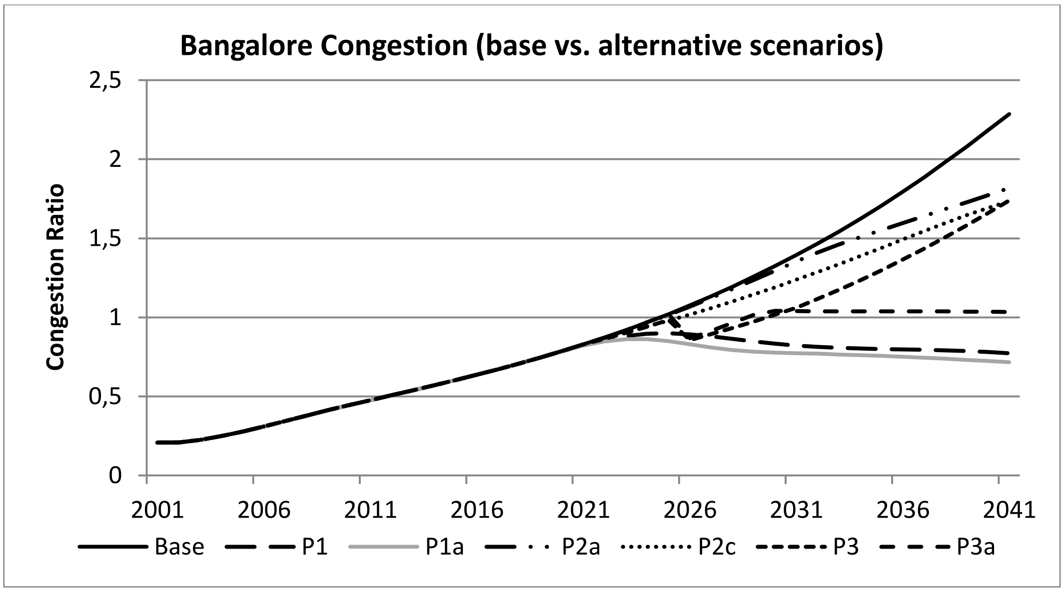


Figure 49: Congestion ratio Bangalore (base vs. alternative scenarios)

- *Scenario P3 – Road Network Expansion*

In the third scenario we explore a supply side measure to reduce traffic jam. In the prevailing mental model of city authorities, expanding and improving road infrastructure seems to be a promising strategy to solve transport challenges. We model this by adding 150 road kilometers to the existing network (2021-2031). Moreover, we assume that the construction of ring roads is completed by 2025, shifting the network archetype from a radial structure to a ring-radial structure, which, according to Mühlich et al [2015], improves overall network congestion performance. The result is, similar to scenario P2 that the traffic situation degrades slower. In contrast to the P2 scenarios, the effect is only short- to medium term. In the long run, this policy is not effective to contain congestion.

Scenario P3a investigates the (theoretical) road network expansion required to maintain average network speeds of 20 km/h. We model this by calculating the difference between actual and desired journey speed in every time step (*Journey Speed Discrepancy*). If this parameter becomes negative, a balancing feedback is triggered to bring the system back to the desired state. The control function reads as follows:

$$\text{New Road Development} = \frac{\text{Journey Speed Disrcepancy}}{\text{Journey Speed Adjustment Time}} * 0.05 * \text{Road Length} \qquad (28)$$

with *Journey Speed Adjustment Time* modeling an information time lag in the system. In order to improve average journey speed, we assume 5% of total *Road Length* to be added per time step. Clearly, this is an arbitrary assumption, but corresponds well with the overall travel demand growth observed in Bangalore. As we can see in Figure 50, this approach is unfeasible both from a financial and political point of view.

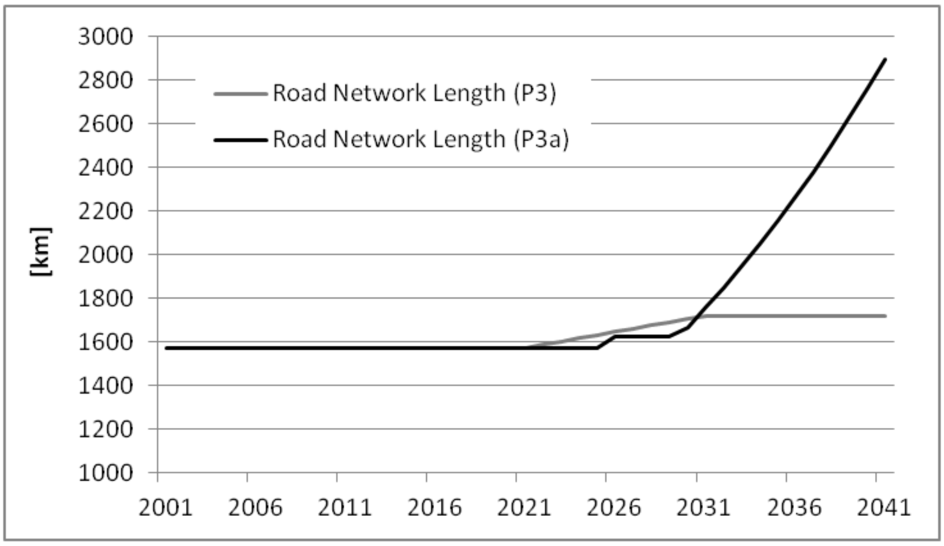


Figure 50: Bangalore road network expansion (scenario P3 vs. P3a)

It is important to note that the DUTM-i does not capture the important function of a well-maintained road network providing connectivity within a metropolitan region for the local economy to work. Instead, it evaluates whether transport demand growth can be mastered by expanding infrastructure only, which – as the results convey – cannot be achieved in the case of Bangalore.

5.2.4 Trend Scenario

In the trend scenario, we look at a mix from the scenarios outlined above. On the supply side, we assume 210 km of road added to the network by 2025, primarily to form a ring road and relieve the city center. As a consequence, overall network capacity gradually increases to 15,000 PCU per km a day, due to more flexibility to avoid traffic jams and a better distribution of the traffic flows. Simulation results show that this measure has the desired effect on reducing congestion, however, the growing population and vehicle ownership fully offset the achieved results until the horizon year 2030. Therefore, a quota system is proposed in 2025 to control the vehicle fleet growth dynamics. Starting with 200,000 cars per year, the maximum number of new registrations is reduced to 150,000 by 2030. The quota system is accompanied by the planned improvement of mass transit services (completion of metro Phase II and BRT corridors) and restrictions for vehicle use in the urban area (e.g. parking, access to city center) to promote mode shift in the population. The shift, represented by the fractional decrease rate of vehicular trips is more moderate compared to Scenario P1, as it only reaches a maximum of 0.1 for two-wheelers and 0.15 for cars at congestion levels of 1.2 and 1.3, respectively. Compared to the base scenario, two-wheeler trip rate remains similar (0.22), whereas car trips per capita remain stable at 0.18 and do not follow the exponential growth path from the base scenario. Similar to scenario P1, public transport has to carry more passengers, but at a lower incremental rate:

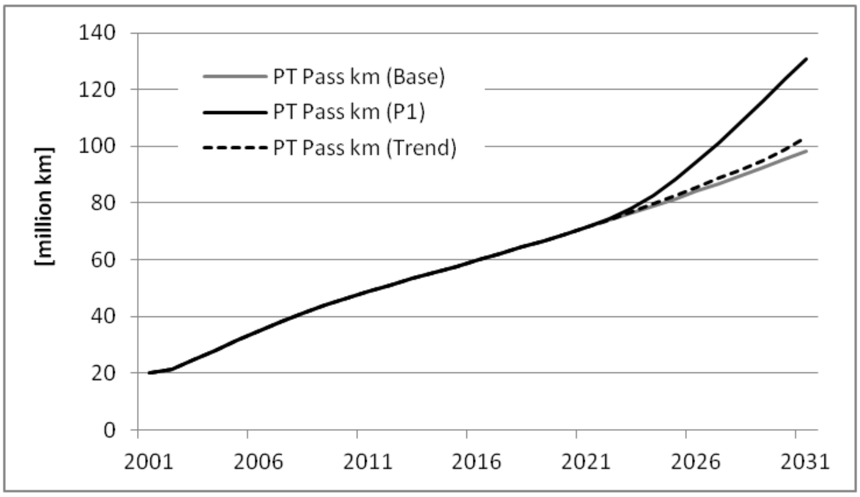


Figure 51: Bangalore public transport passenger kilometer scenario comparison

The vehicle quota and the moderate mode shift, stabilize the congestion ratio in Bangalore at around 0.94. The network, thus, still remains susceptible to traffic jams in the peak hours, but can provide a good overall level of service. The public transport mode share of nearly 59% in the horizon year and a significantly smaller passenger car fleet support the vision of the CTTS to provide a sustainable transport system for the Bangalore Metropolitan Area.

5.3 Chandigarh

5.3.1 Chandigarh City Profile

Chandigarh is a city and a union territory located in northern India and is the capital of states Punjab and Haryana. As a union territory, the city is ruled directly by the central government and not part of either of the states. Chandigarh is a planned city, completed in 1960, and based on the Master Plan prepared by the renowned architect, Le Corbusier. It is a premier center for education and quickly emerging as a major IT hub in North India. The city tops the list of per-capita income, averaging 22,800 INR in 2008. The layout follows a strict grid pattern, with new districts added preferably along the east-west axis. Chandigarh Urban Complex (CUC) includes the surrounding villages and extends to 114 km². Chandigarh has high standards of living and economic strength, making it an attractive place for its 1,360,000 inhabitants (per Census 2001). The city experiences extreme climate and uneven distribution of rainfall (monsoon). In summer, temperatures can climb up to 45°C, whereas in January, they might be as low as 0°C. Chandigarh is also known as a particularly green city, with natural forests covering 9.6% of the urban area [RITES, 2009, p26ff].

The road network in the CMP study is 487 km, covering all primary and secondary roads. Because of the grid layout, the streets follow a consistent hierarchy, with “V2/V3” roads dividing the sectors and “V4/V5” roads providing for connectivity within the sector. Average number of lanes is identified to be 4.6 and average network journey speeds are 34-37 km/h, depending on time of the day. It is important to note that there is practically no scope for widening of roads in Chandigarh, except for some geometric improvements at junctions, reducing the strategic options in the case of travel demand increase.

The high income levels have led to a significant increase in the number of registered motor vehicles and, in the absence of a viable public transport system, their preferred use. As a result, the traffic situation has worsened, with heavy congestion on many roads. Chandigarh also attracts a lot of regional traffic because of its role as administrative center of two states, but does not have adequate public inter-city transport options. In total, 602,779 vehicles were registered in the city in 2005 with two-wheelers accounting for 71.5% and Cars/Jeeps for 27% of the registrations. The public bus system is run by the Chandigarh Transport Undertaking (CTU) that operates 417 busses, of which 280 serve local/suburban routes. In addition to this, a number of IPT modes, such as the ubiquitous auto-rickshaws (1,788 registered) offer transport services.

The household surveys found the per capita trip rate (including walking) to be 1.32 and 0.9 for motorized trips. Around half of the total daily trips are performed with cars and two-wheelers, while walking accounts for only 17%, which is a comparatively low value. Given the fact that 78% of surveyed households at minimum own a two-wheeler, this modal split is not surprising. The average trip length is 9 km for cars, 6.9 for two-wheelers and 11.5 for busses, which highlights the potential for all three modes to substitute each other and satisfy the mobility needs of the population.

5.3.2 Base Scenario

Chandigarh population is projected to grow significantly to around 5 million by 2030, with an average decadal growth rate of 53%. Growth is strongest until 2010 and an annual growth rate of 6.1% that reduces to 2.7% in the last decade (2020-2030). In the meantime, employment is projected to reach 1.84 million, according to the CMP, which confirms the city's aspiration to become an economic center in Northern India. The study area remains constant at 330 km² for the observed time frame. Some sectors in the CUC will be developed for industrial and commercial use, others have the potential to further be densified. The towns surrounding CUC are subject to rapid growth, as well. Traffic between them and the city are expected to increase and would require respective infrastructures. Average urban density will climb to 15,400 in 2031 transforming CUC into a bustling metropolitan area in the region. Due to densification, average trip lengths will slightly decrease for all modes in our model. Like in the "Business as Usual" Scenario of the CMP, we assume the road network length to remain constant with minor improvements in capacity. In terms of household incomes, it is reasonable to assume growth rates of 4% annually, despite being wealthy, compared to other Indian cities, already. Household size remains constant over the entire simulation period.

The CMP four-stage model calculates a motorized trip rate of 1.2 for 2031, under the assumption that a new metro service and BRT along major corridors are available. Our model derived from our cross-CMP analysis yields values of 1.07 and 1.45 for MTR and PCTR, respectively, resulting in a total of 7.4 million daily trips performed in 2031. The vehicle ownership model projects a significant rise in passenger cars, which mainly substitute two-wheelers and win a share of 74% of the total fleet of 2.6 million vehicles in the horizon year. In this scenario, Chandigarh would be confronted with a congestion ratio of 1.34 and 21.4 million vehicle kilometers travelled daily by cars and motorcycles. The installed road network is unable to cope with such a demand; which makes it unlikely to come into effect. What is more, with average use per vehicle remaining constant, private vehicle trip rate would exceed the projected motorized trip rate in the horizon year. Consequently, feedback loops will come into effect affecting ownership, as well as usage of private motorized modes. In line with the CMP proposals, Chandigarh requires an alternative transport path that provides attractive mass transit systems in order to capitalize on their economic potential. The city reaches the critical volume/capacity ratio of 0.8 in 2023.

5.3.3 Alternative Scenarios

- *Scenario P1 – Mode Shift*

In the mode shift scenario we assume a gradual decrease of vehicle usage above volume-capacity ratios of 0.8 (see Figure 44). Chandigarh has comparatively high vehicle utilization (2.2 trips per car per day) that drops sharply in this scenario. In absolute numbers, utilization reduces to 1.34 daily trips per car and to 1.35 for two-wheelers.

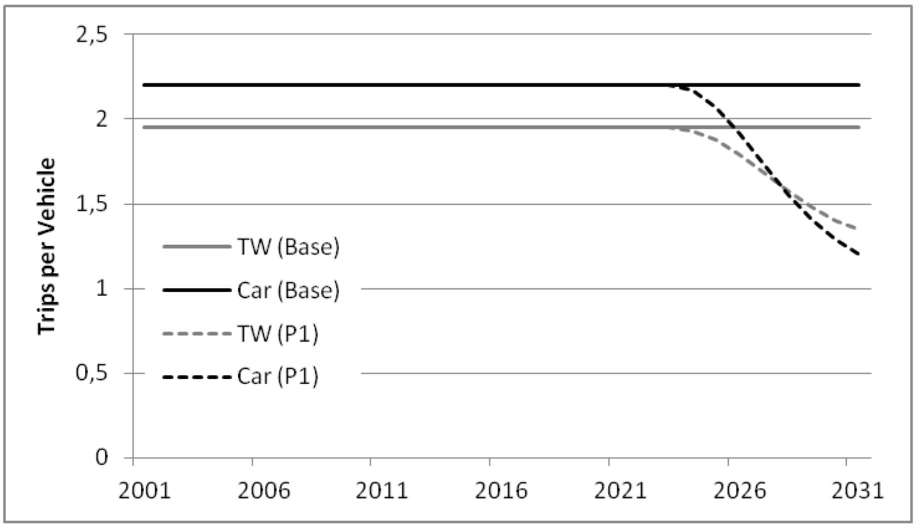


Figure 52: Chandigarh trips per vehicle base vs. mode shift scenario

As a result, public transit ridership triples from 0.14 in the CMP reference year to 0.44 trips per capita in 2031. This translates into a mode share of 41% of all motorized trips and 18.4 million passenger kilometers. Congestion passes the critical level of 0.8 in 2023, overshoots to 0.97 in 2027 due to time delays in the system and rebounds back to 0.89 beyond the horizon year.

We compare the results to the CMP transport demand forecast, which assumes a well-established mass transit system with four metro corridors and nine BRT corridors in place. The CMP projects, a total of 5.6 million trips (DUTM-i model: 5.4 million), of which 3.1 million are by public modes. The P1 scenario yields 2.4 million trips, which is lower than the CMP results for this particular year[18]. In terms of size, the planned mass transit network will cover 145 km of BRT lines and 57 km of metro lines in 2031. The metro alone will have the capacity to transport 800,000 passengers per day. Similar to our model approach, the CMP does not have a mode choice model in the transport demand forecast, but assumes that the public transport availability will promote mode shift. Because the CMP also lacks the vehicle ownership growth dynamics, it does not include the important fact that people's desire to own cars will actually rise and may inhibit mode shift. In our next scenario, we explore the alternative to reduce the vehicle fleet and to achieve acceptable levels of road traffic in the horizon year.

[18] The DUTM-i reaches the three million mark four years later, due to modeled time delays in system response.

- *Scenario P2 – Vehicle ownership reduction*

In the case of Chandigarh, the vehicle ownership growth model estimates are lower than in reality. This means that the citizens have more cars than they should have according to their disposable income in the base year. On the other hand, the annual growth rates between 2001 and 2010 are smaller than the Dargay et al. [2007] model. Therefore, we can conclude that the open loop (base) scenario is unlikely to become effective, as there are feedbacks already in action that slow the motorization of the population. In the P2 scenario we assume a reduced desire of citizens to own cars (feedback structure 2A). In the case of Chandigarh we use the following values for cars and two-wheelers:

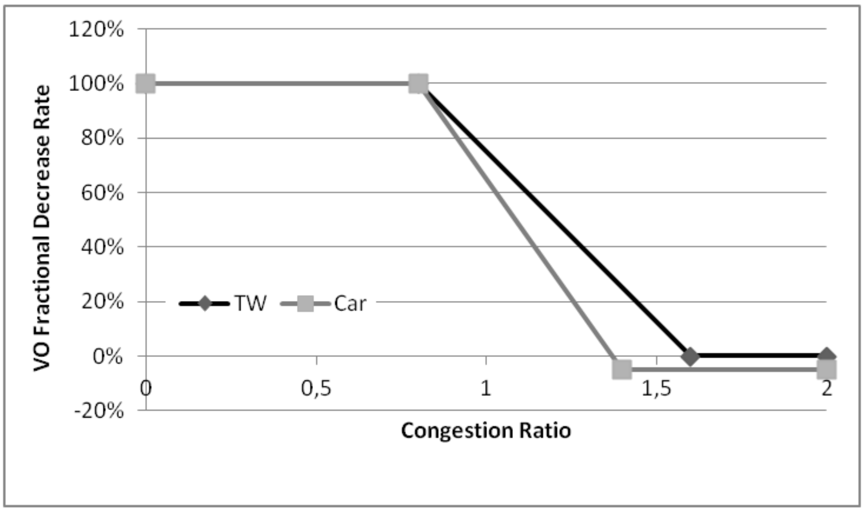


Figure 53: Chandigarh private vehicle ownership fractional decrease rate

Because of the relatively high motorization level in the reference year, we even suppose a slight negative decrease rate above volume/capacity ratio of 1.4, which leads to a constant number of cars on the road, as population growth compensates the declining per capita ownership. The key take-away from this scenario is that the positive effect on congestion ratio takes much longer than in the mode shift scenario and two-wheelers will partly offset the lower car sales. The more realistic development of reduced ownership, accompanied by mode shift is investigated in more detail in the trend scenario.

Although the CMP does not provide any indications that vehicle restrictions are planned to be introduced, we investigate the effectiveness of vehicle quotas. In 2020, new vehicle registration are capped at 80,000 cars per year and reduced by 5,000 cars per year in the following six years, which results in maximum 50,000 cars registered by 2026. Compared to the base scenario, congestion ratio is lowered to 1.16 in the horizon year, yet 45% above the desirable level of 0.8.

- *Scenario P3 – Road Network expansion*

In this scenario, we first explore the impact of the road improvements planned in the CMP [RITES, 2009, p.175]. These include both widening of roads on 19 km of the existing network, as well as adding 11 km of new roads by 2021. The congestion trend for all scenarios (Figure 54) reveals however, that this has very little effect. Alternatively, we simulate a more aggressive scenario, with an addition of 50 km of roads by 2021 (scenario P3a), but the growth dynamics of road traffic are too strong to be mitigated only by supply side measures.

5.3.4 Trend Scenario

In the trend scenario, we combine the three alternative scenarios. The road improvement program (P3) remains untouched. Moreover, we assume a decelerated growth of vehicle ownership, as suggested by the validation data from the Road Transport Yearbook [MoRTH, 2012a] in the first decade of the simulation. Finally, the trend scenario assumes a successful mode shift through introduction of attractive mass transit options by 2031 with a longer rate of adoption. As a result, passenger car trip rate is reduced by a third, compared to the base scenario, while two-wheeler trip rate increases to 0.36. Public transit use is projected to significantly increase in this scenario beyond the horizon year because the positive effects of reduced vehicle ownership (vehicles per 1000 inhabitants) are outset by population growth of the city. The fully operational metro and BRT services now form an attractive alternative for daily commute, reducing the reliance on cars for convenient connectivity in the city. However, in absolute number of trips, cars will continue to be dominant. Congestion ratio reaches a level of 1 in 2031, which is above the desired level of 0.8, but still within acceptable bounds. Similar to other big cities in India, peak hour congestion management will remain a challenge in such a scenario.

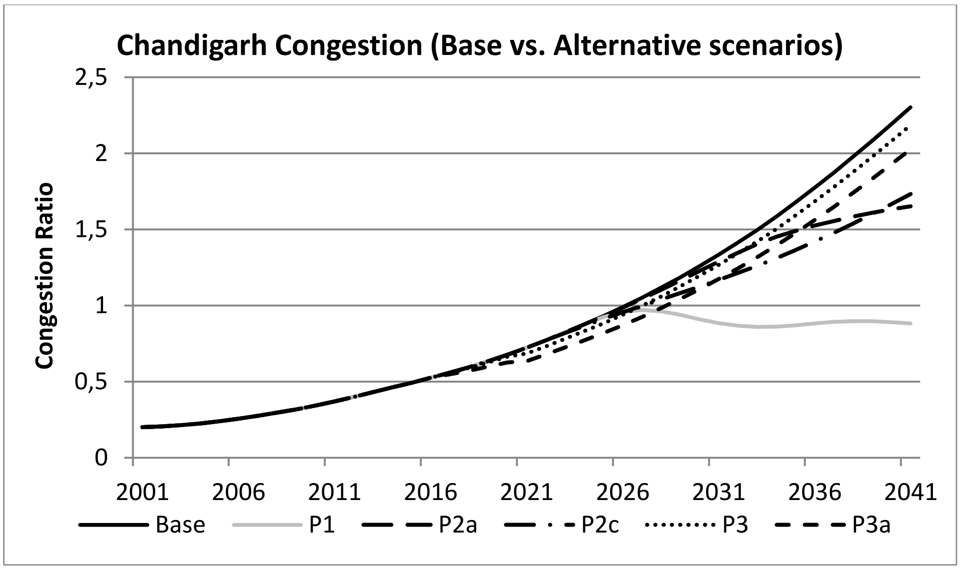


Figure 54: Congestion ratio Chandigarh (base vs. alternative scenarios)

5.4 Delhi

5.4.1 Delhi City Profile

Delhi, officially called the National Capital Territory (NCT) of Delhi, is the capital of the Republic of India. As another Union Territory, it resembles closer to that of a state, with its own legislation and ministers governing the city. It is delimited by the states of Haryana and Uttar Pradesh, whose neighboring cities (e.g. Ghaziabad, Noida) together with Delhi, form the “Delhi National Capital Region (Delhi NCR)”. Depending on which borders are drawn, Delhi is home to a population of 16 to 25 million. This makes it the second most populous city in India and the third largest urban area globally. Many inhabitants, however, do not speak of Delhi as one city, but rather an agglomeration of many cities. This is because Delhi had a number of different rulers in the past centuries on today’s area of 1,483 km². Most notably, the British built New Delhi in the nineteenth century as a symbol of the Empire’s power. Situated in Northern India, Delhi has a continental climate with temperatures varying between 7 and 40°C throughout the year. The monsoon season begins in late June and ends early September.

The heavy rain falls during this period can lead to flooded streets and, consequently, severe traffic disturbance – changing a twenty minute trip to a three hour journey [RITES, 2011].

Delhi has a huge road network. According to the City Development Plan [Delhi CDP 2006, p231], it totals 28,500 km (as of March 2001). However, many of those roads only have a collector or feeder function. The overall capacity is provided by the primary and secondary roads, which connect the city districts and neighborhoods. In the CMP, developed by RITES in 2011, an inventory of these roads updated them to be 2368 km. In our model we draw upon this data, also because it yields more realistic results for the dynamic simulation. On average, the number of lanes is 3.34, with 950 km being four lanes or more, which is "*perhaps the highest in Indian cities*" [RITES, 2009, CH2, p29]. Despite the largely expanded road network (a three-fold increase in total road kilometer compared to 1971), Delhi is heavily congested, with the majority of roads operating above the reasonable volume/capacity ratio of 0.8. Average journey speed during peak periods is 22.2 km/h and 26 km/h for off-peak periods. Hence, there is no great variation throughout the day.

Together with the city's economic development in the last decades, vehicle ownership has grown exponentially and totals 7.2 million vehicles as of 2011 [MoRTH, 2012a]. This constitutes a 33-fold increase compared to 1971. The majority of the fleet are two-wheelers (4.4 million), but the passenger car fleet is of significant size as well (2.1 million). In total, Delhi has a larger vehicle fleet than Bangalore and Mumbai combined. Despite this, the CMP household survey reveals that 47% of households do not possess any motor vehicles yet. One reason for the continued, strong demand for cars and two-wheelers is the inadequate public transport service. The Delhi Transport Corporation (DTC) operates a fleet of 3,100 buses, which are complemented by some 2,600 private buses under DTC operation and about the same number being operated independently. Although DTC has made considerable efforts to modernize the fleet (e.g. with low-floor air-conditioned CNG buses), the private buses, in particular, remain unsafe and uncomfortable to use and is not regarded as a viable transport option for those who can afford to purchase a private vehicle. Commonly viewed as a success story, Delhi Metro on the other hand, offers convenient and fast connectivity around the city. The network presently extends to 213 km (160 stations) and carries 2.6 million passengers daily [Delhi Metro Rail Corporation Ltd., 2016]. In its final stage (Phase IV), expected to be completed in 2021, it will expand to 413 km, covering most of the Capital's area. Interestingly, the passenger survey conducted for the CMP reveals that 75% of metro passengers are motor vehicle owners, which is an indication that metro is mainly used by upper and middle income groups. Due to lack of a convenient bus system, only 5% of passengers come to the metro by this mode.

The household interview survey finds per capita trip rate to be 1.38 (0.91 excluding walk) and 0.76 for motorized trips. In total, around 23 million trips are being performed by Delhi residents. Modal split is still favorable to non-motorized transport modes, which have a share of 45% of total trips. Among the vehicular trips, cars make up 13.7% of the trips and two wheelers 21.3%, with an average trip length of 9.1 and 11 km, respectively. In comparison to 2001 values, share of bus trips has declined from 60% to 41%. Given the nearly equal average trip length (10.2 km), those trips were substituted by private modes.

5.4.2 Delhi Base Scenario

Delhi NCT population is envisaged to grow to 24.3 million in 2021, which equals a compound annual growth rate of 2.8% per year from 2011. We assume that the population growth will continue in this pace until 2030, and Delhi to become home for 31.8 million people. The area of Delhi remains constant for the simulated time-frame, as new land is predominantly developed in the surrounding towns, such as Noida, Gurgaon and Ghaziabad. Consequently, average urban density increases from 12,275 to 21,400 in the horizon year. The areas where this densification will happen are located outside the city center, which already has density values of more than 25,000 today. According to the Function (18), average trip lengths decline by 0.7 km compared to 2001 levels. Corresponding with the CMP "Business as usual (BAU)" scenario, there is no further road improvement included in the base scenario. Income is assumed to grow at a net rate of 4% per year, different to the CMP BAU scenario that only has 2%. Household size remains constant during the simulation.

The base scenario computes lower motorized trips (18 million) than the CMP four-stage model for 2021 (25.5 million trips, equal to a motorized trip rate of 1.05). Because the CMP was not prepared for the horizon year, we cannot validate the DUTM-i Delhi results in the horizon year. The vehicle ownership model yields a significant rise for passenger cars and continued growth of two-wheeler fleet until 2020. Share of two wheelers and passenger cars in total daily trips is around 30% for both, public transport provides 40% of the trips and the remaining journeys are performed without motorized vehicles. However, this suggested base scenario is only of theoretical value. As shown in the CMP street surveys, congestion in Delhi has already reached the tipping point at major streets that operate above the desirable V/C ratio of 0.8. It is therefore, unrealistic to expect further unlimited growth of vehicle usage. The simulation yields a congestion ratio of 0.8 on the entire network level for 2021. The Delhi metro is a well-accepted substitute for motor vehicle owners on their daily commute to work, as the passenger survey revealed. The alternative scenarios will explore the magnitude of the shift to public transport ridership in more detail.

5.4.3 Alternative Scenarios

- *Scenario P1 – Mode Shift*

Under the assumption that the average use pattern of motorists is the same as today, Delhi private daily motorized trip rate would increase to 0.6 in the horizon year. In this scenario, we investigate the reduction of vehicular trips that are needed to maintain congestion at the desirable value of 0.8. We refer to the function from Figure 44, which assumes a stronger fractional decrease rate of car usage over two-wheelers due to the lower maneuverability and ease of finding a parking spot.

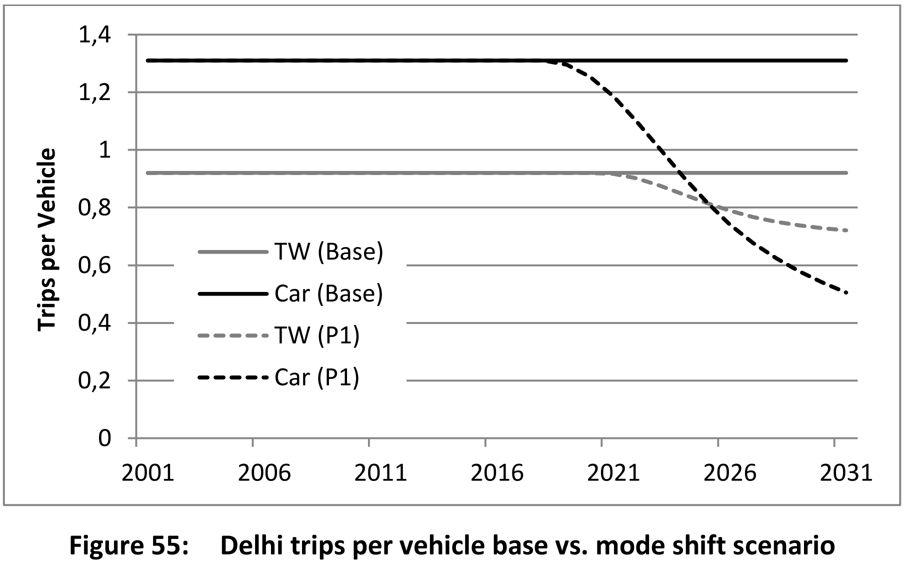


Figure 55: Delhi trips per vehicle base vs. mode shift scenario

The simulation run shows that in such a scenario, the car utilization drops as low as 0.45 trips per vehicle when ownership follows the base scenario growth path. Given the cost associated to purchasing and maintaining a car, as well as being able to park it, it is likely that people will not buy as many cars as projected in the base case. While use per vehicle declines, public transport passenger volume jumps accordingly: the number of trips more than doubles to 17.2 million trips compared to the base scenario, equivalent to a 64% share in the modal split (excluding non-motorized modes of transport) and totaling 148 million passenger km travelled on a daily basis in 2031. We now check, whether the CMP accounts for such a mode shift and find that the RITES suggested scenario in Delhi CMP calculates 10.4 million trips by public transit in 2021, which is a higher volume than in the P1 scenario (7.3 million).The DUTM-i calculates the same amount of trips for 2024. In order to handle the passenger surplus the RITES scenario in the CMP report proposes to extend the network (metro, light-rail and BRT) to 736 km. In terms of utilization, the busiest metro corridors in the RITES scenario operate at 21,000 phpdt (peak hour peak direction traffic). Maximum capacity for Delhi metro system is 60,000-80,000 phpdt [Sharma et al., 2013], hence the light rail network should be feasible to handle the additional passenger volume until 2031, as well.

- *Scenario P2 – Vehicle ownership reduction*

Delhi has the largest urban vehicle fleet in India today, and we assume ownership levels to moderately rise to 500 vehicles per thousand in the base scenario (including two-wheelers and cars). As congestion exceeds the desirable level 0.8 in 2020, we expect lower growth rates than in the past decade. In our model we use the function presented in Figure 46 to check the impact of reduced purchases to the system.

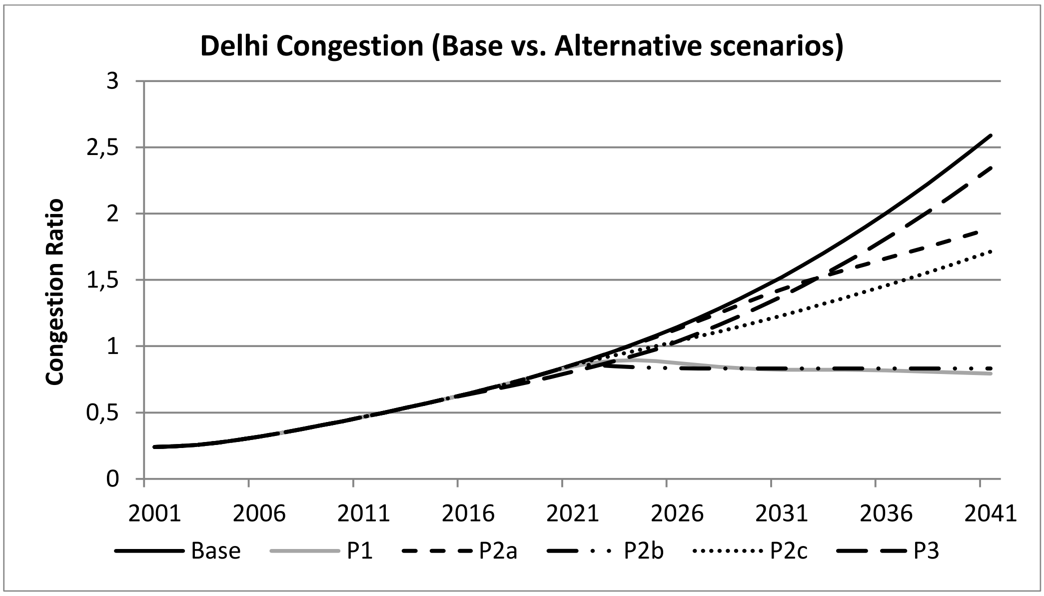


Figure 56: Congestion ratio Delhi (base vs. alternative scenarios)

The P2a scenario changes the trend curve from exponential to linear, yet does not solve the congestion issue in the simulated time-frame. In the P2b scenario, we calculate the (theoretical) maximum number of vehicles, which would be allowed to roam Delhi to limit volume/capacity ratio to 80%. In comparison to the base scenario, stock of two-wheelers would have to be 2 million less in 2031 and the car fleet would be restricted to 4 million units (-60%). Such a significant cap is unlikely to happen without strict regulations on vehicle ownership, such as quotas or entry restrictions. In the P2c scenario, we investigate the introduction of a vehicle quota for Delhi. Starting with 150,000 new cars in 2020 and reduced by 10,000 annually in the following five years. The simulation results are similar to P2a with respect to congestion, but we find a greater number of two-wheelers on the road because they are not regulated by the quota. In China, similar schemes have been introduced and gasoline-powered scooters were banned from urban areas along with the car registration cap. As a consequence, sales of the popular electric bikes and e-scooters soared and are a ubiquitous mean of transport in cities like Beijing or Shanghai. The key takeaway for the P2 scenarios is that Delhi will not be able to master the urban transport challenge in 2031 with reduced vehicle ownership alone.

- *Scenario P3 – Road Network Expansion*

From the transport system analysis, we do not expect road network expansion to be an appropriate policy option for the projected demand surge. Nevertheless, we simulate a reasonable road expansion of 10% (250 km) between 2015 and 2025 to assess its impact. As Figure 56 shows, the curvature of the exponential growth is shifted to the right, which means that congestion is eased in the short-term, but not mitigated in the long-term.

5.4.4 Trend Scenario

For the Delhi trend scenario, the results from the alternative scenarios are combined to project a feasible state of the city's transport system in 2031. The required mode shift alone would result in a very low utilization per vehicle; therefore, we expect that the vehicle sales will be affected, too. The Delhi CMP addresses the measures required to meet this surplus demand by proposing three high capacity mass transit systems to be installed or expanded until 2021.

- Metro – extend 6 and build 3 new corridors with a total length of 156.9 km.
- Light Rail – 1 new corridor with a total length of 40.7 km.
- BRT – extend 1 and build 16 new corridors.

It also presents a second scenario, with high parking charges in the study area and even more BRT routes (total length of 681 km). However, already the first BRT line in Delhi was subject to operational difficulties and has not met the expectations in terms of providing good transportation service. Therefore, we assume the first scenario to be more realistic in terms of expected supply in 2021. Although Delhi introduced bans for Diesel cars in 2015 (as a reaction to severe air pollution in the city), there has not been any political discussion on introducing vehicle quotas in India's capital to date. The CMP, too, does not mention any form of vehicle restrictions. For these reasons, we do not include a quota system in the trend scenario.

Compared to the base scenario, we assume the overall motorization rate curve to be more moderate, resulting in 440 vehicles per thousand inhabitants in the horizon year. Moreover, vehicle utilization does reduce significantly (-24% for cars and -19% for two-wheelers), but not as drastically as in the P1 scenario. Finally, we assume road construction to continue, adding 100 km to Delhi's network between 2015 and 2025.

As a result, public transport demand increases to 11.3 million trips (98 million passenger km) in the horizon year – up 3.3 million compared to the base case and equivalent to a share of 46% in the modal split. At the same time, congestion steadily grows to 1.1, but remains stable in the years that follow[19]. Delhi will, therefore, continue to have congestion problems, particularly around peak hour and in the

[19] The simulated time-frame ends in 2031. However, for validation purposes simulation runs were performed beyond the horizon year.

case of irregular incidents, such as heavy monsoon rains or a traffic incident on key arterial roads. Furthermore, it is very important to terminate the construction of ring roads to have a high-capacity ring-radial network layout that guides through-traffic around the center and offers alternative routes for reaching destinations within the city's boundaries. Because Delhi roads are still going to be populated with a great number of private and public vehicles in 2031, stringent regulation of tailpipe emissions for all types of motorized vehicles must be implemented in order to ensure acceptable air quality. Figure 57 provides an overview of the development of selected indicators, in comparison to the base scenario:

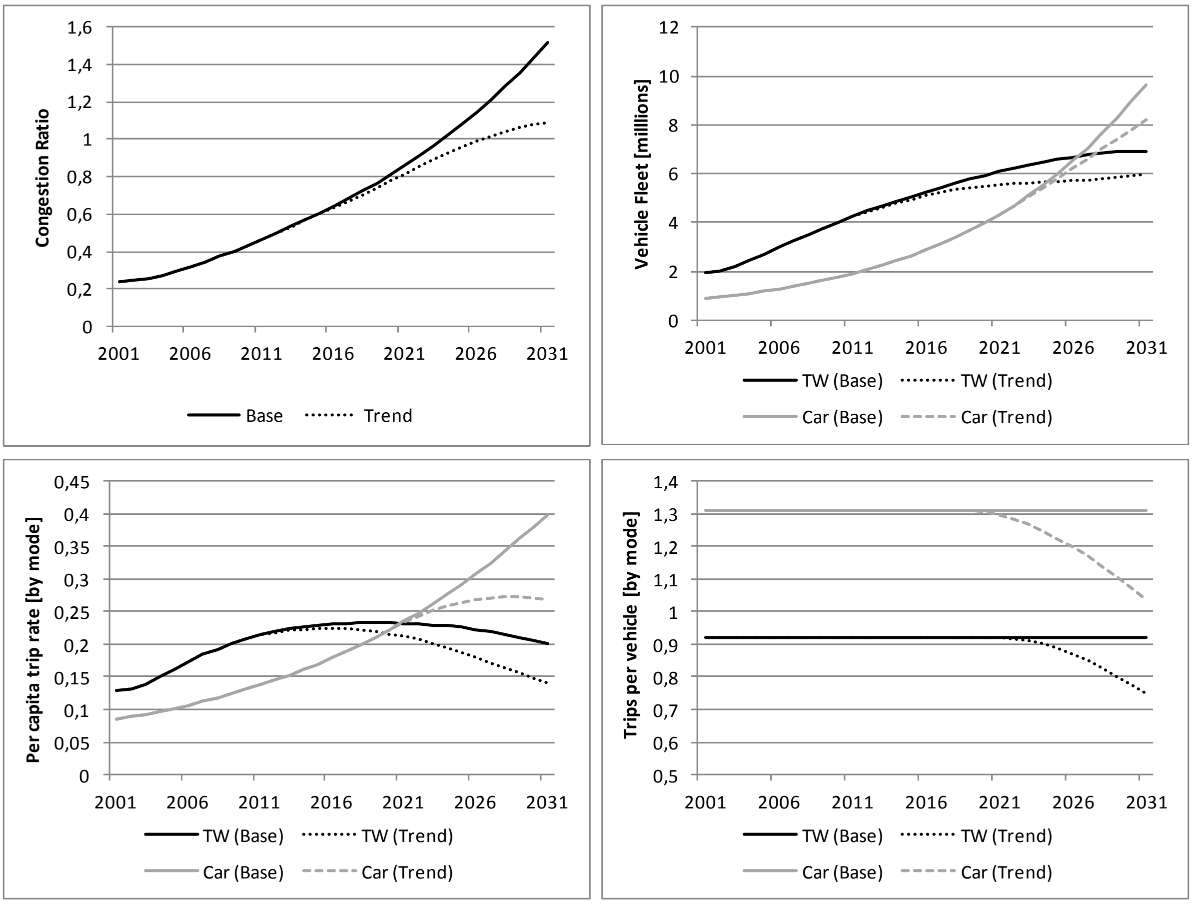


Figure 57: Selected mobility indicators for Delhi (base vs. trend Scenario)

5.5 Hyderabad

5.5.1 Hyderabad City Profile

Hyderabad is the capital of the recently inaugurated 29th Indian state of Telangana and de jure capital of Andhra Pradesh. Located in southern India, Hyderabad is the largest city in the state and the sixth largest urban agglomeration in India [GoI, 2011] covering an area of 625 km². The so-called Greater Hyderabad Municipal Corporation (GHMC) consists of erstwhile Municipal Corporation of Hyderabad (MCH or Hyderabad district) and the surrounding Rangareddy and Medak districts, which span 175 km² and 452 km², respectively. The Comprehensive Transportation Study (CTS) was prepared for the Hyderabad Metropolitan Area (HMA) which covers approximately 7,200 km² and includes an additional 860 villages, municipalities and census towns. Similar to Bangalore, congestion problems are predominantly focused on the city itself, therefore the DUTM-i for Hyderabad is set up for the GHMC. Apart from being the administrative capital, Hyderabad is the economic center of the state, representing about 30% of the state GDP and offers a large workforce, due to the demographics and education facilities. The population of entire HMA is 9.5 million, of which about 6.8 million live in the GHMC area. Within GHMC, growth predominantly takes place outside the core city, contributing 90% of the 1.3-1.4 million population increase in the 2001-2011 decade. Hyderabad has a tropical climate with an annual mean temperature of 26°C. The hot period (more than 40°C) starts in April and is followed by the south-west summer monsoon, which brings heavy rainfall between June and September [LEA Associates, 2013].

The road network inventory was carried out in 2011 and yields a total of 4,900 km for the entire Hyderabad Metropolitan Area. GHMC has 1,242 km of roads, with 44% of them being undivided two-lane roads and 94% having formation widths smaller than 30 meters. As of today, there exist very few high-capacity roads within the study area (the average number of lanes on the network is 3). Footpaths are available for 44% of the road network in the city itself, but only 12% in the surrounding districts. Therefore, pedestrians and cyclists have to operate on the same road space as light and heavy duty vehicles, making these modes highly unattractive to use. Like other larger cities in India, Hyderabad is already congested: traffic count surveys suggest 35% of the screen line and inner cordon and 37% of the mid-block locations operate above the desired V/C ratio of 0.8. Average journey speeds are between 20 and 23 km/h in erstwhile MCH and 27-31 km/h in the rest of GHMC, indicating heavy traffic conditions throughout the day.

The total number of motorized vehicles registered in the study area is 3 million. Two-wheelers constitute 71% and passenger cars 16%, thus, 87% of the fleet is privately owned. Compared to 2001, the number of vehicles has nearly tripled, with particularly significant increases in two-wheeler sales. This yields a motorization level of 275 vehicles per 1,000 inhabitants. Results from the Household survey reveal that the most profound effect of vehicular ownership is on work trips: more than two-thirds of people owning a motor vehicle use it for daily commute. Public transport services are provided mainly by buses, the MMTS (Multi-Modal Transport System) light-rail and suburban rail systems. The total number of buses operated by APSRTC (Andhra Pradesh State Road Transport Corporation) is 3,650, and complemented by 100 contract carriers. The majority of them are of "ordinary" type, which means that they are neither air-conditioned, nor low-floor and generally uncomfortable to use. Total number of passengers is estimated to be around 3 million daily. The MMTS rail system began its services in 2003 and presently operates 121 schedules on a normal working day along 3 corridors covering 43 km and 26 stations. The sub-urban rail system operates an additional 51 schedules covering 54 km and 19 stations. However, service quality of MMTS/sub-urban is not very high, because the trains have to share the track with the south national railways, which results in frequent service delays and limited possibilities to increase the tact. Total number of MMTS passengers in 2012 was 54 million annually, which equals approximately 216,000 passengers per working day.

From the household surveys, average per capita trip rate (including walking) for HMA is shown to be 1.20. In erstwhile MCH PCTR is a little smaller (1.07), whereas the rest of GHMC districts are above average (1.33). Motorized trip rate is estimated at 0.75, with a value of 0.73 in MCH and 0.89 in the rest of GHMC, which is consistent as the share of mechanized modes for both areas is approximately 67%. Little more than half of the trips are work-based, followed by 33% education related and 10% home-based trips. With regard to modal split, 40% of the trips are performed by non-motorized modes of transport, the rest of the trips are predominantly made by either using two-wheelers (24%) or buses (21%). Average trip lengths for the base year are estimated to be 11.8 km for cars, 12.1 for two-wheelers and 15.1 for buses. The household survey reveals that most of the trips take up to 30 minutes and only 6-7% of the trips take longer than an hour.

5.5.2 Hyderabad Base Scenario

The DUTM-i base scenario for Hyderabad is referenced against the CTS Scenario *S5N1*, which reflects the current Master Plan land-use scenario. In accordance with this scenario, Hyderabad's population is projected to grow to 10.5 million in the horizon year 2030. The GHMC area remains constant for the simulated time frame; therefore, population density nearly doubles from 8,700 to 16,400 people per km². Following the model developed in cross-CMP data analysis, average trip lengths reduce by 0.5 km at the same time. In the CTS scenarios, the trip lengths only reduce for two-wheelers; an increase is anticipated for cars and buses. According to the CTS road network plan *N1,* a new outer ring road and radial roads (in total 277 km) will be added. They are currently under construction and will be fully operational by 2018. Another key infrastructure project is the construction of Hyderabad Metro Rail. After completion of Phase I in 2017, 3 lines with 66 stations and 72 km will be operational. In phase 2, another 85 km will be added. With a frequency of 3 to 5 minutes during peak hours, the system is expected to carry about 1.7 million passengers per day by 2017 and 2.2 million by 2024 [Hyderabad Metro Rail, 2016].

The calculated daily travel demand is 16.2 million trips, equal to a per capita trip rate of 1.55. The model calculated from the CMP analysis yields a motorized trip rate of 1.2, which is slightly above the reference value (1.08). Hyderabad CTS employs a logistic function to estimate vehicle ownership, which calculates 90 passenger cars and 585 two-wheelers per 1,000 inhabitants for the horizon year 2031. In the DUTM-i, we project a significantly larger share of passenger cars in the vehicle mix (170 cars/1,000), but a similarly high level of overall motorization (611). Consequently, the share of public transport is expected to drop to 26%. Despite more cars on the road, two-wheelers remain the preferred mode of transport, taking a share of 47% of mechanized trips. Yet, the base scenario will not come into effect because the road network is unable to cater to such demand. The desirable V/C ratio is exceeded in 2022 and climbs to a value of 1.2 in 2031. As correctly identified by the urban planners, Hyderabad requires high capacity mass transit options to promote mode shift away from private vehicles. In the alternative scenarios we will explore whether the proposed measures, like the metro service, are adequate to satisfy the expected demand for public transport.

5.5.3 Alternative Scenarios

- *Scenario P1 – Mode shift*

Despite reaching undesirable levels of traffic in the horizon year, Hyderabad is in a good position to master the urban transportation challenge because the use per vehicle (i.e. two-wheelers) is relatively high. In the P1 scenario, a desired level of 0.8 in the horizon year is anticipated. After an initial overshoot from 2020-2025, we find that volume-capacity ratio steadily declines to 0.86 in 2031. Under the condition that there is no change to the vehicle ownership growth model, trips per car reduces by 55% (0.41) and utilization per two-wheeler by one third, respectively. In terms of vehicle trip rates (on a per capita basis), cars remain constant (0.11), whereas two-wheeler trip rate further grows from 0.55 in 2022 to 0.57 in 2031. This is an interesting finding, because it infers that Hyderabad has to primarily focus their mode shift efforts on motorcycle and scooter riders. An extended temporal view on the base scenario shows that only beyond 2040, cars would become the dominant mode[20].

[20] Assuming continued growth for population and income (GDP per capita).

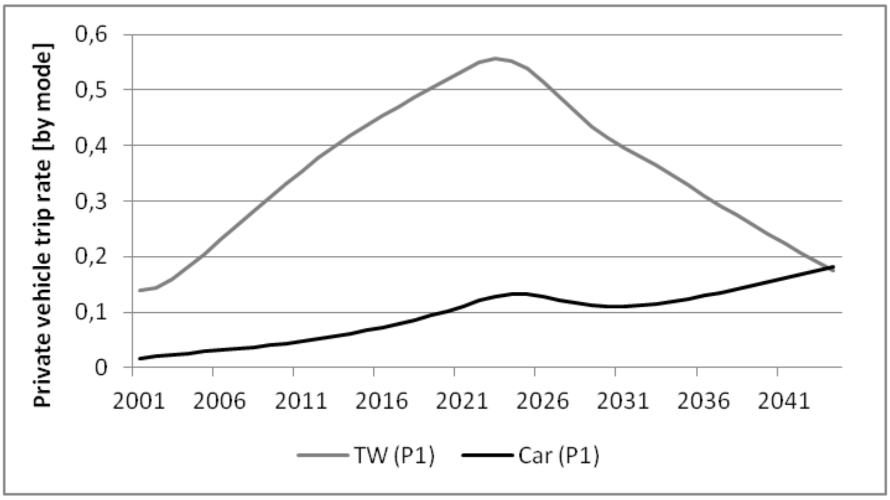


Figure 58: Private vehicle trip rates in the mode shift scenario

Compared to the base scenario, the P1 scenario would add 3.2 million trips to the public transport system, cumulating to 96 million passenger kilometers travelled daily. The share of public transport in the city's modal split would then constitute 59%; two-wheelers would make up another 32%.

Hyderabad CTS does not explicitly elaborate on a strong mode shift scenario. However, three alternative network scenarios (N2- N4) are investigated, which all contain significant investments in mass transit: 339 km of potentially new public transport corridors are added to the 172 km already committed in the base scenario and the land use maps show that these corridors are within the GHMC area. Our simulation results can convey that the full expansion of public transport may not be required: compared to the base case, its capacity should triple, whereas in the DUTM-i P1 scenario, travel demand merely doubles.

- *Scenario P2 – Reduced vehicle ownership*

In the base scenario, we compare vehicle ownership growth to the logistic growth model of Hyderabad CTS, which projects 675 vehicles (cars and two-wheelers) per 1,000 inhabitants in 2030. Such a high motorization is unlikely to happen, because road capacity is limited within the study area and we simulate the implication of lower vehicle ownership to the system in scenario P2. First, we change the variable *vehicle substitution factor*[21] from 0.61 to 0.5 in 2031, which lowers total ownership. Second, we apply the negative *linear fractional decrease* rate, which simulates fewer people opting to buy a vehicle when the daily traffic situation worsens. Despite lower pace of ownership growth and 1.3 million vehicles less on the road by 2031, congestion ratio remains above the acceptable level (1.07) and, more importantly, continues to rise. This is due to population growth, which adds new vehicles to the fleet, although vehicles per capita remain constant. Scenario P2b explores the required reduction of vehicle ownership to maintain V/C ratio of 0.8. In this scenario two-wheeler and car ownership would constitute only 0.27 and 0.07 in 2031, respectively, which is equivalent to the level of 2016. In other words, Hyderabad per capita vehicle ownership would gradually decrease at the rate of population growth under the condition that the use pattern (1.6 trips per two-wheeler and 0.9 per car) remains unchanged. Also, a vehicle quota system alone is not able to mitigate the congestion issues in Hyderabad and is therefore, not outlined in more detail here.

[21] The vehicle substitution factor models owners of two-wheelers switching to cars, if they can afford to.

- *Scenario P3 – Road network expansion*

In scenario P3a we simulate that the additional intermediary ring road is constructed as well (107 km). As we would expect from the system analysis, this measure helps to ease congestion, but cannot be regarded as the only solution. In scenario P3b, we simulate the road construction that would theoretically be required in the DUTM-i to satisfy the base scenario road transport demand and maintain an average network speed of 15 km/h:

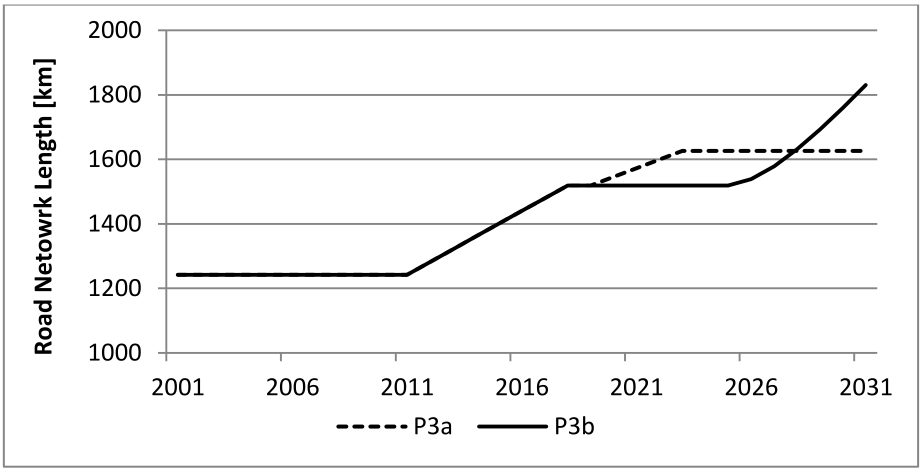


Figure 59: Hyderabad network lengths in road expansion scenarios

As Figure 59 shows, there is already a big gap between the base and the P3b scenario (312 km). However, the dynamic perspective is even more important in this context because the road network would have to continue to linearly increase at a rate of 70 km per year in order to provide the necessary capacity. This underscores that supply-side measures are not a sustainable solution in a dynamic demand growth scenario for Hyderabad.

5.5.4 Trend Scenario

Hyderabad is one of the largest urban agglomerations in India and has proposed a comprehensive transport strategy for the horizon year for both transit and road networks. The city will develop around a dense center with high-capacity radial corridors and a connecting ring structure. In the trend scenario, we assume the intermediary ring road and an extensive public transport network to be available. This promotes mode shift, on the one hand, and caters to the population desire to own and use private vehicles on the other. Similar to the CTS, a lower overall motorization than in the base scenario is assumed for the horizon year with 0.29 two-wheelers and 0.25 cars per inhabitant. Due the good public transport availability, passenger kilometers increase by 11 million (+20%) compared to the base scenario and, hence, private trip rate reduces to 0.63 – equal to a 42% of all daily trips and 55% of mechanized trips. Road capacity is going to be fully utilized on the network level in 2031, resulting in an average journey speed of 14 km/h. However, from a dynamic view, congestion ratio will further decrease and network speed rebound to 18 km/h beyond the investigated time-frame.

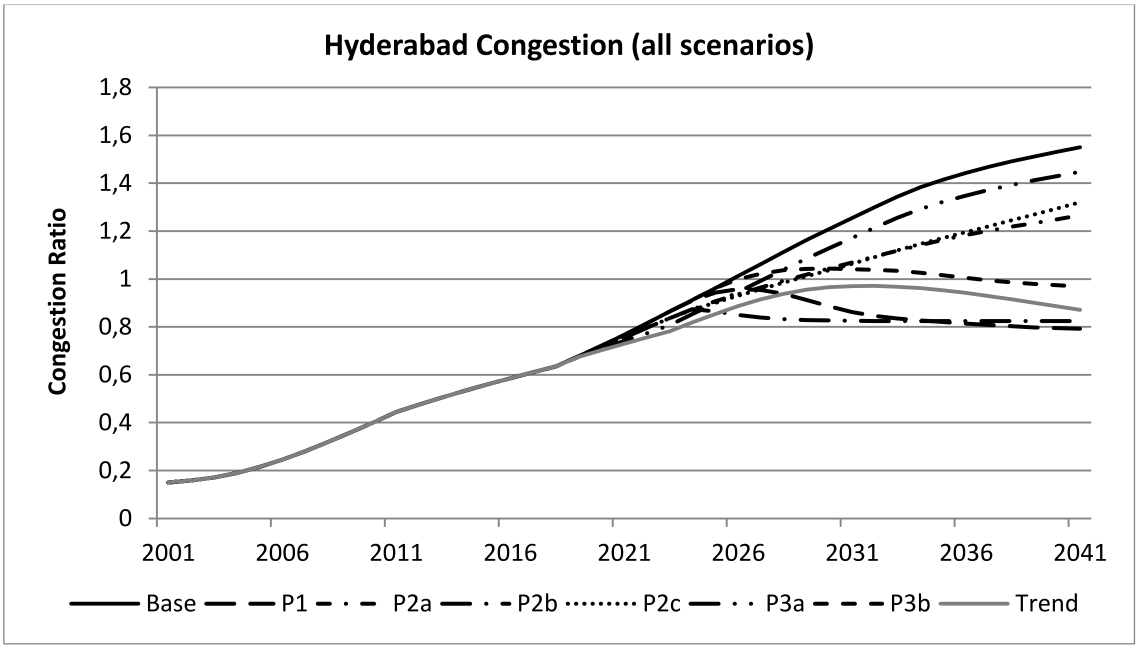


Figure 60: Hyderabad congestion ratio (all scenarios)

5.6 Indore

5.6.1 Indore City Profile

Indore, situated on the banks of rivers Khan and Saraswati, is the largest city and economic center of the Indian state of Madhya Pradesh and located 190 km west of the state capital Bhopal. It is a premier center for education, medical institutes and a major industrial hub of Central India. The CMP study area is Indore Planning Area as defined by the city's Master Plan and covers 505 km² out of which 130 km² is under the authority of Indore Municipal Corporation (IMC). Similar to our other study cities, the traffic problems to be solved focus on the city itself, with new land development mostly limited to the surrounding districts. Therefore, we refer to the IMC area in the DUTM-i simulation model. As per Census 2011, Indore urban area is home to 2 million people, which means that the city's population nearly quadrupled in the last 40 years. Located in the heart of India, climate is subtropical and affected by the southwest monsoon, which brings heavy rainfalls July through September. It is warm throughout the year with daily mean temperatures ranging from 18 to 32°C and peaks of 41°C in May [RITES, 2012].

Indore has a good road network consisting of primary (arterial), secondary (sub-arterial) and tertiary (collector) roads, which are predominantly arranged in a ring radial pattern and totals 458 km in length. For the preparation of the CMP, 270 km of the networked were surveyed in more detail; 60% of the network has right of way between 10-30m indicating the limitations of their carrying capacity. The average journey speed observed is 16.4 km/h in peak and 21.5 km/h in off-peak hours. Due to heavy congestion, speed drops to less than 10 km/h on 27% of the network in the peak hour and 32% of the survey location show V/C ratio greater than 0.8.

The rapid economic development coupled with strong rise of population in the recent past has contributed to a large increase of traffic. Share of public transit is low; instead, citizens are turning to personal vehicles (particularly two wheelers), adding even more traffic and deteriorating local air quality. As of 2010, there are 854,000 two-wheelers and 120,500 cars occupying Indore's roads. The fleet grew at a rate of 9% and 14%, respectively, in the last ten years. The household survey shows that only 17% of the households do not possess any motorized vehicle at all. The public transport system in the city is essentially road based both in organized and unorganized ways. Set up in 2005, The Atal Indore City Transport Services Ltd. (AICTSL) manages and operates the public bus system with private sector participation. Indore was the first city in India to introduce such a private-public partnership (PPP) model and the AICTSL operates, in total, 110 buses on 24 major routes on a network length of 277 km; 37 of them are modern low floor buses with real-time vehicle tracking and a completely digital ticketing system. Under the JNNURM funding scheme, AICTSL received a sanction of 175 additional buses, partly fueled by compressed natural gas (CNG). Indore has also been approved to implement 5 BRT corridors, of which the first became operational in May 2013 [ICTS Ltd., 2006]. The public transport is complemented by IPT services, such as private minibuses (500), auto rickshaws (~14,000), metro taxis (100) and others, which do not operate on formal routes and have cheaper or equal fares as AICTSL buses.

The travel characteristics in the study area are as follows: on average, 2.56 million trips were performed daily, which is equivalent to a PCTR of 1.12 including walking and 0.82 for motorized trips only. Modal share of non-motorized transport is 27%, whereas the share of public transport (including IPT) is 28%. City bus services only account for a third (9%) of the trips. The dominant mean of transport are two-wheelers, which take a share of 40% (cars contribute a marginal 5.6% of trips). Average trip length for motorcycles is 6.8 km compared to 8km typically travelled by bus.

5.6.2 Indore Base Scenario

Indore grows from a population of 1.6 million to nearly 4 million in the horizon year 2031. In order to be able to absorb this growth, the Master Plan proposes to extend the city area to 340 km². As the new planning area encompasses 505 km² altogether, we assume further land development in the decade up to the horizon year to 410 km². Average urban density reduces slightly from 12,400 to 9,400 people per km² in the simulated time frame. Average daily trip is expected to become longer, reaching a maximum for all modes in 2021. The road network will be adapted to meet this demand as well. Indore CMP identifies four growth corridors, which will shape the mobility of the city in the future. Although there are not any specific new road projects stated, we assume a 10% improvement of road capacity until 2021 in our base scenario, particularly due to the growing importance of the ring road to guide traffic around the city center. Another key infrastructure project is a metro rail network for Indore, which is currently in the planning phase and can be considered for the alternative scenario analysis.

Total daily travel demand in 2031 is expected to be 4.6 million trips (PCTR = 1.2). The share of motorized modes is 70%, due to continued strong growth in vehicle ownership. In particular, passenger car registrations are expected to soar between 2020 and 2030, as larger parts of the population will be able to afford them. Following the ownership model, 1.2 million two-wheelers and 1 million cars will make up the private vehicle fleet, which translates into motorization of 590 vehicles per 1,000 in the final time step. At the same time, modal share of public transport will have been reduced to half compared to 2011.

The base scenario is highly improbable to come into effect. Congestion ratio on the network level will exceed the desirable level of 0.8 by 2027 and become greater than 1.0 in 2031. The average journey speeds in such a scenario drop below 10 km/h, indicating constant gridlock on all major roads. The improvement of the ring road provides short-term relief, but is not sufficient to meet the ever growing road traffic in the longer term.

5.6.3 Alternative Scenarios

- *Scenario P1 – Mode shift*

In the P1 scenario the implications of mode shift for Indore transport system are investigated. We assume a desirable V/C ratio of 0.8. Although that point is only reached in 2027, daily public transport trips already more than double in 2031, compared to the base case and more importantly, would be continuing to grow exponentially thereafter. On the other hand, private vehicle trips drop by 22%, but remain the majority (66%) of all motorized trips and account for 47% in the modal split (incl. non-motorized transport). Due to a time lag in the system, congestion ratio overshoots to 0.9 in the horizon year, but steadily declines back to 0.8 in the following decade and average journey speed rebounds to the current levels. As the vehicle ownership model remains untouched in the P1 scenario, average utilization per vehicle has to decline with the shift to public transport. When we look at the simulation results, we find that for passenger cars, this value would decrease to 0.8 – that is 36% lower than in the base scenario.

In the CMP, the so-called “CMP scenario” analyzes strong mode shift, too. Unfortunately, the results are peak-hour based and the modal split figures include cycling, but not walking. Therefore, we cannot link them to the P1 results for a plausibility check.

- *Scenario P2 – Reduced vehicle ownership*

Different to the preceding study cities, congestion in Indore only becomes critical towards the end of the simulation and in the succeeding decade. Because the system has significant time-delays, the reduced ownership feedback loop is without effect in the scenario simulation. From a dynamic perspective, however, it is important to note that the exponential growth curve of car ownership is discontinued at an early stage in Indore, which means that the city will unlikely reach moderate car ownership of 300 per 1,000 inhabitants, unless utilization drops. In such a scenario cars primarily serve as a status symbol and are going to be used for leisure trips, rather than a daily mean of transport. In scenario P2b, we investigate a very strong feedback loop, where ownership is restricted to maintain desirable V/C ratio of 80%. In this case, two-wheeler and car fleet combined would have to remain constant at 1.7 million vehicles, which means that motorization level would gradually decline at the fractional population growth rate (2.7% p.a.).

- *Scenario P3 – Road construction*

The P3 scenario investigates the effectiveness of supply-side measures in Indore. Because the road network for Indore is relatively small today, a moderate expansion of 70 km between 2021 and 2028 can provide enough capacity to cater the demand increase in the short-term as the simulation results suggest. Although this does not hold true in the long-run, authorities would be able to gain precious time to establish a suitable public transport service promoting mode shift to mass transit before the road network becomes too strained.

5.6.4 Trend Scenario

Indore is in the best position among the study cities to come up with a proactive transport strategy, rather than only reacting to the dynamic demand growth. The "CMP Transport Scenario" outlines the key actions to be taken

- Road network expansion: complete construction of (in total) four ring roads to bypass through traffic around the city center and provide circular connectivity.
- Public transport availability: construction of metro light rail system with 6 lines operating on 78.5 km throughout the city [Indore Metro Rail, 2016].

In the DUTM-i trend scenario we therefore, adopt the assumption of the P3 scenario of 70 km additional new roads being built until 2031. Furthermore, we assume the mode shift to commence at the end of the simulation period because key public transport infrastructure projects, such as the metro line and improved city bus systems, are going to be available. Compared to the base scenario, there are 11% more public transport trips (540,000 in total), mainly through less use of cars. Congestion ratio is only slightly above the desirable level (0.86) and stabilizes at around 1 throughout the next decade.

It is important to note that for Indore, the dynamic model is of particular value to decision makers. If we only draw upon the model result for the horizon year 2031, we would infer that supply side measures are adequate to meet the demand. From a dynamic perspective, however, this conclusion proves to be deceptive, as more road capacity only provides short-term relief to exponential demand growth.

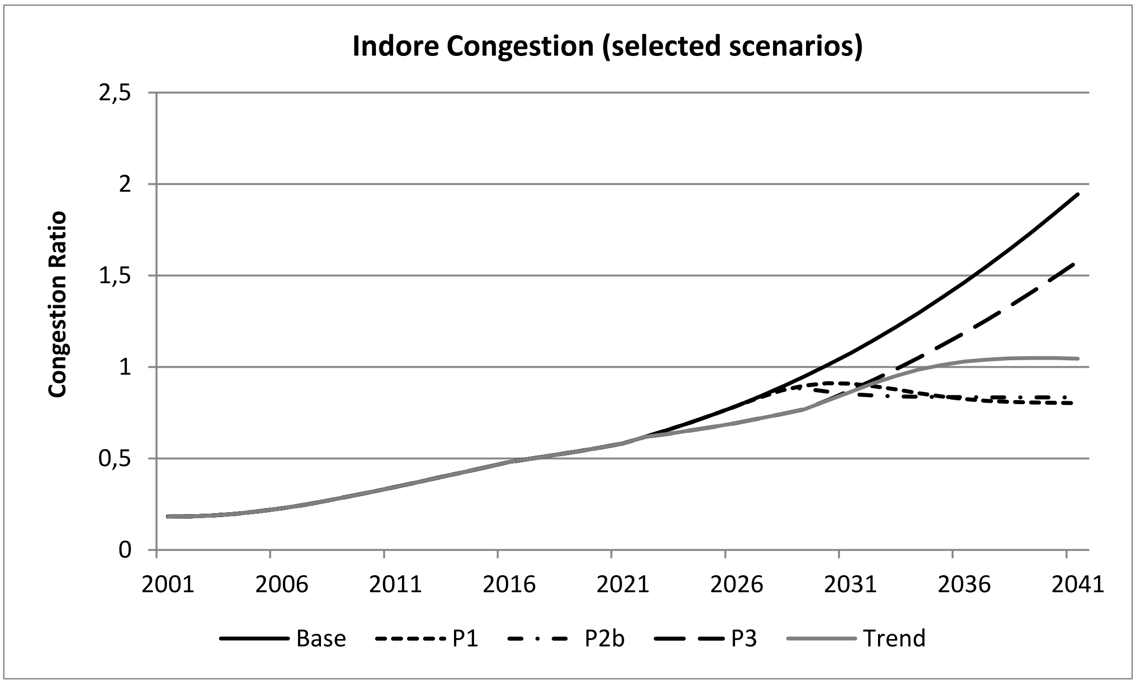


Figure 61: Indore congestion ratio (selected scenarios)

Yet, Indore is in a better position than the other study cities because the city has sufficient time to prepare for this scenario and the absolute amount of required investments is smaller than for the larger metropolitan areas in India.

5.7 Jaipur

5.7.1 Jaipur City Profile

Jaipur is the capital and largest city in the state of Rajasthan, situated in Northern India, 260 km southwest of Delhi. It is a fast growing city, boasting annual population growth rates of 5-8% over the last decade. In addition to being the commercial capital of Rajasthan, Jaipur is also a prime tourist destination in India with around 1.3 million people visiting annually. Forming the urban core, most traditional economic activities are located in the “Walled City” (6.7 km²). The city itself is known as Jaipur Municipal Corporation (JMC), which covers an area of 282 km². For the CMP study, however, all areas that have influence on the mobility issues of the city were taken into account, forming the much larger Jaipur Development Area (2651 km²). In the DUTM-i, we draw upon the area stated in the CDP (1,464 km²), because it delimits the area under planning authority of Jaipur. As per Census 2011, the city is home to 3.5 million people and expected to more than double until the horizon year 2031. Jaipur has a continental climate with mild winters and hot summers; during the monsoon season, there are frequent, heavy rains, but flooding is not common [Wilbur Smith Associates, 2010].

JDA has a total of 1,500 road kilometers, which also include small rural roads. For our model, we refer to the network length used in the CMP transport model (635 km), because we also benchmark against its calculated travel demand. In preparation of the CMP, a road survey was performed for a smaller part of the network. It showed that more than 50% had 4 lanes, and an average of 3.6 lanes. Average Journey speed is observed to be 28 km/h, which indicates acceptable traffic volumes on the major corridors. In the center, speed drops to 16 km/h, reflecting the design limitations of the old city to cope with higher traffic volumes.

According to data from the Indian Ministry of Road Transport and Highways [MoRTH, 2012a], a total of 1.69 million vehicles were registered in Jaipur (as of 2011). Two-wheelers make up 74% of the fleet, while passenger cars account for a little more than 15% of the fleet. Compared to CMP data for 2008, the fleet has expanded annually by 8.5%, which is a slight slowdown against the previously observed annual average growth rate of 13%. Considering the average household size to be around 5, we observe that Jaipur has a high motorization level of around 2 vehicles per household. It is reasonable to assume that people are going to strive to substitute their two-wheelers for more comfortable automobiles, if they can afford to. The public transport system in Jaipur is currently based on (mini-) buses and considered inadequate in terms of comfort and frequency. The formal city bus system, Jaipur City Transport Services (JCTSL) is operated by the Rajasthan State Road Transport Corporation (RSRTC) and operates a fleet of 400 buses, of which only 20 are air-conditioned [Driver Conductor, 2016]. Private operators fill the gap of public transport supply, but they only focus on the profitable routes. This causes confusion and too many buses on certain routes. Moreover, these vehicles are old and uncomfortable to use. Only recently, Jaipur officially opened the first metro line with 9 km of length and 9 stations [Jaipur Metro Rail, 2016]. The “pink” line will be fully operational by 2018, and the second line (“orange”) is expected to be available in the next decade. Despite this, the network remains very limited in scope by providing a mode option on two corridors only.

The per capita trip rate in Jaipur is 1.06 (including NMT) and 0.73 for motorized trips, which is equal to a total of 3.7 million trips performed daily in JDA. Similar to the other study cities, a great part of trips are performed by either walking or cycling (31%). Although bus services are poor, 21% still use public transport, whereas private vehicles dominate with 34%; auto-rickshaws and taxis serve the remaining 14% of daily peak-hour trips, as estimated in the CMP transport demand model. The average daily trip length across all modes is calculated to be 6.5 km.

5.7.2 Jaipur Base Scenario

Consistent with the CMP projections, we assume Jaipur population to grow to 6.6 million in 2031, with annual growth rates slightly decreasing from 3.4% to 3% in the last decade of the simulation period. As large parts of JDA are still undeveloped, we do not expect the study area to change. Density for entire JDA is very low, reaching only 4,500 in the horizon year. However, most of the people in the study area live in and around the metropolitan area (JMC), which accounts for 87% of JDA total population, resulting in urban density observed to be 10,800. We assume that urban growth will dominantly take place at the fringes of JMC, which is also envisaged in the city's Master Plan. We, therefore, follow the CMP model assumptions that trip lengths will increase towards the horizon year. For the base scenario, only phase I of the planned ring road is expected to be operational by 2020 and the second metro line to be operational by 2031.

Total transport demand in the horizon year is projected to reach 9.2 million trips, which is equal to an average daily trip rate of 1.38, out of which 83% are mechanized trips. Cars and two-wheelers account for 4.7 million trips, while public transport cumulates to just 2.7 million, representing a share of 37% of mechanized transport. Despite high growth rates in passenger car ownership, two-wheelers remain the majority of the vehicle fleet in 2031[22]. Compared to the reference year, the overall fleet size nearly quadruples.

In terms of transport supply, the road network in the base scenario is assumed to remain constant at 635 km, as the CMP does not provide information on any road projects in the construction phase. Despite this restrictive assumption, the DUTM-i for Jaipur only reaches the critical level of congestion in 2030. This is consistent with the CMP business-as-usual scenario that yields V/C ratios between 0.7 and 0.9 on major corridors for the same year. One of the reasons for this simulation outcome is that occupancy rates observed in the primary traffic surveys prove to be particularly high for passenger cars (in average 2.6).

The base scenario results demonstrate that road capacity is not a restricting factor for transport demand in Jaipur. Still, we can expect peak hour traffic jams and travel time losses to occur more frequently beyond 2025 (V/C ratio > 0.62) because the Walled City is confined to take up more road-based transport. As the SD model does not include the required spatial representation to capture such an effect, we cannot convey a more detailed analysis, but from a dynamic perspective, the DUTM-i shows that the V/C ratio will degrade at an increasing rate beyond the horizon year. Therefore, Jaipur is advised take a pro-active approach and gradually ramp up high-capacity public transit service and offer citizens an adequate alternative to their private vehicles, once the desirable levels are close to be imminent.

[22] Vehicle fleet composition: 2.46 million two-wheelers and 1.87 million cars

5.7.3 Alternative Scenarios

For Jaipur, we do not assess the three feedback structures in more detail. Instead, we perform sensitivity analysis for Congestion Ratio with respect to three input variables (see Figure 62):

- **Car occupancy** – by reducing this value to 2.2 (observed in Delhi) the slope of the trend curve gets steeper and the desirable level is passed two years earlier.
- **Vehicle Ownership** – The base scenario assumes high overall motorization for 2030 and beyond. Lowering the value from 0.63 to 0.55 (as in 3 other study cities), the desirable V/C ratio is exceeded 1 year later and leads to decreased slope of the exponential growth function.
- **Maximum Road Capacity** – assuming a maximum road capacity of 600 PCU/h, the desirable level is exceeded 5 years later and inclination of the trend curve is lowered, as well.

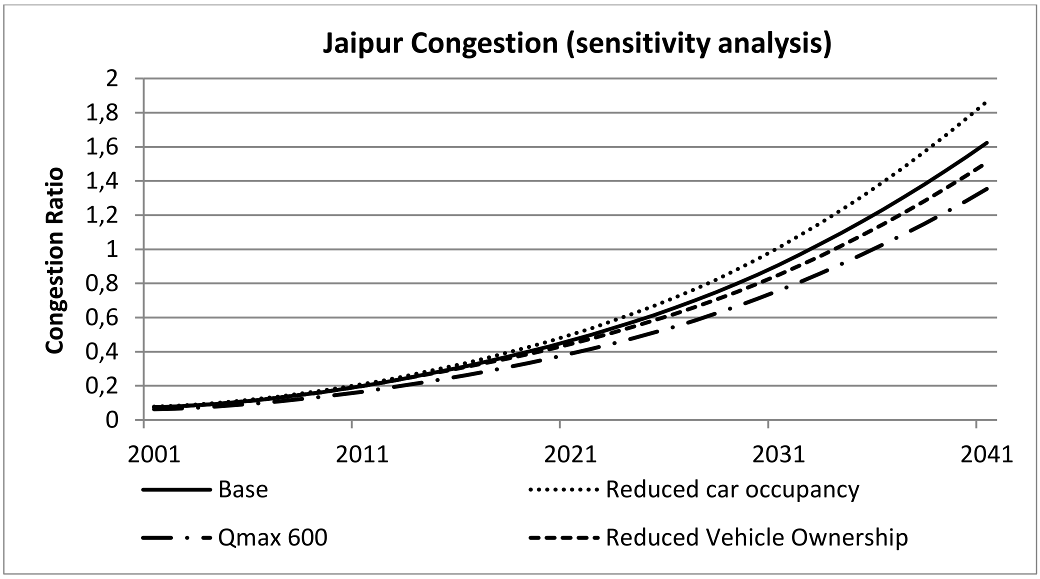


Figure 62: Sensitivity analysis for Jaipur base model

The sensitivity analysis is a mean to identify possible levers in the system. In case of the transport system model in the DUTM-i, we find that increasing capacity on the existing network (not building new roads) is a powerful mean to decelerate the exponential growth curve. The limited impact of policies targeted to reduce vehicle ownership seems counterintuitive at first glance, but analysis of simulation results explains this system behavior. If vehicle ownership, in general, is limited, people will opt for a car, if they can – the reduction is then mainly focused on two-wheelers, which do not help to significantly reduce congestion, given their small footprint on the road. For a policy to be effective, it has to specifically target cars and two-wheelers, because people will switch between these modes if one of the two remains unregulated. The situation observed in Chinese cities after the introduction of car lottery schemes support this finding.

5.8 Study City Comparison

The selected study cities represent a profile of urban mobility in India. Although different in terms of population size, geographic location, urban form and available infrastructures, they share the common challenge to cater to the needs of a dynamically growing number of inhabitants and to provide for efficient transportation. A comparison of the base scenarios demonstrates that all of the study cities need to proactively layout a comprehensive transport strategy because “business-as-usual” will result in unacceptable levels of road traffic on the entire network level, except for Jaipur, in the investigated time-frame.

5.8.1 Base Scenarios

For Delhi, the city with the largest vehicle fleet in India, the base scenario also estimates the worst level of congestion, followed by Bangalore. The road network of medium-sized cities, such as Jaipur and Indore, is projected to be less strained. Also, the trend for smaller cities is less dynamic (i.e. the inclination of the curve is not as steep as for the two megacities).

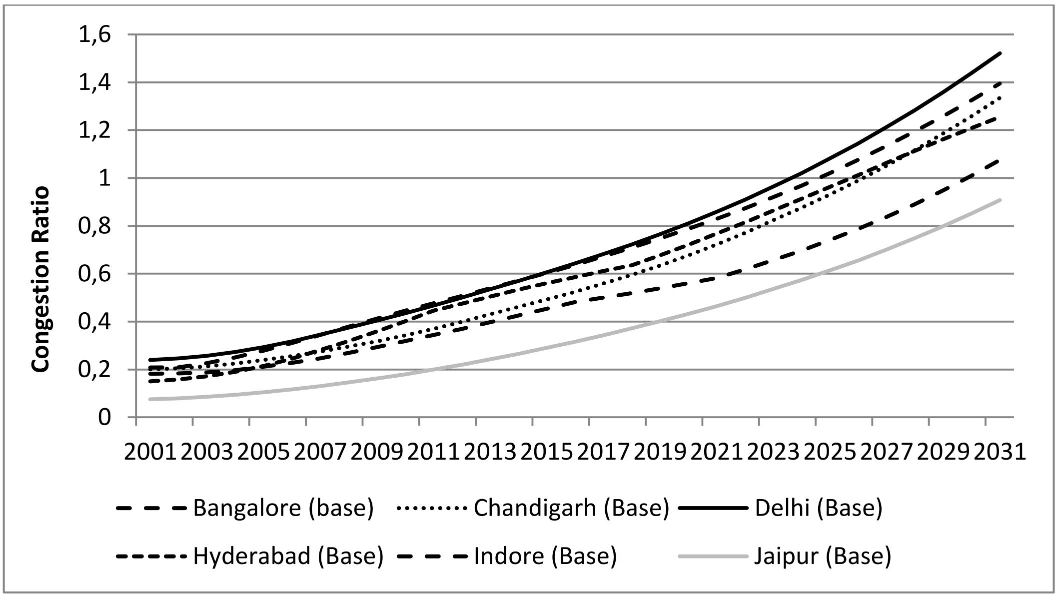


Figure 63: Congestion ratio all study cities (base scenarios)

Chandigarh constitutes a special case for two reasons. First, the city has an unconventional urban form, even to international standards. The strict grid layout with sectors has the disadvantage that it does not distribute the traffic flows as efficiently as ring-radial layouts, found in the other study cities. Second, the Capital of Punjab state has the highest average per-capita income of all Indian cities, which results in a particularly high level of car ownership. Consequently, congestion is of more concern than the similarly sized cities Indore and Jaipur. An interesting observation can be made for Hyderabad: in contrast to the other study cities, V/C ratio does not grow exponentially beyond 2031. A closer analysis of the simulation data reveals that Hyderabad is close to India's maximum motorization level[23] in the horizon year (0.61) and only increases moderately beyond that point in time. Also, the impact of two-wheeler substitution by passenger cars in terms of reduced space efficiency is offset by the higher average passenger occupancy. Consequently, we see a moderate linear trend, but still above the desirable value of 0.8.

In the DUTM-i, transport volume is driven by the number of trips (trip rates x population) and their average length. In direct comparison, Hyderabad has the highest motorized trip rate (1.22) in the horizon year, followed by Jaipur and Bangalore. Delhi, despite congestion ratio of 1.5, only scores 0.85, which is also the second lowest share of motorized transport of all investigated cities.

[23] 0.68 [Dargay et al., 2007]

Table 15: Trip rates for all study cities (2031 – base scenario)

Indicator	Bangalore	Chandigarh	Delhi	Hyderabad	Indore	Jaipur
Per capita trip rate	1.46	1.45	1.37	1.55	1.19	1.38
Motorized trip rate	1.09	1.07	0.85	1.22	0.84	1.15
Trip rate (two-wheeler)	0.22	0.25	0.20	0.58	0.39	0.30
Trip rate (car)	0.29	0.82	0.40	0.24	0.32	0.45
Trip rate (public transport)	0.58	0	0.25	0.40	0.12	0.40

The mode-specific trip rates paint a more detailed picture on the respective travel preferences in the study cities. Although Delhi shares the lowest motorized trip rate with Indore, car usage (0.4 trips per capita) is comparatively high. Chandigarh constitutes an outlier with car trip rate of 0.82 – more than twice the value estimated in Delhi. Hyderabad, on the other hand, is dominated by two-wheelers, whereas public transport takes the highest share in Bangalore. Non-motorized transport has not explicitly been modeled in the DUTM-i, but we can calculate NMT share as a residual value of PCTR minus MTR. It has an average share of 26% of all trips performed in the horizon year across the investigated cities. This result underscores the need for proper pedestrian and cyclist facilities in order to improve safety and convenience for those vulnerable road users (see, for example, [Mohan and Tiwari, 2000]). The DUTM-i simulation cannot convey general trends for trip lengths, as they are dependent of the spatial travel patterns and not represented in this aggregate model. Yet, we can derive differences between them based on the calibration (to the reference year) and the estimation model presented in Chapter 3: we see that trip distances are particularly long in Hyderabad (Car/TW: 11.7 km in 2031) and that public transport trips are longer than private vehicle trips in all study cities, except for Delhi.

5.8.2 Trend Scenarios

When we turn to the trend scenarios for the investigated cities, we find that all urban transport networks will operate above the desirable level in the horizon year. Particularly, Delhi will remain highly congested unless the city government decides to introduce stringent measures (e.g. registration caps to confine private vehicle ownership and usage). In Chandigarh, the high per capita income and preferred usage of cars call for policy intervention as well. Typically, the number of captive users reduces when overall income level rises. This means that the expectations towards public transport are going to be higher: citizens will demand for comfortable means of transport (e.g. A/C busses and metro services) that are safe to use and provide seamless connectivity in the city.

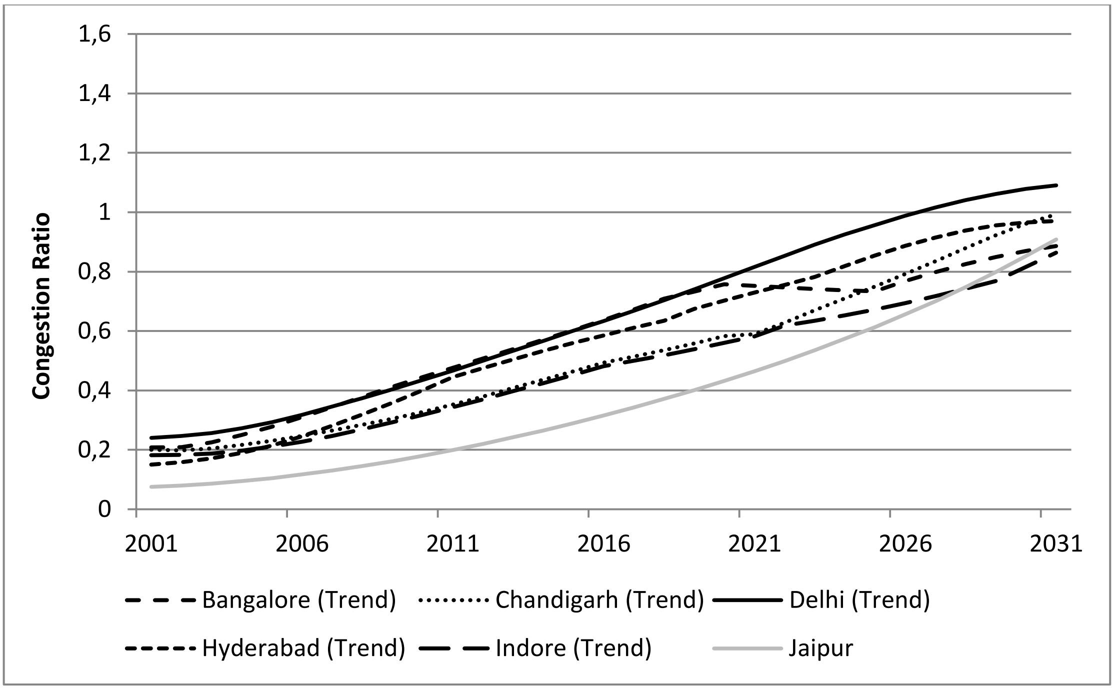


Figure 64: Congestion ratio all study cities (trend scenarios)

From a dynamic perspective, the feedback structures *Mode shift* (P1) and *Reduced Vehicle Ownership* (P2) come into effect between 2020 and 2025 for the large cities (Bangalore, Delhi and Hyderabad) and towards the end of the next decade for medium-sized cities (Chandigarh, Indore, Jaipur). Five cities remain stable around the V/C ratio of the horizon year, only Hyderabad "overshoots" to 0.97 in 2031 and rebounds back to 0.87 in the following decade.

The modal split (excluding walking and cycling) in the trend scenarios is favorable towards public transit, which becomes the dominant mode in four of the study cities, with Bangalore in a leading position (60%). Indore and Chandigarh maintain their high shares of two-wheelers and cars, respectively. Non-motorized travel increases slightly to 27.5% compared to the base scenario, due to reduced vehicle ownership in all study cities.

In summary, the trend simulation results for the selected study cities confirm the recommendations of the CMP documents and yield comparable results for transport demand and the split into the different modes. Beyond that, our results provide valuable information on the system dynamics of the study cities and their critical time paths for deploying effective transport strategies. We also have findings contradictory to the CMP recommendations. In the case of Chandigarh, for example, the construction of a metro system must be questioned, provided only 600,000 public transport trips estimated for 2031.

Table 16 provides a summary of key indicators for all study cities in the trend scenario for 2031 and the relative change compared to the starting year, including multiples of travel demand and vehicle ownership. Dynamic comparison between the base and the trend scenarios is presented in the appendix (A-4).

Table 16: Key indicators (trend scenario 2031- all study cities)

Indicator (Comparison to 2001 in %)	Bangalore	Chandigarh	Delhi	Hyderabad	Indore	Jaipur (base)
Congestion Ratio	0.89 (+326%)	0.99 (+395%)	1.09 (+354%)	0.97 (+546%)	0.86 (+375%)	0.91 (+1106%)
Daily PCU km [million]	23.7 (+480%)	15.2 (463%)	53.9 (+372%)	28.8 (+746%)	6.0 (+550%)	10.4 (+1106%)
Daily Trips by TW [million]	4.6 (+289%)	1.85 (+132%)	4.5 (+152%)	4.6 (+502%)	1.5 (+202%)	1.9 (+437%)
Daily Trips by car [million]	3.2 (+1322%)	2.84 (+3067%)	8.5 (+621%)	1.99 (+2253%)	1.2 (+2084%)	3.0 (+3364%)
Daily Trips (Public)	11.4 (+394%)	0.6 (+145%)	11.3 (+606%)	5.5 (+1697%)	0.54 (23%)	2.7 (+240%)
Motorized Mode Share	72% (+63%)	73% (+11%)	59% (+73%)	77% (+188%)	71% (+17%)	83% (+54%)
Per-capita trip rate	1.47 (+47%)	1.42 (12%)	1.30 (+34%)	1.5 (+92%)	1.2 (+17%)	1.38 (+62%)
Per capita Income [2005 USD]	5,137 (+224%)	10,242 (+224%)	7,265 (+224%)	6,584 (+224%)	8,131 (+224%)	7,580 (+224%)
Population [million]	18.1 (+116%)	5.1 (+275%)	31.8 (+129%)	10.5 (+89%)	3.9 (+137%)	6.6 (+146%)
Private trip rate	0.43 (+156%)	0.92 (+41%)	0.41 (+92%)	0.63 (+311%)	0.7 (+106%)	0.75 (+341%)
Public trip rate	0.63 (+129%)	0.12 (-35%)	0.36 (+208%)	0.52 (+849%)	0.14 (-48%)	0.40 (+38%)
Road Length	1,781 (+13%)	537 (+10%)	2,468 (+4%)	1,626 (+31%)	370 (+37%)	635 (0%)
Urban Density [pop/km²]	4,571 (+19%)	15,500 (+275%)	21,400 (+129%)	16,400 (+89%)	9,500 (-24%)	8,900 (-24%)
Vehicle Ownership (TW)	0.23 (+87%)	0.20 (-33%)	0.19 (+35%)	0.30 (+249%)	0.33 (+28%)	0.37 (+118%)
Vehicle Ownership (Car)	0.22 (+731%)	0.274 (+814%)	0.26 (297%)	0.25 (+1398%)	0.26 (+860%)	0.28 (+1308%)

6 Conclusions

In this thesis, we have studied in detail the present status of urban mobility in India and the proposed planning documents for more than 25 cities. Based on the main research question *"What are the implications of urbanization and economic growth for the urban transport system in India?"* we developed a generic model framework to simulate demand growth over a longer period of time and taking into account dynamic feedbacks in the system.

Data collection for setting up the model was found to be challenging because transport-related data for a greater number of cities in India is not readily available. All of the reviewed planning documents – the CMP's – were prepared with traditional four-stage travel demand models, which included comprehensive data collection in primary and secondary surveys, but unfortunately they are poorly documented. The models and raw data are only accessible in a few cities, which have sufficient capacity to utilize them beyond the CMP study itself. In the other cases, written reports including some of the original information were found to be the only public source of urban transportation data.

Yet, by mining all available documents, we were able to establish a collection of relevant macroscopic indicators for these cities, allowing us to test for statistically significant relationships among them and compare cities to each other. We found that motorized per capita trip rates are dependent on vehicle ownership and that average trip lengths and urban density are negatively correlated – thereby confirming previous research results, which call for compact city structures to contain overall travel demand.

We then turned to the system characterization and model building process. On the demand side we identify two exponential growth processes: urbanization and private motorization as a consequence of economic development (higher disposable income). Combined, these two have already resulted in a rapid and large expansion of the private vehicle fleet in India, particularly two-wheelers in the past decade. With India's economic boom projected to continue until the horizon year 2030, passenger cars are likely to substitute motorcycles under the pre-condition that the system is an "open-loop", and hence, able to accommodate the higher number of vehicles in the fleet. The econometric reference model for car ownership growth by Dargay et al. [2007] includes a "*saturation level*". However, this model is actually not designed for analysis on city level, as it does not include the specific boundary condition of a city, namely the available transport infrastructure and the interrelation between supply and demand. In our study, we close this gap and test the hypothesis that saturation will be reached at a much lower motorization level than estimated by this model for India as a country.

In a comprehensive literature review, existing transport model techniques were investigated with respect to their data requirements and ability to include time dependence and feedback. The traditional four-step travel demand model, although widely in use, fails to include such *time paths* and requires detailed data in order to produce useful results. Therefore, "*System Dynamics*" emerged as the best fit to the demands of our study, notably because of the highly flexible model framework and the foundation in dynamic system analysis and simulation. On the downside, validating the model assumptions and simulation output required substantial effort and multiple sources of data. With the *Dynamic Urban Transport Model for India* (DUTM-i) we propose a complementary approach to state-of-the-art models that is able to accommodate for the dynamic interrelations between transport supply and demand and reveal the critical time paths for the six study cities we selected. The sample of study cities represents a cross-section of urban India with respect to city size, geographic location and network structure.

With the DUTM-i, we aim to equip political decision makers and academic research in the field with a useful tool to test the dynamic response of the urban transport system to high-level demand management strategies based on input variables that can be modified in different scenarios. Through controlled parameter variation and sensitivity analysis, we are able to identify the key leverage points to balance the urban transport system at an acceptable level of service. Moreover, the model provides information on its status on a per-year basis rather than only for a single future point in time. In the field of System Dynamics, the DUTM-i belongs to the family of *"small"* models, which refers to the number of variables used. Such models are primarily designed to enhance system understanding and to disclose dynamic trends, rather than representing the investigated system in great detail, where existing models are likely to perform much better due to a higher level of sophistication and spatial modeling. The DUTM-i follows a core principle of System Dynamics: that growth processes are not infinite because they are constrained by a certain "*carrying capacity"*, which is defined by the available resources the (modeled) system consumes. In the case of urban transport, infrastructure supply generally acts as limitation to road travel demand growth. If this restriction is eased by building new roads, concerns over environmental pollution typically lead to artificial restraints (regulatory standards and travel demand management schemes), which promote the use of more eco-friendly modes of transportation (namely public transit and non-motorized travel). In the context of our study, physical transport capacity restraints were identified to be the dominant feedback in the system. Although air pollution is of pressing concern in many of India's cities, there are currently no mitigation policies under consideration. Impacts to technical vehicle specifications (e.g. tailpipe emissions) are not incorporated in our model, but discussed qualitatively in the section on alternative transportation concepts for India.

6.1 Implications from Simulation Results

From our model runs, we could convey that the study cities are projected to exceed their road capacity in the base case within the simulated time-frame. Therefore, feedback structures will come into effect, with different implications for decision bodies within the transport system.

Urban space limits road travel demand growth in India by 2031

The simulations for the study cities demonstrated that the planned road networks are not going to meet the future demand on an acceptable level of service in the base scenario. Network expansion alone is not enough – independent of city size – because of exponential growth in road travel demand. Hence, more efficient means of transport will be favored and must be made more attractive to use through policy measures. The limited amount of road space affects both moving (roads) and stationary traffic (parking), whereby the specific threshold value is unevenly distributed over time and space in the city. For example, the maximum amount of vehicles the central business district is able to absorb is going to be reached earlier than residential areas with parking facilities located in the outskirts of the city. State-of-the-art models, such as the ones prepared for the CMP, allow simulation of this important finding due to network representation in more detail; yet the DUTM-i indicates that 5 of 6 study cities are on a critical time-path and will reach network capacity before the horizon year 2031.

High-capacity public transit required for large cities

From a systems perspective, we see that mode shift (i.e. reduction of trips per vehicle) has the greatest impact to reduce congestion under the condition that alternative modes are available and provide significant travel time benefits, which is only the case if the public transit network is decoupled from private vehicular traffic. In the trend scenarios, public trip rate is highest in Bangalore (0.63), followed by Hyderabad (0.52) and Jaipur (0.4). In terms of daily passenger km traveled, Bangalore maintains the top position (103 million), followed by Delhi (97.8 million) and Hyderabad (71.3 million), whereas Jaipur will only have to provide for around 18 million passenger kilometers. Compared to 2015, the three largest study cities would have to augment their public transport capacity (including IPT modes) from 150 to 272 million passenger km per day. From a dynamic perspective, the passenger volume grows at an accelerating rate in these cities beyond 2020. Consequently, large cities require a high capacity network that can be deployed quickly and at scale until the horizon year and beyond. As trip lengths in Indian cities are relatively short (majority less than 10 km), bus systems will serve as the backbone of urban transport, complemented by metros along the corridors in large cities.

Reduced private vehicle utilization due to mode shift

Adversely, the shift to public transport results in lower vehicle utilization. But less driving, does not have to necessarily imply ownership drops to the same extent. Cars, in particular, are considered a status symbol by many people in India and people will keep their vehicle, even if they don’t use it to get around the city most of the time. This may seem counterintuitive at first sight, as we stated earlier that ownership is the main driver for travel demand growth, but we observe this behavior also in developed cities. In other words, the mode shift feedback loop is stronger than reducing ownership, because mental barriers to give up on-demand door-to-door mobility that a private vehicle offers are very strong [Diekstra and Kroon, 1997]. People do not necessarily behave in economically rational ways. They form their decision based on a number of psychological factors, which are outside the model scope. Total cost of ownership remains to be one of the most important and can be influenced by policy measures (e.g. through taxation, parking fees, etc.) and could support adoption of alternative options such as car-sharing, which is becoming increasingly popular and provides on-demand access to vehicles, too, yet helps to reduce the number of cars on the road.

Increased car occupancy decelerates road travel demand growth dynamics

Average car occupancy in Indian cities were found to be significantly higher than in European or American cities, and auto-rickshaws often operate at or above the design capacity, too. Sensitivity analysis of the DUTM-i shows that the number of passengers per vehicle constitutes a strong lever in travel demand, because it is directly proportional to its incremental rate of change. Let us assume, for example, daily demand yields 200,000 passenger km (pkm). Doubling the occupancy from two to four persons per vehicle cuts effective vehicle km driven on the network by 50,000. We now double demand to 400,000 pkm and find that vehicle km (now: 100,000) are reduced by the same factor. In the case of the study cities, road travel demand is in the millions and, therefore, constitutes a powerful leverage point. However, the effect is symmetric: when occupancy halves, the amount of vehicles doubles accordingly. In the light of new mobility services offerings, such as ride-sharing and carpooling, which aim to increase the vehicle yield by connecting customers that share similar routes with applications on smart mobile devices, this is a relevant finding. Policy instruments should therefore, be evaluated under consideration of their implications to occupancy.

Network capacity improvement decelerates road travel demand growth dynamics

On the supply side, analysis of equation 26 shows the potentials to reduce congestion:

$$\text{Congestion Ratio}_t = \frac{(\text{Daily Car Equivalent Vehicle km})_t}{(10 * \text{Road Length} * \text{Avg Lanes}) * Q_{max}} \quad (29)$$

Variation of any parameter in the enumerator by a certain percentage would result in the same degree of congestion relief. From a systems perspective, however, this surfaces an important finding: capacity (Q_{max}) improvement is incrementally as effective as building new roads (*Road Length*). In India, we typically find heterogeneous traffic mix on the road (including slow-moving traffic, such as cycle rickshaws, pedestrians and animal carriages), on-street parking and curbside hailing, which hinder smooth traffic flow and reduce the design capacity of the road. It is partially compensated by low adherence to traffic laws and lane discipline [Suresh and Umadevi, 2014]. Better road design (e.g. dedicated pedestrian facilities) and stricter law enforcement provide opportunity to lower congestion at a much lower cost than building new ones. Especially for large cities, which already have an extensive road network, traffic engineering measures should be prioritized. Moreover, so-called Intelligent Transportation Systems (ITS) using real-time traffic information and smart routing have the potential to distribute traffic flows more evenly across the network and increase the overall level of service. Completed ring roads are a prerequisite, due to their distribution and bypass functions.

In summary, we were able to draw important conclusions for transport planning bodies in India. We conveyed that mode shift is crucial for cities of all sizes and the most powerful lever to the urban mobility challenge in India. In large cities, the absolute growth in passenger volume, calls for quick and highly scalable public transit options, whereas small and medium-sized cities will require an adequate institutional framework in place to organize and fund public transport in a way that the mobility needs of their population are fulfilled. On the other hand, system analysis shows that road "capacity increase" can successfully delay an undesirable level of congestion, without calling for high capital expenditures, which mode shift ultimately requires: they aim to use (existing) urban space as efficiently as possible.

Population density and projected population growth in India's cities magnifies the urban transport challenge to a point, where multiple policies have to be combined to manage growth dynamics. In the trend scenarios, we present a feasible strategy mix for the study cities based on the specific boundary conditions and the proposals in the CMP documentation. With the DUTM-i, we also offer a convenient tool to test alternative assumptions and projections in a transparent and traceable framework.

6.2 Alternative Transportation Concepts for India

By means of the Dynamic Urban Transport Model for India (DUTM-i) we were able to find key levers for managing travel demand growth in the selected study cities and formulate conclusions based on the simulation results. We now discuss available and emerging alternative transportation concepts with respect to their specific fit to future urban mobility in India. This discussion is structured in new public transport solutions, private vehicle concepts and new forms of mobility services, which are enabled by digital technologies (i.e. ride and car sharing). Based on these findings, we then look at their impact on the system, both qualitatively and by using the DUTM-i for extended analysis.

6.2.1 Public Transport Solutions

Currently, six Indian cities[24] have a fully operational metro system. Two of them feature more than one line, but only Delhi can truly be referred to as a network, connecting the city on 6 lines and 213 kilometers. Many projects in India are underway, investing both in expansions, as well as adding new networks in several cities (e.g. Chandigarh, Indore and Hyderabad). In the latest budget, Government of India has reserved USD 1.5 billion to modernize the urban transport systems in more than two million cities [UITP India, 2017]. In addition, a number of cities have other types of light-rail systems in place (e.g. Mumbai) that provide mass transportation services, particularly for daily commuting.

In our simulations, we demonstrated that all study cities will need high-capacity public transport networks to achieve acceptable levels of congestion in the horizon year and found corresponding planning proposals in their CMP documents. However, from a dynamic perspective, the time horizons for implementation must be criticized. Large-scale metro projects have long lead times and usually do not progress according the original timeline. First plans for Delhi metro, for example, were already available in the 1980's, but operation only began in 2011. Current planning and construction timelines are much shorter (e.g. Jaipur metro), yet establishing a network that is adequate to satisfy the daily transportation needs of a larger share of the population usually takes much longer.

A cheaper and less difficult solution on high capacity corridors are Bus Rapid Transit Systems (BRTS). Widely successful in South America, the concept of grade-separated bus lanes with larger stations and an own ticketing system has been adopted in 12 cities, of which Ahmedabad BRTS is viewed as the Nation's most successful implementation. In contrast, Delhi BRTS was never able to live up to the expectations and remains dysfunctional still today.

Figure 65: BRT system in Ahmedabad [ITPD, 2015]

This raises the question: in which cases is BRTS a viable option and can it act as a substitute to rail-bound public transport? There is no easy answer to this, but our simulations suggest that especially the large cities in India will not be able to meet the demand only with BRTS: Delhi and Bangalore will have to provide the capacity of around 100 million passenger km per day in the trend scenario. Even if we assume many of the trips are performed within a 5-6 km radius, the dimensions of Indian megacities call for metro systems that provide quick and comfortable connectivity throughout the city.

Medium-sized cities like Jaipur, on the other hand, are confronted with less than a fifth of this demand in absolute numbers. Here, city administrations should conduct thorough cost benefit analyses with

[24] Bangalore, Chennai, Delhi NCR (incl. Gurgaon), Jaipur, Kolkatta, Mumbai

respect to metro systems, which require high capital investment and are expensive to operate, but may be underutilized and subject to relatively high fare subsidies [Advani and Tiwari, 2005]. BRTS are not only significantly cheaper to build and run, but also allow for more flexibility with respect to network layout and adjusting capacity. In terms of passenger capacity, BRTS are in the range of tramways and other light rail transport (LRT) systems commonly found in European (and some North American) cities, where they either act as a complement to the metros (e.g. Vienna) or as a substitute (e.g. Strasbourg). Typically, rail-bound vehicles have higher perceived passenger ride comfort, but compared to buses, are still more expensive to install and operate. An interesting reading on the advantages of BRTS over light rail is given by [Hensher, 2016]. A review of BRT systems funded under the JNNURM scheme and already operational is provided by [Pai and Hidalgo, 2009].

6.2.2 Intermediary Public Transport

Currently, the lack of public transportation in Indian cities is compensated by various forms of "Intermediary Public Transport" (IPT) modes. The ubiquitous auto-rickshaws are a familiar part of every Indian city and provide valuable first- and last-mile connectivity, as well as serving shorter trips, either in form of shared (pooled) services or as a low-cost alternative to taxis. Other popular IPT services include Tata Magic, Minibuses and cycle rickshaws. Despite being affordable, providing high maneuverability in congested streets and consuming relatively little fuel per passenger, IPT has some major disadvantages, such as low vehicle safety standards, air and noise pollution, as well as disrupting traffic flow by illegally stopping on-road while waiting for or picking up new customers. Currently, there are no policies or projects in place which aim to integrate these modes effectively into the overall system. In fact, the stance of authorities over IPT in most cities remains ambiguous, as auto-rickshaws are viewed as outdated and old-fashioned, rather than being valued as an important part of the transport system. Formalizing these services in a way that mitigate their main disadvantages and respect the needs of their operators promise to provide more mobility in Indian cities at relatively low additional cost.

Figure 66: Electric rickshaw [Mayuri Saera Electric Auto, 2017]

As the IPT sector is mostly informally organized, operators have come up with a number of innovative solutions, such as electric propulsion vehicles (i.e. electric cycle rickshaws), pooling services ("shared" auto) and even regular shuttle services (e.g. school transport), all of which have to be evaluated separately in terms of their benefits to providing transportation, which formal public transport services fail to deliver.

6.2.3 Alternative Road Vehicle Concepts

The legislative document regulating all aspects of road transport in India (e.g. vehicle registration, driver licensing, etc.) is the Motor Vehicles Act [MoRTH, 1988]. The Central Motor Vehicle Rules (CMVR) [MoRTH, 1989] translates its legislative provisions into exercisable rules and technical specifications, which are relevant for receiving the necessary permits for type approval and on-road operation. Any new vehicle offered on the Indian market falls into one of the pre-defined categories, although private users almost exclusively purchase either passenger cars (M category) or different types of two-wheelers, which are summarized under the L-category, in accordance with international standards.

In 2015, the CMVR were amended with a new vehicle category Q (so-called "Quadricycles"), with a maximum engine power output of 15 kW, a maximum speed of 70 km/h and a maximum weight of 450 kg. Targeted for urban use, these vehicles are restricted from using motorways and primarily promoted as a safer alternative to the three-wheeled auto-rickshaws. The amendment was spurred by Bajaj Motor Company, which is also the largest manufacturer of auto-rickshaws in India. However, there is an ongoing legal dispute pending at India's Supreme Court, whether these vehicles should be available for private users or only for commercial use (as are three-wheelers in India). In an attempt to gain public support for a favorable sentence, Bajaj has even launched an online campaign [Bajaj Auto, 2017].

Figure 67: Quadricycle Bajaj Qute [Bajaj Auto, 2017]

The Bajaj quadricycle is marketed as a green and safe vehicle for urban use, therefore, we simulate its potential to relieve congestion compared to standard passenger cars by adjusting the PCU values, as the dimensions of microcars are smaller and suggest a better utilization of road space. Compared to the 6.52 m² footprint of one of India's best-selling passenger cars, *Maruti Suzuki Swift*, the only vehicle potentially falling into the Q category, the *Bajaj Qute*, covers mere 3.61m². Provided that headways and speeds for both vehicles in urban traffic are more or less equal, the Qute is 45% more space efficient and, like auto-rickshaws, is rated with a PCU value of 0.8 in highly congested traffic [Arasan and Krishnamurthy, 2008]. For the experiment, we assume an initially linearly increasing share of quadricycles from 2018 to 2023, saturating at around 10% and continuing to grow at a slower rate until the horizon year. All other settings correspond with the trend scenario in the respective city:

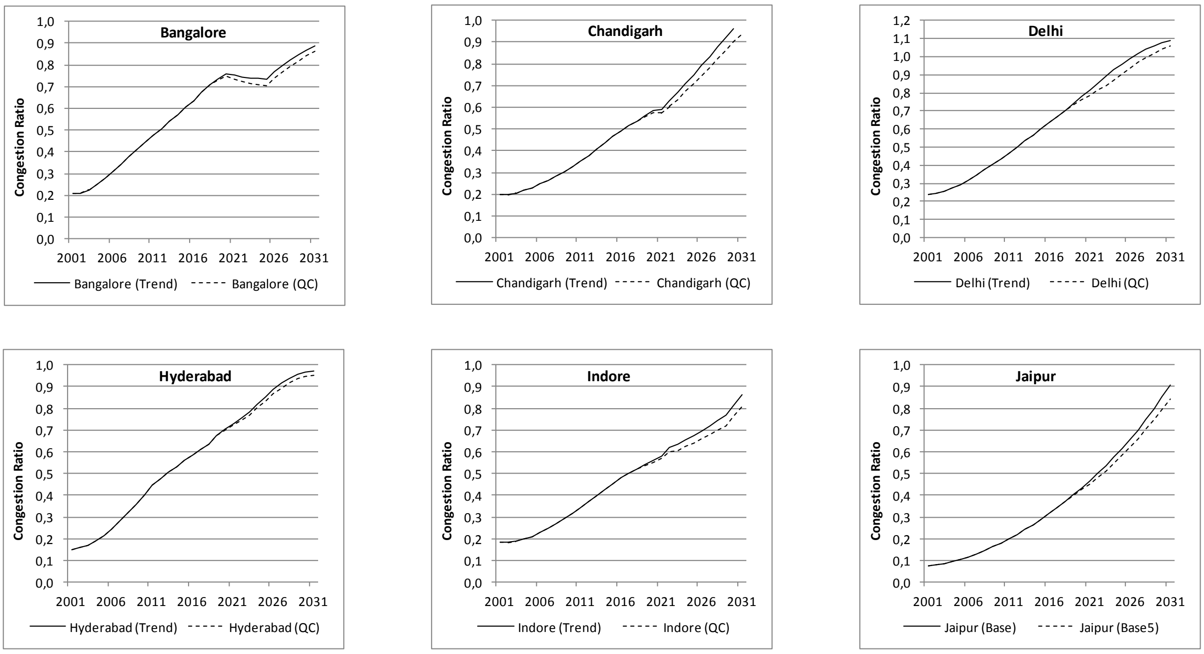


Figure 68: Quadricycles in DUTM-i trend scenarios

The results show that even a quick and significant diffusion of this new vehicle type (which is rather optimistic), does not have a big impact on the congestion ratio. In System Dynamics terms, vehicle ownership increases so quickly, that it outpaces the space efficiency gains of smaller vehicles. Japan is the best-known example of promoting small cars as a means to manage transport demand. The so-called *Kei-Car* vehicle category is dimensionally smaller and less powerful than standard passenger cars. Although they remain popular (primarily because of the lower total cost of ownership through fiscal incentives), they have not provided a sustainable solution to the urban transport challenges in Japan. In Europe, quadricycles (falling under the homologation category L7e) lack relevant consumer interest still today, due to the low driving performance and safety standards.

A key trend in the automotive industry is the shift to electrified propulsion systems in the future, namely hybrid and battery electric vehicles, pushed by legislation to reduce carbon emissions in the transport sector. China, in particular, is supporting the transition to electric vehicles both to mitigate severe air pollution in the large cities and to become a technology leader in the automotive space. In India, electric mobility has not been on the political agenda so far. General CO_2 fleet emission standards for vehicle manufacturers have been mandated by the Central Government [Ministry of Power, 2014] for 2020, but they are technologically agnostic and do not necessarily involve pure electric cars. This leaves India as a slow follower in the adaption of zero emission vehicles, particularly compared to the regional competitor China. In the DUTM-i, the vehicle's fuel type does not close any balancing feedback loops, although deteriorating air quality through vehicle emissions may likely trigger counteracting policies, such as driving bans, emission standards or vehicle quotas. A discussion on this topic is included in the outlook section.

A second relevant change in road transport is the advent of autonomous vehicle (AV) technology. Preliminary research results suggest that AV's have the potential to significantly reduce the amount of vehicles when operating as a shared mobility service [Fagnant and Kockelman, 2014] or largely increase the maximum road capacity through reduced headways and improved driving behavior compared to human drivers [Fernandes and Nunes, 2010]. Several interesting concepts have been presented by vehicle manufacturers, and autonomous fleets are already tested under real-world conditions. Apart from sensing equipment and intelligent computer algorithms in the vehicle itself, AV's require advanced infrastructures, such as high-precision maps and advanced telecommunication technology. Commercial readiness is, therefore, not expected before the next decade and there is presently no indication that AV's are going to be deployed in India at a larger scale. Moreover, the heterogeneous traffic on India's roads present a particular challenge for autonomous systems engineering, which means that AV's have to be tested under local conditions before being ready for operation. For these reasons, this technology leap was not investigated in more detail in this study, but could become relevant beyond the simulated time-frame.

6.2.4 New Mobility Concepts

In the last couple of years, car- and ride-sharing services have been embraced by a growing number of people around the globe and attracted significant funding from private investors. Companies like Uber or Zipcar claim to be at the forefront of a momentous shift away from personal vehicle ownership towards shared mobility on demand. Whether they really are as fundamentally new as commonly stated or simply a smarter solution of existing services remains an open discussion. Yet, they collectively achieve to leverage digital technologies in a way that offers a simple, seamless user experience via smart phone applications, which existing transport services (e.g.: taxis) usually do not. This attracts the young, tech-savvy urban population and offers a superior match of demand and supply with reduced cost.

One of the key enablers for their success in European and North American cities is the high regulation of the urban transport sector, in particular, legislation governing the commercial transport of people[25], as well as the bundle of demand management schemes (e.g. parking charges), which have made private car ownership and usage in dense urban areas increasingly expensive and unattractive. In India, the boundary conditions are rather different: various forms of IPT services are readily available to fulfill people's need for mobility and are relatively cheap compared to formal chauffeured services, such as taxis. What are "shared autos", if not ride sharing? The problem of current (semi-) public transport schemes in India is the inadequate level of safety and comfort – the main reason people to switch to private vehicles. The market potential for ride sharing in India is therefore, a service that fits between the affordable IPT services (unsafe, uncomfortable) and regular metered taxis (expensive). India's largest online transportation service "*OLA*" tries to address exactly this gap. However, concerns over driver credibility and customer data security have been accompanying the startup company since its foundation in 2010. Yet, to date, ride-sharing only constitutes a small share of total trips in the cities where they operate the service. In the DUTM-i, ride-hailing is included in the residual public transport demand, which is projected to grow significantly in the trend scenarios. Our model, thus, suggests an increased market potential for ride-sharing in India in the future, especially where public transport cannot meet customer's demand for safe and convenient travelling.

[25] Most cities prohibit intermediary transport services, apart from taxis and chauffeured limousines

Car sharing, on the other hand, is still insignificant, despite several new businesses (e.g. Zoomcar, Myles) having started operation in the large cities. The rationale behind car sharing is that short-term rentals are, in total, less expensive than ownership unless the vehicle is used regularly. Companies offering shared cars are banking on Indian consumer's price consciousness in the long term [Philip, 2014], regardless of being viewed as a status symbol today. The simulation results support their assumption that more traffic congestion is going to reduce utilization of owned vehicles, which benefits the economics of car sharing for private users. For a more detailed analysis of the potential of car sharing, the DUTM-i needs to be extended because it does not represent mode choice in an adequate way. Research on this topic has only been conducted in Europe and suggests that car-sharing customers rely on a good transit network, cycle and pedestrian facilities for most of their daily trips and use cars complementary [Becker et al., 2015]. Hence, the choice of transport mode is on a per trip basis, whereas the DUTM-i uses average values. In general, the benefits of car sharing are subject to ongoing research and involve many factors outside the scope of the model in this study. The interested reader is directed to studies from the World Resource Institute (WRI) Ross Center for Sustainable Cities, which completed a study on car sharing in emerging markets [Lane et al., 2015].

6.3 Outlook

The computer simulation model in this thesis investigates the growth dynamics of urban mobility in India and its limitations. Calibration and validation of the model was performed on the basis of data extracted from the CMP documents. The selected study cities are viewed as a representative cross-section for India. The structure, parameters and interrelations of the DUTM-i, make it possible to apply the model to any other Indian city that has collected the necessary input data. In theory, this includes all cities, which were encouraged to prepare a CMP under the JNNURM funding. Out of the more than 50 candidates, we only identified 25 cities with sufficient documentation and compiled their key transport indicators for comparison. The public documentation for the six selected study cities was found to be comprehensive enough to calibrate and validate our model approach. As the CMP's follow the guidelines issued by the Central Government, all cities that have prepared such a planning document, should be in possession of the necessary data and can build up the DUTM-i without need for further data collection. Cities that have not collected data through primary and secondary traffic surveys must do so, before programming the DUTM-i.

As the DUTM-i is designed as a generic framework to study urban travel demand in India, the model cannot be transferred to other countries without changes. In particular, the time-dependent function of motorized trip rate and average trip lengths were derived from the cross-CMP analysis, which is only valid in the Indian context and would have to be estimated separately. The remaining structure of the model, particularly the growth functions, can be adapted to other regions because it is based on statistics from international organizations, which provide data for a wider number of countries. On the city level, comparable boundary conditions need to be existent: a developing economy, rapid urbanization and motorization (particularly two-wheelers), inadequate public transit, considerable income growth in the future and high population density. Examples for possible peer cities include Ho Chi Minh City (Vietnam), Karachi (Pakistan) or Jakarta (Indonesia). As is the case for the Indian study cities, reference data from a transport study or planning document is a pre-requisite for calibration purposes.

Finally, we turn to the question whether or not the conclusions drawn from the system analysis can be generalized. In other words, is there a generic code of urban transport for high-density cities in developing Asia? The results of this study do not provide a complete answer, but the observations were consistent over the sample cities, despite exhibiting very different local boundary conditions. All of them reached the car ownership saturation level well before the estimations from the econometric reference model. Larger cities did so earlier and at slightly lower motorization than the smaller cities in the sample. This result seems very plausible, if we compare the per capita car ownership to more developed Asian peers, like Seoul (0.16) or Tokyo (0.3) [Kenworthy and Laube, 2001], as well as their availability of public transport. System level conclusions can be carried forward to cities with similar boundary conditions too: road network expansion is not a viable strategy to counteract exponential growth on the demand side and will only lead to short-term relief, rather than being a sustainable solution to ease congestion; vehicle occupancy is an important leverage point to improve the space-efficiency of private motorized transport in cases where public transport options are not available or feasible. Finally, the role of IPT services should be reconsidered in the urban transport mix. In most developing and emerging countries – not only in India - various means of informal transport services exist to fill the gaps in public transit. Being loosely regulated in most cases, they flexibly adapt to their customer's requirements in terms of fares and operations. On the other hand, IPT is also a source of low vehicle safety and comfort level, driving people to utilize private motorized modes. The intelligent integration of these transport services would allow cities to potentially leapfrog high levels of private motorization, which is restricted by the available road space, without the public sector having to provide the complete service on its own, which is not possible in many cases due to financial and institutional constraints.

The quantitative computer simulation model DUTM-i provides a tool to explore the growth dynamics and limitations of urban mobility in India. Being a *small* System Dynamics model, it is designed to deliver insights into the expected development of the transport system in the next fifteen years under consideration of dynamic feedback, which state-of-the-art transport models are not able to include. Clearly, further research is needed to take more details into account and enhance its explanatory power.

A mode choice sub-model would allow for more accurate representation of the mode shift feedback loop and for disaggregation of the urban population in "homogenous user groups" to investigate their behavior in terms of avoiding long travel times for their trips. Travel cost and feedbacks triggered by their dynamic changes could be integrated as well. From the literature review, we did not find a mode choice model applicable to this study. Also, the CMP's did not necessarily develop them separately and used the household survey data for mode split estimation instead. Two of the selected study cities estimated a logit model, but were not transferable, because they were neither sufficiently documented nor did they fit to the parameterization of the DUTM-i.

Due to its level of aggregation, the DUTM-i cannot provide information for flaws on the network level. This is particularly relevant for cities that have networks, where most of the travel demand runs on a smaller proportion of it. The DUTM-i would not identify this capacity restraint and the accompanying feedback structures. Moreover a certain level of disaggregation could support prioritization of transport projects by providing a dynamic perspective to the (static) cost-benefit analyses.

The developed scenarios and analyses act on the assumption that the public sector is willing and able to deploy the necessary transport strategies in the future. From a system modeling perspective however, additional feedback loops may become effective in case the required measures are not taken. The DUTM-i is incomplete to this respect: in the prevailing mental model of urban systems, we would expect transport supply shortage to hinder the movement of people and goods – the basis for economic activities – and cause environmental pollution, which lowers the relative attractiveness of the city as a place to work or live in and, consequently, less population growth. Moreover, the relationship between economic growth and transport investment is not reproduced in the DUTM-i because it is very difficult to model, both in terms of which parameters to consider and the time (duration) at which the impacts become effective. This complexity is augmented by the scale of the analysis, which happens on the national, regional or local level. Comprehensive research on this topic has been conducted by Banister and Berechman [2000], which point at the different aspects of how transport investment may affect the economy. One of the conclusions they draw on the local level is that better transport infrastructures do not necessarily create more labor, but improve labor productivity. Productivity gains, however, do not necessarily have to infer higher income levels or more jobs created. Thus, we can observe diminishing returns in transport investment, a finding that is also supported by Litman [2017]. Yet, we have to acknowledge that there is little empirical evidence available and these are qualitative findings, rather than validated functions that can be integrated in the DUTM-i. Alternatively, cost-benefit analyses are the standard mean to capture the expected positive (economic) impacts of transport projects. These analyses focus on the trade-off between investment cost and the projected mobility improvements (e.g. passenger km travelled), rather than the more general implications for economic growth. Therefore, we cannot draw upon them to close this feedback loop.

With respect to the relationship between the transport system and the attractiveness of a city, a formal link is even more difficult: numerous indices (e.g. Mercer Quality of Living Ranking) aim to measure the relative quality of life drawing on different factors, such as safety, living cost, job opportunities and, in many cases, the service level of the transport system. Evaluation is mostly on a qualitative basis only and does not make any statement how population growth is affected. We, therefore, have to acknowledge that both feedback loops would provide an open, yet relevant, research question in the further extension of the DUTM-i.

The simulation period for this study was chosen to be 30 years, as most of the planning documents were prepared for the horizon year 2031 and acted as a useful reference to validate the model assumptions and results. However, the study city simulations revealed that an extension of the time-frame to 2041 would provide interesting research opportunities, due to the feedback structures fully unfolding as a consequence of exceeding the desired level of congestion towards the end of the time horizon in this study. Such an extended simulation would need additional data, in particular related to population and income growth trends.

In general, we advocate a better and more comprehensive data collection for urban transport in India. This is the basis to set up and run computer simulation models and allows to benchmark cities against each other to share best-practices. The CMP guidelines are a firm basis to ensure that data is comparable and should continue to be used for newly commissioned studies. The indicators for 25 cities presented in this study are a first attempt to show the potential of such a data pool. Next to consolidation of existing mobility data, regular updates are of great importance. We showed this with the example of population projections, which are an important input for planning authorities and can vary significantly depending on the time they were carried out.

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Appendix

A-1: Key Indicators Derived from Examined Planning Documents (25 Indian cities)

City	POP [people]	AREA [km²]	HHS [people]	HHI [INR]	VOS [veh/1000]	PCTR [trips]	ATL [km]	Land Use Distribution: Residential	Commercial	Transport
Agra (2011)	2,230,882	520	4.50	13,200	232	1.15	4.9	50%	13%	11%
Amritsar (2014) [1]	2,014,626	1,394	5.50	17,392	309	1.20	5.6	52%	10%	17%
Bangalore (2010)*	10,300,000	8,005	4.20	11,230	282	1.28	10.1	n.A.	n.A	n.A
Chandigarh (2009)	2,117,497	114	4.50	22,857	280	1.32	6.1	38%	9%	7%
Chennai (2006)**	7,896,000	1,189	4.35	n.A.	201	1.32	n.A.	25%	8%	
Delhi (2011)	16,715,962	1,483	4.42	15,369	261	1.38	6.0	43%	10%	19%
Gangtok (2010)	94,145	77	5.07	n.A.	n.A.	0.96	n.A.	n.A.	n.A	n.A
Hyderabad (2011)*	9,409,184	7,204	4.40	14,000	275	1.19	n.A.	7%	3%	2%
Indore (2012)	2,290,608	505	3.70	16,075	n.A.	1.12	6.2	n.A.	n.A	n.A
Jabalpur (2005)** [2]	1,051,314	106	5.75	8,899	214	1.47	n.A.	52%	14%	15%
Jaipur (2011) [3]	3,558,378	2,939	5.40	9,280	316	1.06	6.5	46%	13%	16%
Kochi (2006)** [4]	605,335	95	4.16	n.A.	n.A.	0.77	n.A.	48%	5%	3%
Kolkatta (2008)	16,690,000	1,875	4.80	14,524	n.A.	1.40	n.A.	47%	13%	8%
Ludhiana (2011)	2,416,168	1,270	4.80	13,414	374	1.33	5.5	10%	4%	3%
Meerut (2011)	2,192,151	142	4.20		161	0.90	5.9	33%	14%	10%
Nashik (2008)	1,300,000	259	4.00	8,579	n.A.	1.68	7.4	27%	8%	8%
Patna (2009)	2,067,803	136	4.10	7,175	176	0.79	5.8	60%	7%	8%
Pune (2008)	5,310,000	1,219	3.10	11,500	n.A.	1.30	n.A.	n.A.	n.A	n.A
Rajkot (2008)	1,254,248	105	4.90	6,029	322	1.29	3.7	41%	8%	13%
Ranchi (2006)**	1,213,279	173	5.85	n.A.	140	2.25	n.A.	40%	15%	20%
Shillong (2010) [5]	318,393	27	5.00	14,000	112	1.50	3.5	49%	1%	14%
Surat (2008)	3,171,873	334	4.50	8,000	n.A.	1.13	5.0	n.A.	n.A	n.A
Varanasi (2006)** [6]	1,376,956	80	7.30	n.A.	246	1.13	4.9	38%	10%	9%
Vijayawada (2006)*	966,759	62	4.30	5,347	n.A.	1.36	4.2	28%	5%	16%
Visakhapatnam (2011)	1,746,000	534	4.00	n.A.	255	1.66	4.1	n.A.	n.A	n.A

* CTTS ** CDP   Reference area for Land Use Distribution: [1] 142 km² [2] 73 km² [3] 1464 km² [4] 330 km² [5] 55 km² [6] 116 km²

A-2: Full List of DUTM-i Model Variables (with Units and Type)

Nr.	Name	Unit	Type
1	Acceptable VO[ ]	Vehicles/pop.	Aux
2	alpha	Dmnl	Aux
3	Area	km^2	**Stock**
4	Average Daily Traffic Flow Q	PCU/day	Aux
5	Average Journey Speed	km/h	Aux
6	Average Trip Length[ ]	km	Aux
7	beta	Dmnl	Aux
8	Congestion Ratio	Dmnl	Aux
9	Daily Car Equivalent Vehicle km[ ]	PCU km	Aux
10	Daily motorized trips[ ]	Trips	Aux
11	Daily Public Passenger km	Passenger km	**Stock**
12	Daily Road Passenger km[ ]	Passenger km	**Stock**
13	Daily Total Passenger km	Passenger km	Aux
14	Daily Vehicle km[ ]	Vehicle km	Aux
15	Desired JS	km/h	Aux
16	DPPKM Growth	Passenger km/year	*Flow*
17	DRPKM Growth[ ]	Passenger km/year	*Flow*
18	Expected DPPKM	Passenger km	Aux
19	Expected DRPKM[ ]	Passenger km	Aux
20	Expected VO[ ]	Vehicles/pop	Aux
21	FINAL TIME	30	SETUP
22	Fractional Income Growth Rate	Dmnl	Aux
23	Fractional Population Growth Rate	Pop/year	Aux
24	Fractional TpV decrease rate[ ]	Dmnl	Aux
25	Fractional TpV increase rate[ ]	Dmnl	Aux
26	gamma	Dmnl	Aux
27	INITIAL TIME	0	SETUP
28	JS Adjustment Time	Years	Aux
29	JS Discrepancy	km/h	Aux
30	Motorised Trip Rate	Trips/pop	Aux
31	Motorized mode share	%	Aux
32	New Land Development	km^2/year	*Flow*
33	New Road Development	km/year	*Flow*
34	Occupancy Rate[ ]	People/vehicle	Aux
35	PCTR	Trips/pop	Aux
36	PCU Factor[ ]	Dmnl	Aux
37	Per Capita Income	2005 PPP USD	**Stock**
38	Population	People	**Stock**
39	Population Growth	People/year	*Flow*
40	Private Modal Share	%	Aux
41	Private Vehicle Trip Rate[ ]	Trips/pop	Aux

42	Private VO Fractional Decrease Rate[ ]	Dmnl	Aux
43	PT Trip rate	Trips/pop	Aux
44	Public Transport Modal Share	%	Aux
45	Qmax	PCU/hour	Aux
46	Quota Decrease[ ]	Vehicles/year	*Flow*
47	Quota Growth[ ]	Vehicles/year	*Flow*
48	Quota Increase[ ]	Vehicles/year	*Flow*
49	Real Income Growth	2005 PPP USD/year	*Flow*
50	Road Length	km	**Stock**
51	TIME STEP	1 (year)	SETUP
52	Total Daily Trips	Trips	Aux
53	TpV decrease[ ]	Trips /(vehicles*year)	*Flow*
54	TpV increase[ ]	Trips /(vehicles*year)	*Flow*
55	Travel Time[ ]	Minutes	Aux
56	Trips per Vehicle[ ]	Trips/vehicles	**Stock**
57	Urban Density	Population/km^2	Aux
58	Vehicle Fleet[ ]	Vehicles	Aux
59	Vehicle Ownership[ ]	Vehicle/pop.	**Stock**
60	Vehicle Quota[ ]	Vehicles	**Stock**
61	Vehicle Substitution factor	Vehicles/pop.	Aux
62	VO Adjustment Time	Years	Aux
63	VO Discrepancy[ ]	Vehicles/pop.	Aux
64	VO Growth[ ]	Vehicles/year	*Flow*
65	Time	Years	SETUP
66	Ref population	People	Aux
67	Ref Vehicle Fleet[ ]	Vehicles	Aux

[ ] … Variable with Subscript (*Transport Mode*)

A-3: Currency Unit Conversion from CMP Data for Vehicle Growth Model in DUTM-i

Dataset: Level of GDP per capita and productivity

Subject	GDP per head of population													
Measure	USD, constant prices, 2005 PPPs													
Unit	US Dollar, 2005													
Time	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Country i														
United States	40911,465	40901,303	41237,152	42004,959	43203,305	44236,587	44986,869	45350,19	44795,237	43169,629	43900,288	44280,576	44989,436	45665,431
India	2304,405	2354,978	2422,976	2548,563	2708,131	2912,114	3140,211	3408,072	3568,751	3697,271	4019,286	4277,112	4428,498	4575,39

Data extracted on 02 Feb 2015 15:05 UTC (GMT) from OECD.Stat

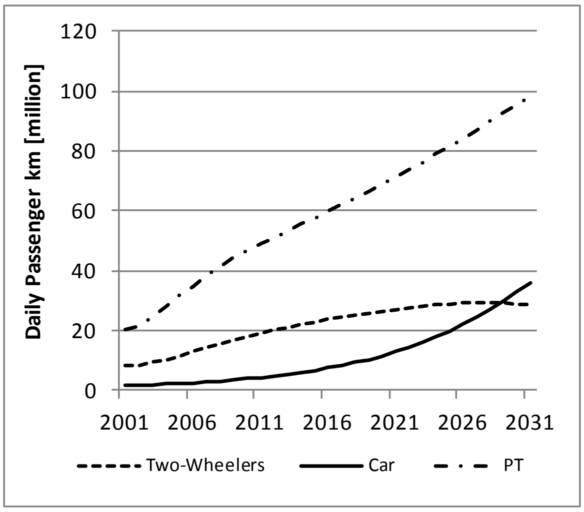
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Real Growth Rates	3,94%	2,19%	2,89%	5,18%	6,26%	7,53%	7,83%	8,53%	4,71%	3,60%	8,71%	6,41%	3,54%	3,32%
GDP per capita 1995 USD,PPP	21.875,4	22.355,5	**2300**[1]	24.193,2	25.707,9	27.644,3	29.809,6	32.352,4	33.877,7	35.097,7	38.154,6	40.602,1	42.039,2	43.433,6
GDP per capita current INR (IMF)	20.900,6	22.048,3	23.409,5	25.578,3	28.561,1	32.053,2	36.594,5	42.013,2	47.954,1	51.924,2	62.437,0	72.086,5	79.722,4	89.329,0
GDP per capita constant prices (IMF)	24.731,5	25.206,3	25.957,4	27.317,2	28.952,8	31.096,5	33.533,9	36.396,2	38.114,0	39.488,3	43.312,4	46.033,2	47.232,0	49.264,9
Exchange Rate 1995 USD PPP/current INR	1,0466	1,0139	0,9826	0,9458	0,9001	0,8625	0,8146	0,7701	0,7065	0,6759	0,6111	0,5632	0,5273	0,4862
Exchange Rate current INR/1995 USD PPP	0,9554	0,9863	1,0178	1,0573	1,1110	1,1595	1,2276	1,2986	1,4155	1,4794	1,6364	1,7754	1,8964	2,0567

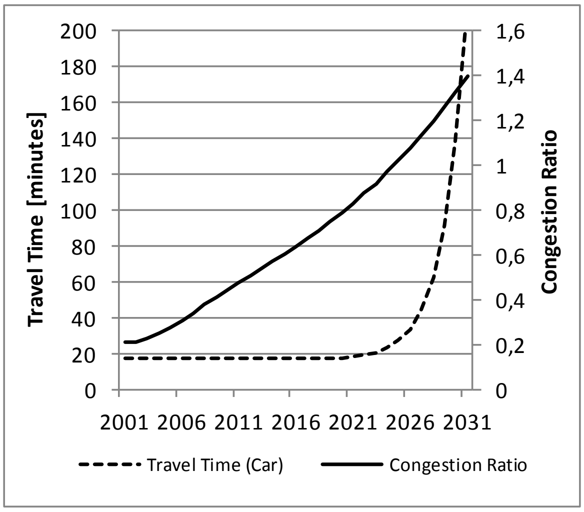
[1] Calibration (Reference) Value from Dargay et al. [2007]

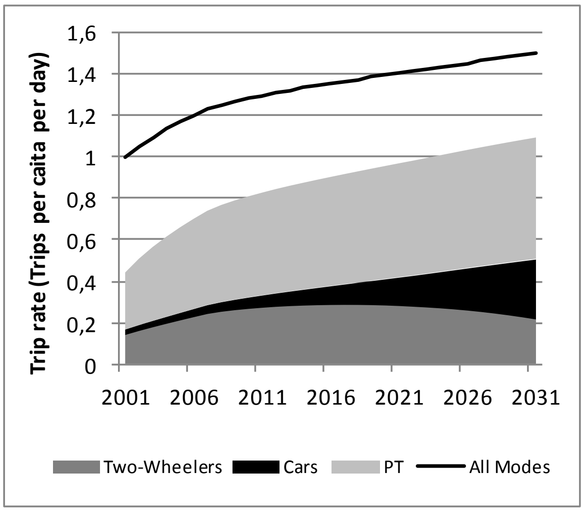
A-4: Standard Diagrams for Study Cities (Model Output)

a. Bangalore

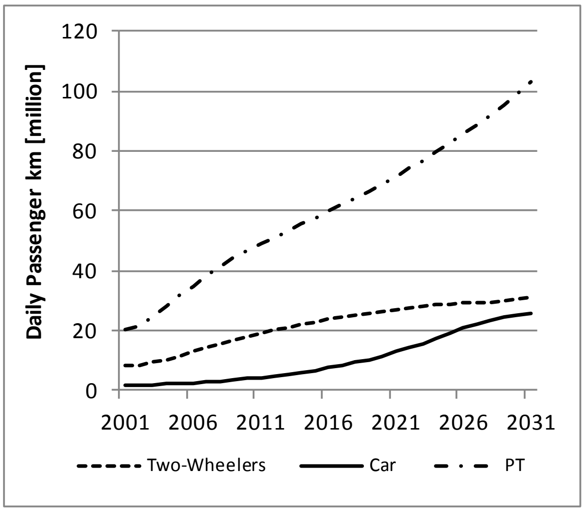
Base Scenario

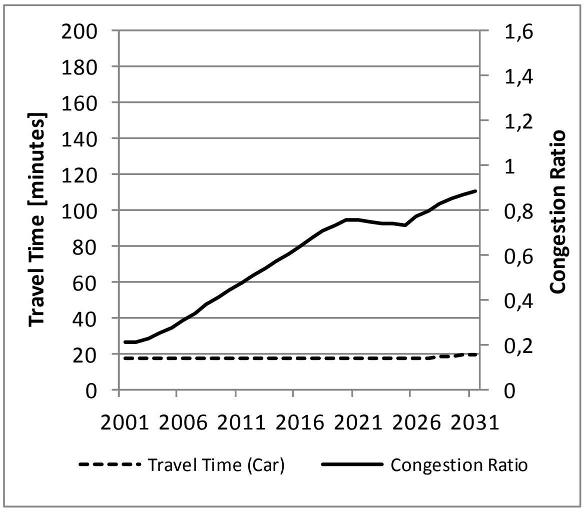


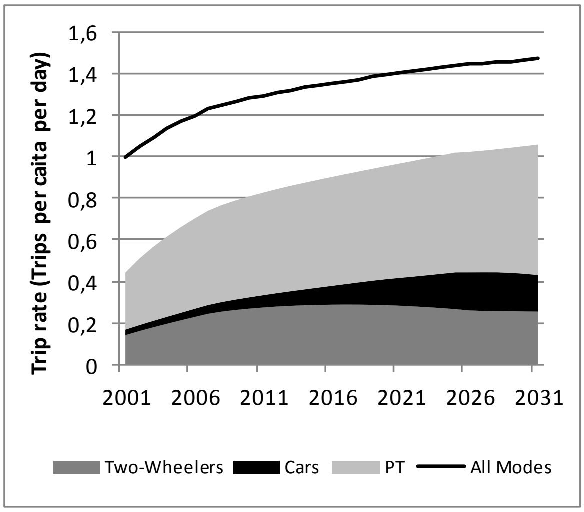




Trend Scenario

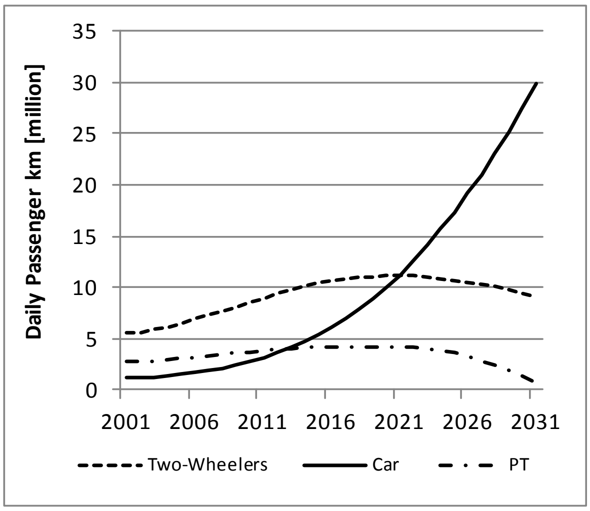


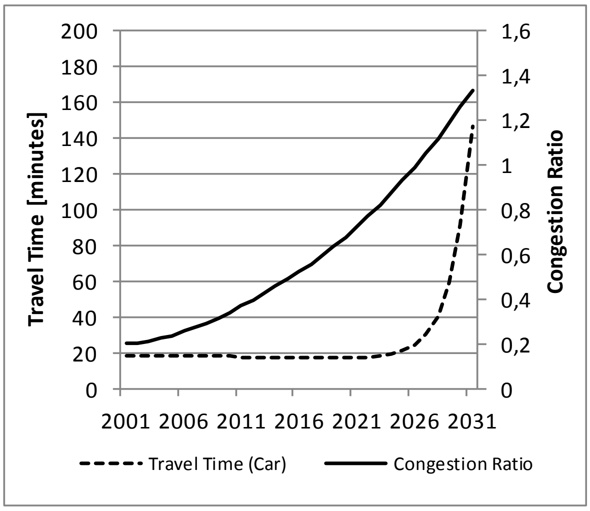


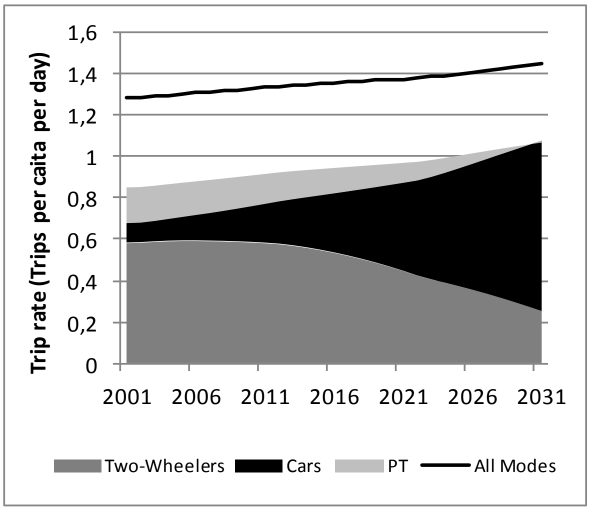


b. Chandigarh

Base Scenario







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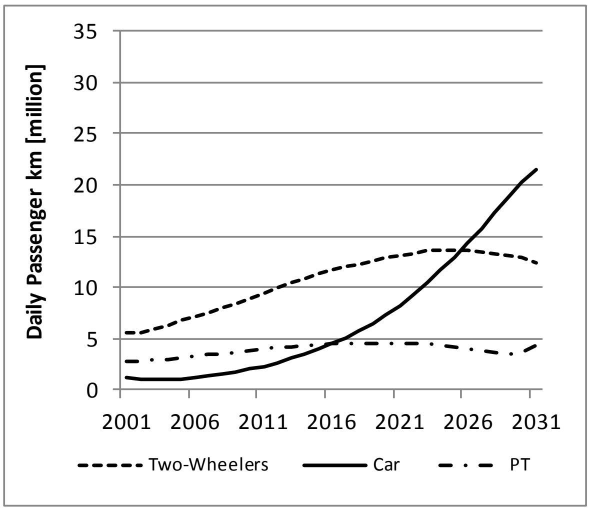
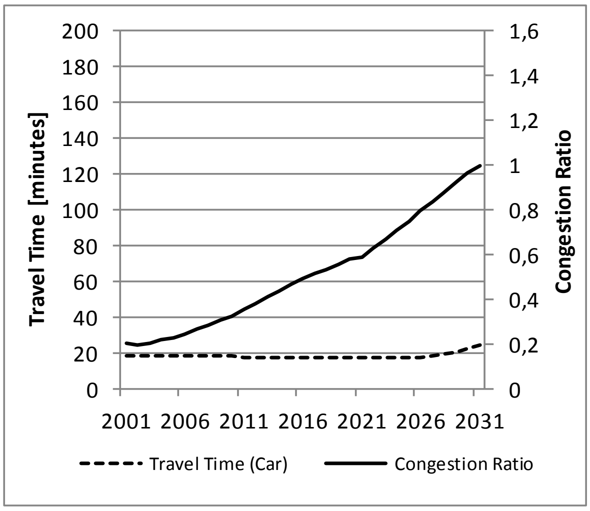
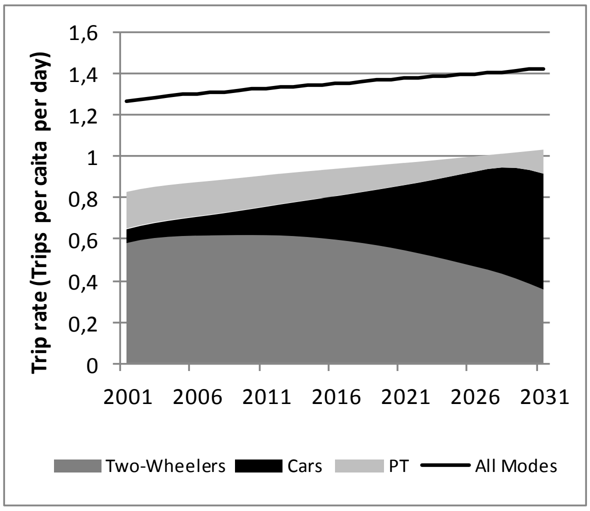
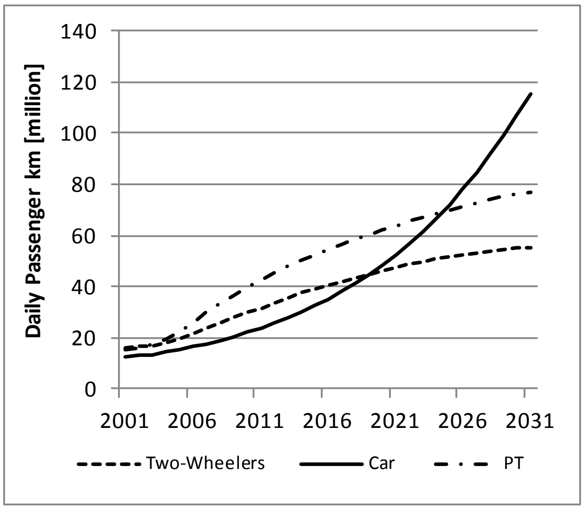


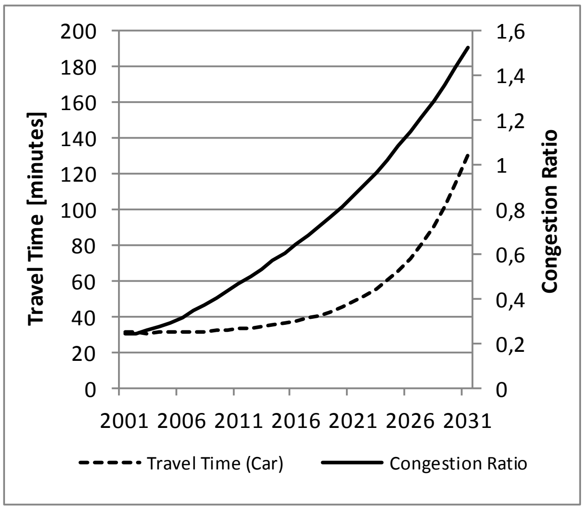


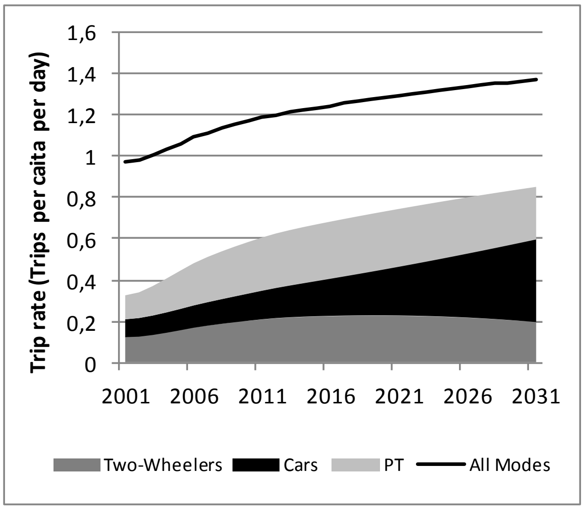


c. Delhi

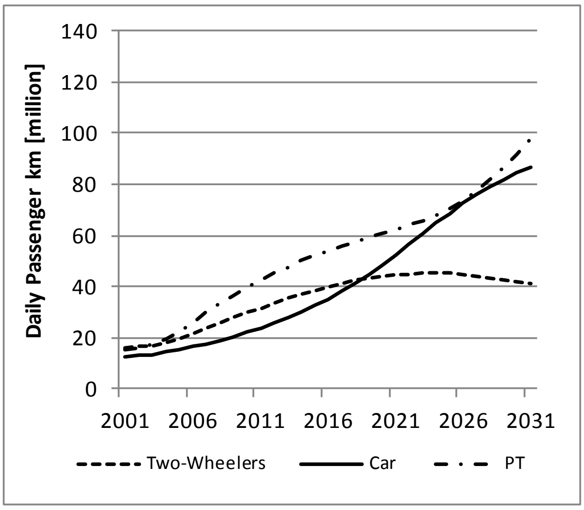
Base Scenario

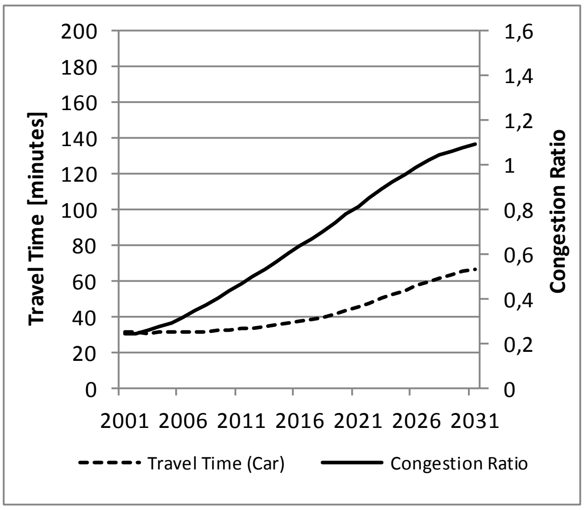


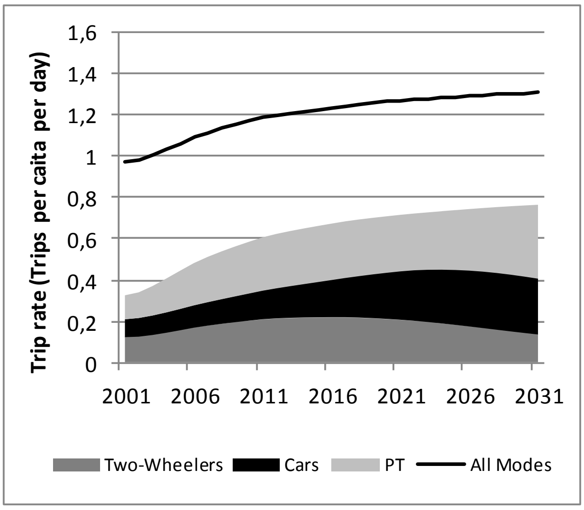




Trend Scenario

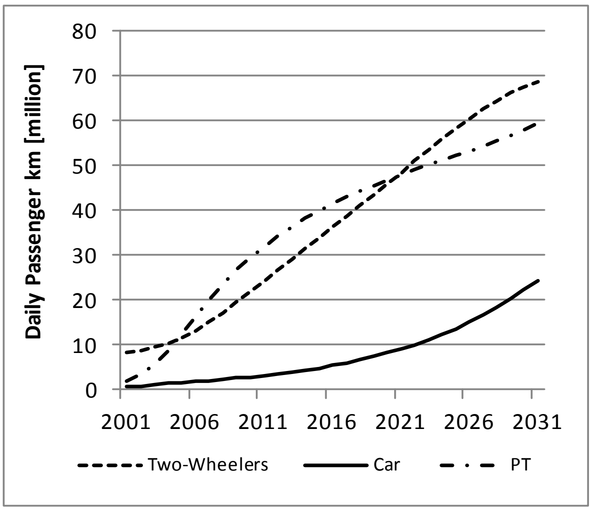


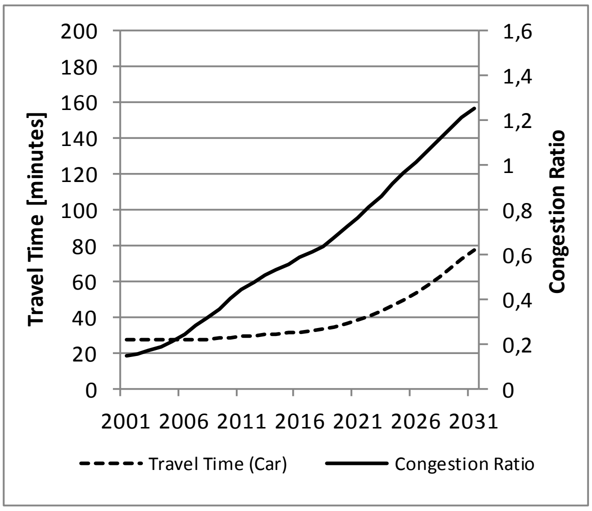


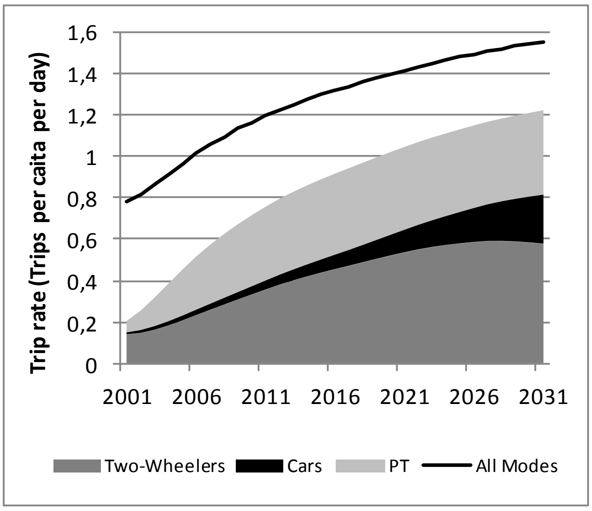


d. Hyderabad

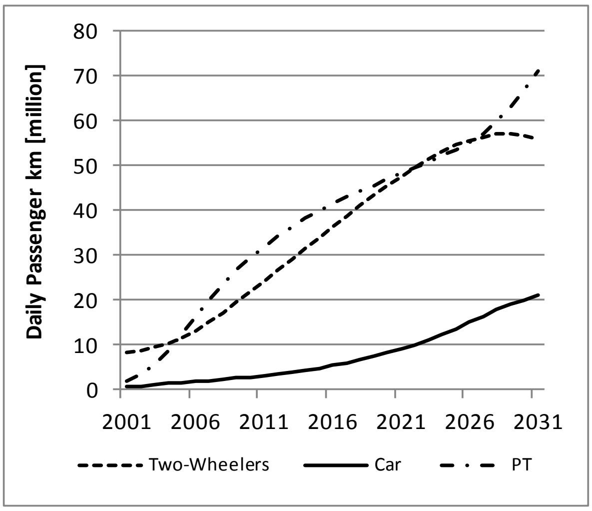
Base Scenario

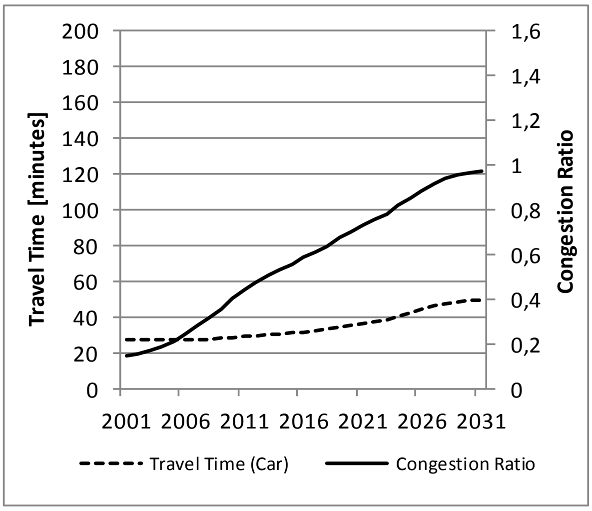


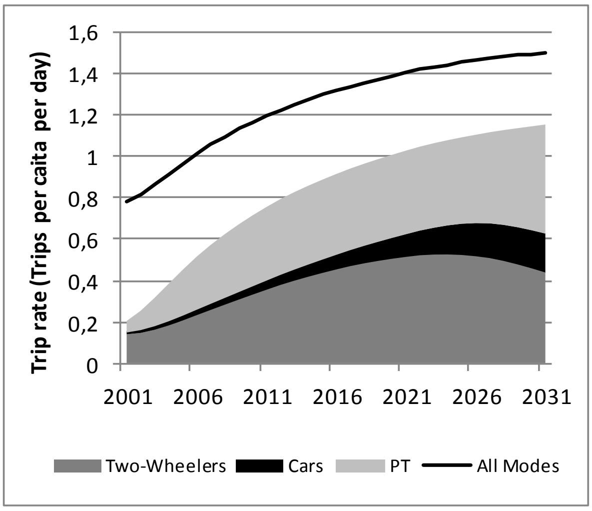




Trend Scenario

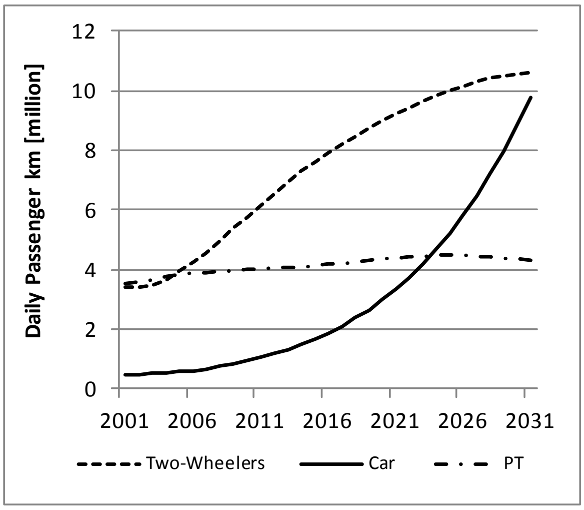


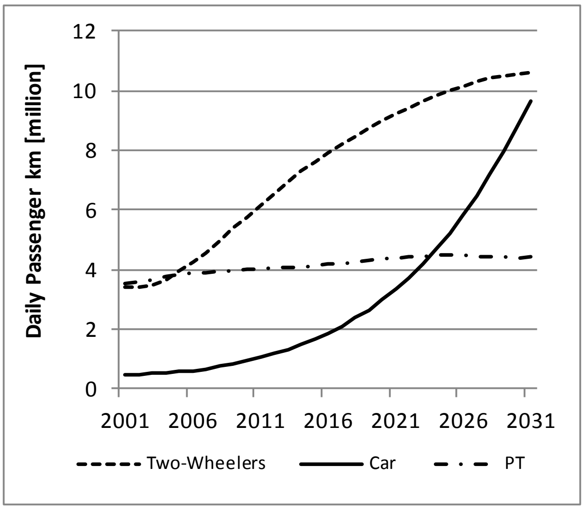


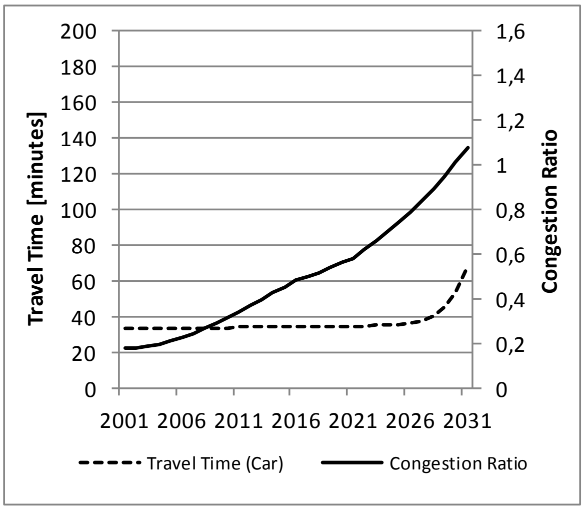


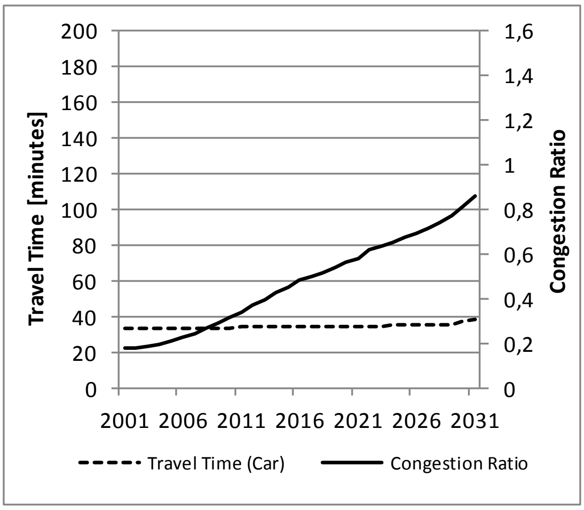
e. Indore

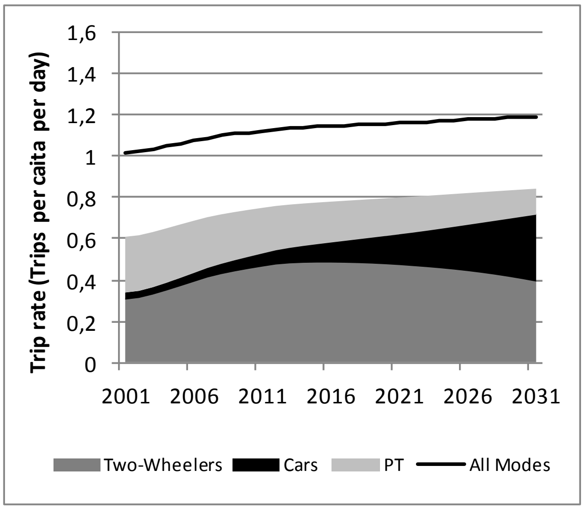
Base Scenario | **Trend Scenario**

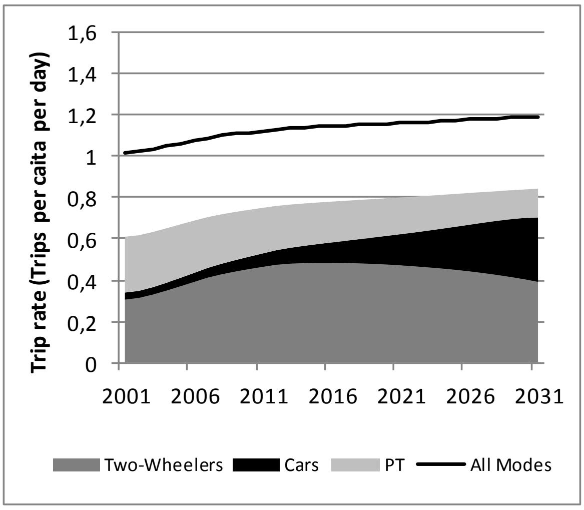






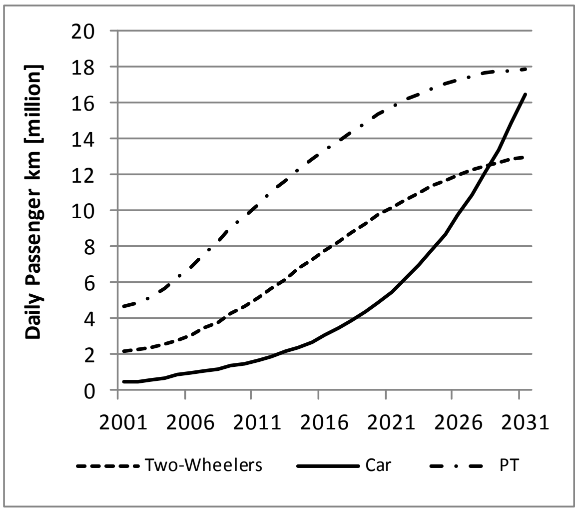


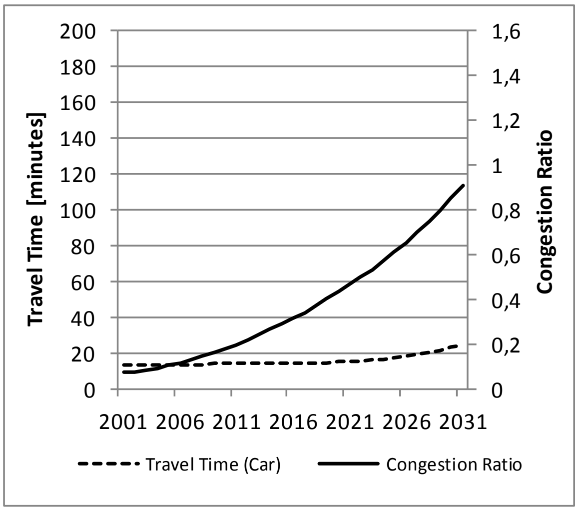


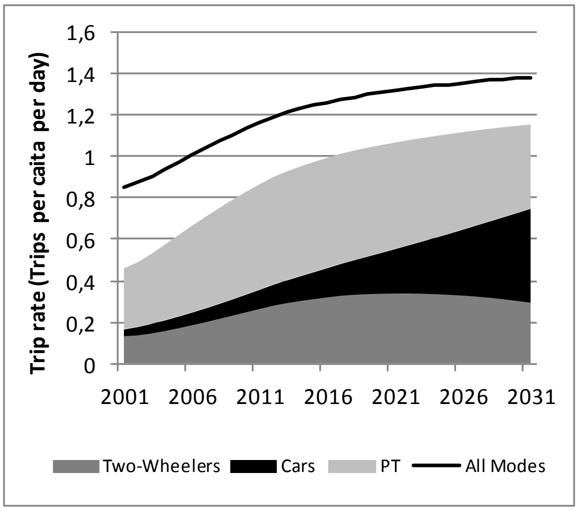


f. Jaipur

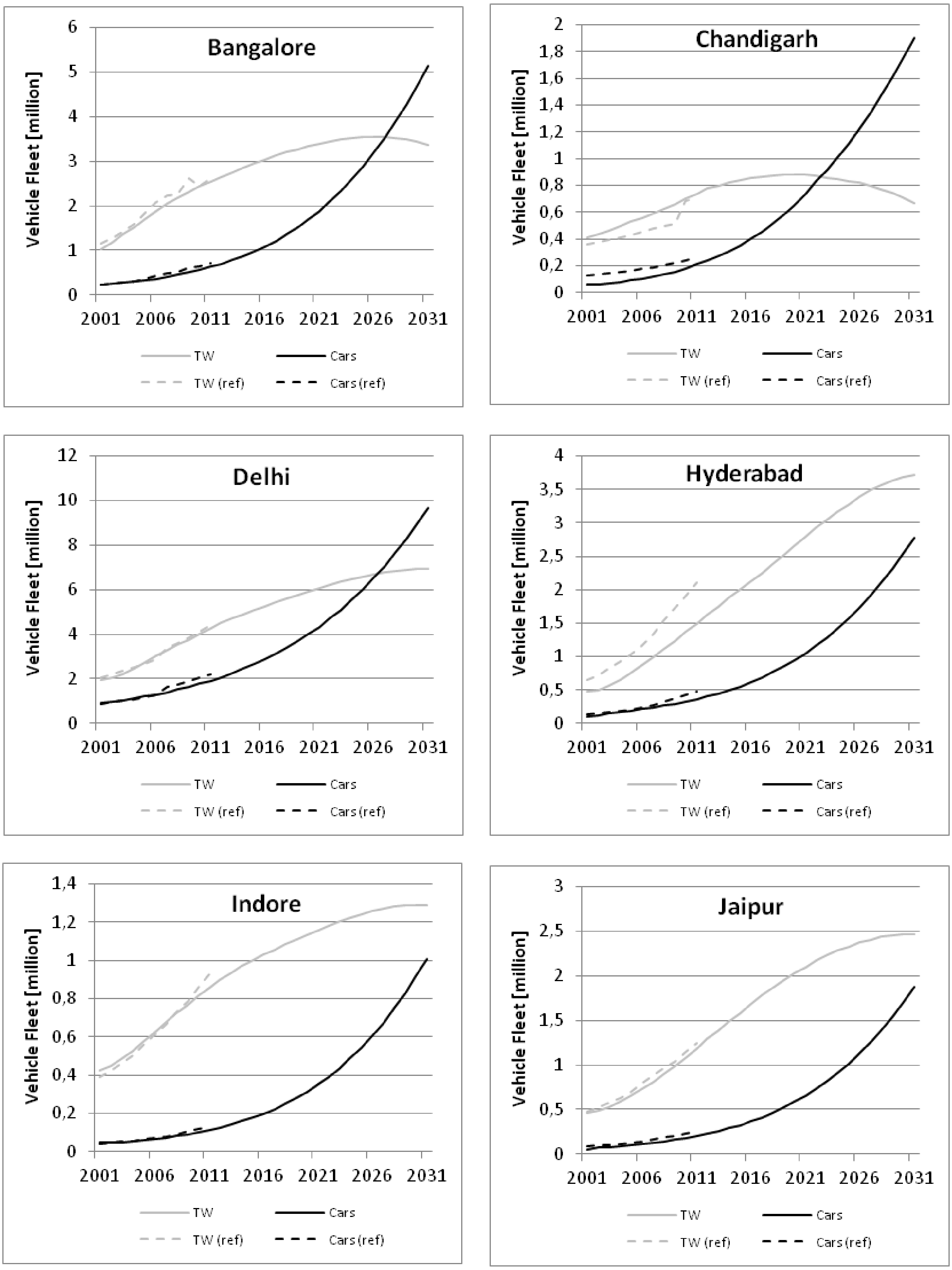
Base Scenario







A-5: Vehicle Fleet-size Model Output Compared to Reference Vehicle Registrations Data



A-6: Full DUTM-i Data Output for Example City (Indore)

Time	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Acceptable VO[TW]	0,260	0,266	0,280	0,296	0,313	0,331	0,348	0,361	0,373	0,382	0,391
Acceptable VO[Car]	0,027	0,027	0,028	0,030	0,032	0,034	0,037	0,040	0,044	0,048	0,052
alpha	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90
Area	132	132	132	132	132	132	146	160	174	188	202
Average Daily Traffic Flow Q	91	91	94	99	105	114	123	135	147	159	172
Average Journey Speed	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,4
Average Trip Length[TW]	6,7	6,7	6,7	6,6	6,6	6,6	6,6	6,7	6,7	6,8	6,8
Average Trip Length[Car]	9,2	9,2	9,2	9,1	9,1	9,1	9,2	9,2	9,2	9,3	9,3
Average Trip Length[PT]	8,4	8,3	8,3	8,3	8,3	8,3	8,3	8,4	8,4	8,4	8,5
beta	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24
Congestion Ratio	0,18	0,18	0,19	0,20	0,21	0,23	0,25	0,27	0,29	0,32	0,34
Daily Car Equivalent Vehicle km[TW]	739.130	739.195	758.209	797.524	852.611	918.846	992.871	1.079.526	1.167.544	1.254.087	1.339.195
Daily Car Equivalent Vehicle km[Car]	184.615	189.576	194.637	203.915	218.099	236.914	259.996	288.528	322.009	360.413	404.005
Daily motorized trips[TW]	507.416	535.288	578.313	629.428	685.436	744.921	807.281	862.723	915.232	966.852	1.018.611
Daily motorized trips[Car]	54.907	56.503	60.471	66.050	72.898	80.895	90.044	100.415	112.123	125.318	140.170
Daily motorized trips[PT]	438.983	450.843	460.791	468.380	473.482	476.144	476.439	477.597	478.947	479.992	480.400
Daily Public Passenger km	3.500.000	3.585.641	3.673.258	3.753.659	3.820.452	3.869.986	3.900.707	3.929.961	3.960.483	3.991.136	4.019.468
Daily Road Passenger km[TW]	3.400.000	3.400.295	3.487.762	3.668.612	3.922.010	4.226.694	4.567.205	4.965.819	5.370.700	5.768.799	6.160.298
Daily Road Passenger km[Car]	480.000	492.896	506.055	530.179	567.059	615.978	675.990	750.172	837.224	937.075	1.050.413
Daily Total Passenger km	7.380.000	7.478.832	7.667.075	7.952.449	8.309.521	8.712.657	9.143.902	9.645.952	10.168.407	10.697.010	11.230.179
Daily Vehicle km[TW]	1.478.261	1.478.389	1.516.418	1.595.049	1.705.222	1.837.693	1.985.741	2.159.052	2.335.087	2.508.174	2.678.391
Daily Vehicle km[Car]	184.615	189.576	194.637	203.915	218.099	236.914	259.996	288.528	322.009	360.413	404.005
Desired JS	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0
DPPKM Growth	85.641	87.617	80.401	66.793	49.533	30.722	29.254	30.522	30.653	28.332	23.529
DRPKM Growth[TW]	295	87.467	180.850	253.399	304.684	340.512	398.614	404.881	398.099	391.499	388.417
DRPKM Growth[Car]	12.896	13.159	24.124	36.880	48.919	60.013	74.182	87.052	99.851	113.339	128.011
Expected DPPKM	3.671.282	3.760.876	3.834.060	3.887.246	3.919.519	3.931.429	3.959.215	3.991.004	4.021.789	4.047.799	4.066.525
Expected DRPKM[TW]	3.400.590	3.575.228	3.849.462	4.175.409	4.531.377	4.907.717	5.364.433	5.775.581	6.166.899	6.551.797	6.937.131
Expected DRPKM[Car]	505.793	519.213	554.302	603.939	664.897	736.003	824.354	924.275	1.036.926	1.163.752	1.306.436
Expected VO[TW]	0,273	0,293	0,312	0,330	0,348	0,366	0,375	0,384	0,392	0,400	0,408
Expected VO[Car]	0,027	0,029	0,032	0,034	0,037	0,040	0,043	0,047	0,051	0,056	0,061
FINAL TIME	50										

Time	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Fractional Income Growth Rate	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%
Fractional Population Growth Rate	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%
Fractional TpV decrease rate[TW]											
Fractional TpV decrease rate[Car]											
Fractional TpV increase rate[TW]											
Fractional TpV increase rate[Car]											
gamma	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68
INITIAL TIME	0										
JS Adjustment Time	3	3	3	3	3	3	3	3	3	3	3
JS Discrepancy	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Motorised Trip Rate	0,61	0,62	0,63	0,65	0,67	0,69	0,70	0,72	0,73	0,74	0,75
Motorized mode share	60,2%	60,5%	61,3%	62,3%	63,2%	64,0%	64,9%	65,5%	66,0%	66,5%	66,9%
New Land Development	0	0	0	0	0	14	14	14	14	14	14
New Road Development	0	0	0	0	0	0	0	0	0	0	0
Occupancy Rate[TW]	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3
Occupancy Rate[Car]	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6
PCTR	1,01	1,02	1,03	1,05	1,06	1,07	1,09	1,10	1,11	1,11	1,12
PCU Factor[TW]	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
PCU Factor[Car]	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
PCU Factor[PT]	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0
Per Capita Income	2.507	2.607	2.712	2.820	2.933	3.050	3.172	3.299	3.431	3.568	3.711
Population	1.640.000	1.687.888	1.737.174	1.787.900	1.840.107	1.893.838	1.949.138	2.006.053	2.064.629	2.124.917	2.186.964
Population Growth	47.888	49.286	50.725	52.207	53.731	55.300	56.915	58.577	60.287	62.048	63.859
Private Modal Share	52,6%	52,1%	52,1%	52,8%	54,0%	55,6%	57,3%	59,3%	61,1%	62,7%	64,2%
Private Vehicle Trip Rate[TW]	0,31	0,32	0,33	0,35	0,37	0,39	0,41	0,43	0,44	0,46	0,47
Private Vehicle Trip Rate[Car]	0,03	0,03	0,03	0,04	0,04	0,04	0,05	0,05	0,05	0,06	0,06
Private VO Fractional Decrease Rate[TW]											
Private VO Fractional Decrease Rate[Car]											
PT Trip rate	0,27	0,27	0,27	0,26	0,26	0,25	0,24	0,24	0,23	0,23	0,22
Public Transport Modal Share	47,4%	47,9%	47,9%	47,2%	46,0%	44,4%	42,7%	40,7%	38,9%	37,3%	35,8%
Qmax	500	500	500	500	500	500	500	500	500	500	500
Quota Decrease[Car]											

Time	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Quota Growth[Car]											
Quota Increase[Car]											
Real Income Growth	100	104	108	113	117	122	127	132	137	143	148
Road Length	270	270	270	270	270	270	270	270	270	270	270
SAVEPER	1	1	1	1	1	1	1	1	1	1	1
Switch FL1	0	0	0	0	0	0	0	0	0	0	0
Switch FL2a	0	0	0	0	0	0	0	0	0	0	0
Switch FL2b[TW]	0	0	0	0	0	0	0	0	0	0	0
Switch FL2b[Car]	0	0	0	0	0	0	0	0	0	0	0
Switch FL2b[PT]	0	0	0	0	0	0	0	0	0	0	0
Switch FL2c	0	0	0	0	0	0	0	0	0	0	0
Switch FL3	0	0	0	0	0	0	0	0	0	0	0
TIME STEP	1										
Total Daily Trips	1.664.495	1.722.305	1.792.773	1.869.623	1.950.086	2.033.054	2.118.146	2.200.448	2.282.596	2.365.905	2.451.067
TpV decrease[TW]											
TpV decrease[Car]											
TpV increase[TW]											
TpV increase[Car]											
Travel Time[TW]	25	24	24	24	24	24	24	24	25	25	25
Travel Time[Car]	34	34	34	33	33	33	33	34	34	34	34
Travel Time[PT]	31	31	30	30	30	30	30	31	31	31	31
Trips per Vehicle[TW]	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19
Trips per Vehicle[Car]	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24
Urban Density	12.424	12.787	13.160	13.545	13.940	14.347	13.350	12.538	11.866	11.303	10.827
Vehicle Fleet[TW]	426.400	449.822	485.978	528.931	575.997	625.984	678.388	724.977	769.103	812.481	855.976
Vehicle Fleet[Car]	44.280	45.567	48.767	53.266	58.789	65.238	72.616	80.979	90.422	101.063	113.040
Vehicle Ownership[TW]	0,260	0,266	0,280	0,296	0,313	0,331	0,348	0,361	0,373	0,382	0,391
Vehicle Ownership[Car]	0,027	0,027	0,028	0,030	0,032	0,034	0,037	0,040	0,044	0,048	0,052
Vehicle Quota[Car]											
Vehicle Substitution factor	0,30	0,32	0,34	0,36	0,38	0,40	0,41	0,42	0,44	0,45	0,46
VO Adjustment Time	3	3	3	3	3	3	3	3	3	3	3

Time	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
VO Discrepancy[TW]											
VO Discrepancy[Car]											
VO Growth[TW]	0,007	0,013	0,016	0,017	0,018	0,018	0,013	0,011	0,010	0,009	0,008
VO Growth[Car]	0,000	0,001	0,002	0,002	0,002	0,003	0,003	0,003	0,004	0,004	0,005
Ref population	1.720.000	1.770.224	1.821.915	1.875.114	1.929.868	1.986.220	2.044.218	2.103.909	2.165.343	2.228.571	2.293.645
Ref Vehicle Fleet[TW]	392.000	425.780	461.458	504.587	554.303	608.547	666.261	728.228	785.265	854.332	930.332
Ref Vehicle Fleet[Car]	43.200	46.649	50.523	55.836	62.508	69.426	78.816	91.249	105.007	120.495	132.003

Time	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Acceptable VO[TW]	0,400	0,404	0,407	0,408	0,408	0,407	0,405	0,404	0,401	0,398	0,394
Acceptable VO[Car]	0,056	0,061	0,067	0,072	0,079	0,086	0,093	0,102	0,111	0,120	0,131
alpha	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90
Area	216	230	244	258	272	286	300	314	328	342	349
Average Daily Traffic Flow Q	185	199	212	226	241	250	259	269	280	291	309
Average Journey Speed	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,4	16,3
Average Trip Length[TW]	6,8	6,9	6,9	6,9	6,9	6,9	7,0	7,0	7,0	7,0	7,0
Average Trip Length[Car]	9,4	9,4	9,4	9,4	9,4	9,5	9,5	9,5	9,5	9,5	9,5
Average Trip Length[PT]	8,5	8,5	8,5	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6
beta	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24
Congestion Ratio	0,37	0,40	0,42	0,45	0,48	0,50	0,52	0,54	0,56	0,58	0,62
Daily Car Equivalent Vehicle km[TW]	1.423.634	1.508.149	1.586.070	1.657.115	1.722.660	1.784.107	1.842.446	1.898.229	1.951.665	2.002.715	2.051.169
Daily Car Equivalent Vehicle km[Car]	453.240	508.713	571.129	641.289	720.090	808.517	907.645	1.018.642	1.142.762	1.281.344	1.435.811
Daily motorized trips[TW]	1.071.005	1.114.596	1.153.561	1.189.962	1.224.762	1.258.348	1.290.800	1.322.027	1.351.844	1.380.002	1.406.213
Daily motorized trips[Car]	156.877	175.658	196.757	220.440	246.998	276.748	310.030	347.209	388.674	434.834	486.117
Daily motorized trips[PT]	479.954	482.593	486.756	491.561	496.517	501.339	505.859	509.962	513.568	516.610	519.036
Daily Public Passenger km	4.042.997	4.059.652	4.085.251	4.121.232	4.164.650	4.211.985	4.260.303	4.307.435	4.351.832	4.392.388	4.428.284
Daily Road Passenger km[TW]	6.548.715	6.937.486	7.295.924	7.622.729	7.924.235	8.206.893	8.475.250	8.731.854	8.977.660	9.212.489	9.435.379
Daily Road Passenger km[Car]	1.178.425	1.322.654	1.484.934	1.667.352	1.872.234	2.102.143	2.359.878	2.648.469	2.971.180	3.331.495	3.733.109
Daily Total Passenger km	11.770.136	12.319.791	12.866.108	13.411.312	13.961.119	14.521.020	15.095.431	15.687.758	16.300.672	16.936.372	17.596.772
Daily Vehicle km[TW]	2.847.267	3.016.298	3.172.141	3.314.230	3.445.320	3.568.214	3.684.892	3.796.458	3.903.331	4.005.430	4.102.339
Daily Vehicle km[Car]	453.240	508.713	571.129	641.289	720.090	808.517	907.645	1.018.642	1.142.762	1.281.344	1.435.811
Desired JS	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0
DPPKM Growth	16.655	25.599	35.981	43.419	47.335	48.318	47.132	44.397	40.557	35.896	26.793
DRPKM Growth[TW]	388.771	358.438	326.805	301.506	282.658	268.358	256.605	245.807	234.829	222.890	198.440
DRPKM Growth[Car]	144.229	162.280	182.418	204.882	229.909	257.735	288.591	322.711	360.315	401.614	442.988
Expected DPPKM	4.076.307	4.110.850	4.157.212	4.208.069	4.259.319	4.308.621	4.354.567	4.396.228	4.432.945	4.464.179	4.481.870
Expected DRPKM[TW]	7.326.257	7.654.362	7.949.534	8.225.742	8.489.550	8.743.608	8.988.459	9.223.467	9.447.318	9.658.269	9.832.259
Expected DRPKM[Car]	1.466.883	1.647.214	1.849.769	2.077.116	2.332.053	2.617.613	2.937.061	3.293.891	3.691.810	4.134.723	4.619.086
Expected VO[TW]	0,409	0,409	0,408	0,408	0,406	0,404	0,402	0,398	0,394	0,390	0,385
Expected VO[Car]	0,066	0,072	0,078	0,085	0,093	0,101	0,110	0,120	0,130	0,141	0,153
FINAL TIME											

Time	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Fractional Income Growth Rate	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%
Fractional Population Growth Rate	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%
Fractional TpV decrease rate[TW]											
Fractional TpV decrease rate[Car]											
Fractional TpV increase rate[TW]											
Fractional TpV increase rate[Car]											
gamma	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68
INITIAL TIME											
JS Adjustment Time	3	3	3	3	3	3	3	3	3	3	3
JS Discrepancy	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Motorised Trip Rate	0,76	0,77	0,77	0,78	0,78	0,78	0,79	0,79	0,80	0,80	0,80
Motorized mode share	67,3%	67,6%	67,8%	68,0%	68,2%	68,3%	68,5%	68,7%	68,8%	69,0%	69,2%
New Land Development	14	14	14	14	14	14	14	14	14	7	7
New Road Development	0	0	0	0	6	6	6	6	6	0	0
Occupancy Rate[TW]	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3
Occupancy Rate[Car]	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6
PCTR	1,13	1,13	1,14	1,14	1,14	1,15	1,15	1,15	1,16	1,16	1,16
PCU Factor[TW]	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
PCU Factor[Car]	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
PCU Factor[PT]	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0
Per Capita Income	3.859	4.014	4.174	4.341	4.515	4.696	4.883	5.079	5.282	5.493	5.713
Population	2.250.823	2.316.547	2.384.191	2.453.809	2.525.460	2.599.204	2.675.100	2.753.213	2.833.607	2.916.348	3.001.506
Population Growth	65.724	67.643	69.618	71.651	73.743	75.897	78.113	80.394	82.741	85.157	87.644
Private Modal Share	65,7%	67,0%	68,2%	69,3%	70,2%	71,0%	71,8%	72,5%	73,3%	74,1%	74,8%
Private Vehicle Trip Rate[TW]	0,48	0,48	0,48	0,48	0,48	0,48	0,48	0,48	0,48	0,47	0,47
Private Vehicle Trip Rate[Car]	0,07	0,08	0,08	0,09	0,10	0,11	0,12	0,13	0,14	0,15	0,16
Private VO Fractional Decrease Rate[TW]											
Private VO Fractional Decrease Rate[Car]											
PT Trip rate	0,21	0,21	0,20	0,20	0,20	0,19	0,19	0,19	0,18	0,18	0,17
Public Transport Modal Share	34,3%	33,0%	31,8%	30,7%	29,8%	29,0%	28,2%	27,5%	26,7%	25,9%	25,2%
Qmax	500	500	500	500	500	500	500	500	500	500	500
Quota Decrease[Car]											

Time	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Quota Growth[Car]											
Quota Increase[Car]											
Real Income Growth	154	161	167	174	181	188	195	203	211	220	229
Road Length	270	270	270	270	270	276	282	288	294	300	300
SAVEPER	1	1	1	1	1	1	1	1	1	1	1
Switch FL1	0	0	0	0	0	0	0	0	0	0	0
Switch FL2a	0	0	0	0	0	0	0	0	0	0	0
Switch FL2b[TW]	0	0	0	0	0	0	0	0	0	0	0
Switch FL2b[Car]	0	0	0	0	0	0	0	0	0	0	0
Switch FL2b[PT]	0	0	0	0	0	0	0	0	0	0	0
Switch FL2c	0	0	0	0	0	0	0	0	0	0	0
Switch FL3	0	0	0	0	0	0	0	0	0	0	0
TIME STEP											
Total Daily Trips	2.538.469	2.624.124	2.710.237	2.797.940	2.887.846	2.980.307	3.075.548	3.173.727	3.274.971	3.379.388	3.487.083
TpV decrease[TW]											
TpV decrease[Car]											
TpV increase[TW]											
TpV increase[Car]											
Travel Time[TW]	25	25	25	25	25	25	26	26	26	26	26
Travel Time[Car]	34	34	34	34	35	35	35	35	35	35	35
Travel Time[PT]	31	31	31	31	31	31	32	32	32	32	32
Trips per Vehicle[TW]	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19
Trips per Vehicle[Car]	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24
Urban Density	10.420	10.072	9.771	9.511	9.285	9.088	8.917	8.768	8.639	8.527	8.600
Vehicle Fleet[TW]	900.004	936.635	969.379	999.968	1.029.212	1.057.435	1.084.705	1.110.947	1.136.003	1.159.665	1.181.692
Vehicle Fleet[Car]	126.514	141.660	158.675	177.774	199.192	223.184	250.024	280.007	313.447	350.673	392.029
Vehicle Ownership[TW]	0,400	0,404	0,407	0,408	0,408	0,407	0,405	0,404	0,401	0,398	0,394
Vehicle Ownership[Car]	0,056	0,061	0,067	0,072	0,079	0,086	0,093	0,102	0,111	0,120	0,131
Vehicle Quota[Car]											
Vehicle Substitution factor	0,47	0,47	0,47	0,48	0,49	0,49	0,50	0,50	0,50	0,51	0,52
VO Adjustment Time	3	3	3	3	3	3	3	3	3	3	3

Time	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
VO Discrepancy[TW]											
VO Discrepancy[Car]											
VO Growth[TW]	0,004	0,002	0,001	0,000	-0,001	-0,001	-0,002	-0,003	-0,003	-0,004	-0,004
VO Growth[Car]	0,005	0,005	0,006	0,006	0,007	0,008	0,008	0,009	0,010	0,010	0,011
Ref population											
Ref Vehicle Fleet[TW]											
Ref Vehicle Fleet[Car]											

Time	2023	2024	2025	2026	2027	2028	2029	2030	2031
Acceptable VO[TW]	0,390	0,385	0,380	0,374	0,236	0,178	0,119	0,058	-0,004
Acceptable VO[Car]	0,142	0,154	0,166	0,180	0,142	0,137	0,133	0,129	0,126
alpha	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90	-5,90
Area	356	363	370	377	384	391	398	405	412
Average Daily Traffic Flow Q	328	348	370	393	419	445	474	505	537
Average Journey Speed	16,3	16,1	15,9	15,6	15,0	14,1	12,6	10,6	8,2
Average Trip Length[TW]	7,0	7,0	7,0	7,0	7,0	6,9	6,9	6,9	6,9
Average Trip Length[Car]	9,5	9,5	9,5	9,5	9,5	9,5	9,4	9,4	9,4
Average Trip Length[PT]	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6
beta	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24	-0,24
Congestion Ratio	0,66	0,70	0,74	0,79	0,84	0,89	0,95	1,01	1,07
Daily Car Equivalent Vehicle km[TW]	2.094.309	2.134.380	2.171.657	2.205.712	2.235.913	2.261.608	2.282.180	2.297.063	2.305.749
Daily Car Equivalent Vehicle km[Car]	1.606.191	1.794.524	2.002.621	2.232.186	2.484.858	2.762.216	3.065.772	3.396.944	3.757.025
Daily motorized trips[TW]	1.431.999	1.456.239	1.478.184	1.497.275	1.513.055	1.525.128	1.533.140	1.536.775	1.535.759
Daily motorized trips[Car]	542.964	605.828	675.165	751.428	835.059	926.480	1.026.082	1.134.218	1.251.188
Daily motorized trips[PT]	519.886	519.476	517.950	515.367	511.751	507.104	501.433	494.744	487.056
Daily Public Passenger km	4.455.077	4.470.432	4.474.552	4.468.179	4.451.958	4.426.319	4.391.515	4.347.706	4.295.020
Daily Road Passenger km[TW]	9.633.819	9.818.148	9.989.622	10.146.274	10.285.201	10.403.398	10.498.027	10.566.488	10.606.446
Daily Road Passenger km[Car]	4.176.097	4.665.761	5.206.814	5.803.684	6.460.629	7.181.761	7.971.007	8.832.054	9.768.265
Daily Total Passenger km	18.264.994	18.954.340	19.670.988	20.418.136	21.197.788	22.011.478	22.860.548	23.746.248	24.669.732
Daily Vehicle km[TW]	4.188.617	4.268.760	4.343.314	4.411.424	4.471.827	4.523.217	4.564.360	4.594.126	4.611.499
Daily Vehicle km[Car]	1.606.191	1.794.524	2.002.621	2.232.186	2.484.858	2.762.216	3.065.772	3.396.944	3.757.025
Desired JS	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0
DPPKM Growth	15.355	4.121	-6.373	-16.221	-25.639	-34.804	-43.810	-52.686	-61.400
DRPKM Growth[TW]	184.329	171.474	156.652	138.927	118.198	94.629	68.461	39.958	9.405
DRPKM Growth[Car]	489.664	541.053	596.870	656.945	721.132	789.247	861.048	936.211	1.014.321
Expected DPPKM	4.485.787	4.478.673	4.461.806	4.435.738	4.400.681	4.356.711	4.303.896	4.242.334	4.172.221
Expected DRPKM[TW]	10.002.477	10.161.096	10.302.926	10.424.128	10.521.596	10.592.656	10.634.949	10.646.403	10.625.255
Expected DRPKM[Car]	5.155.425	5.747.867	6.400.553	7.117.574	7.902.892	8.760.254	9.693.102	10.704.476	11.796.907
Expected VO[TW]	0,380	0,374	0,368	0,360	0,352	0,343	0,333	0,322	0,311
Expected VO[Car]	0,166	0,179	0,193	0,209	0,225	0,241	0,259	0,277	0,296
FINAL TIME									

Time	2023	2024	2025	2026	2027	2028	2029	2030	2031
Fractional Income Growth Rate	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%
Fractional Population Growth Rate	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%	2,9%
Fractional TpV decrease rate[TW]									
Fractional TpV decrease rate[Car]									
Fractional TpV increase rate[TW]									
Fractional TpV increase rate[Car]									
gamma	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68	0,68
INITIAL TIME									
JS Adjustment Time	3	3	3	3	3	3	3	3	3
JS Discrepancy	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Motorised Trip Rate	0,81	0,81	0,82	0,82	0,83	0,83	0,83	0,84	0,84
Motorized mode share	69,3%	69,5%	69,7%	69,9%	70,0%	70,2%	70,4%	70,5%	70,7%
New Land Development	7	7	7	7	7	7	7	7	7
New Road Development	0	0	0	0	0	0	0	0	0
Occupancy Rate[TW]	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3
Occupancy Rate[Car]	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6
PCTR	1,17	1,17	1,17	1,18	1,18	1,18	1,18	1,19	1,19
PCU Factor[TW]	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
PCU Factor[Car]	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
PCU Factor[PT]	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0
Per Capita Income	5.941	6.179	6.426	6.683	6.951	7.229	7.518	7.818	8.131
Population	3.089.150	3.179.353	3.272.190	3.367.738	3.466.076	3.567.285	3.671.450	3.778.656	3.888.993
Population Growth	90.203	92.837	95.548	98.338	101.209	104.165	107.206	110.337	113.559
Private Modal Share	75,6%	76,4%	77,3%	78,1%	79,0%	79,9%	80,8%	81,7%	82,6%
Private Vehicle Trip Rate[TW]	0,46	0,46	0,45	0,44	0,44	0,43	0,42	0,41	0,39
Private Vehicle Trip Rate[Car]	0,18	0,19	0,21	0,22	0,24	0,26	0,28	0,30	0,32
Private VO Fractional Decrease Rate[TW]									
Private VO Fractional Decrease Rate[Car]									
PT Trip rate	0,17	0,16	0,16	0,15	0,15	0,14	0,14	0,13	0,13
Public Transport Modal Share	24,4%	23,6%	0,23	0,22	0,21	0,20	0,19	0,18	0,17
Qmax	500	500	500	500	500	500	500	500	500
Quota Decrease[Car]									

Time	2023	2024	2025	2026	2027	2028	2029	2030	2031
Quota Growth[Car]									
Quota Increase[Car]									
Real Income Growth	238	247	257	267	278	289	301	313	325
Road Length	300	300	300	300	300	300	300	300	300
SAVEPER	1	1	1	1	1	1	1	1	1
Switch FL1	0	0	0	0	0	0	0	0	0
Switch FL2a	0	0	0	0	0	0	0	0	0
Switch FL2b[TW]	0	0	0	0	0	0	0	0	0
Switch FL2b[Car]	0	0	0	0	0	0	0	0	0
Switch FL2b[PT]	0	0	0	0	0	0	0	0	0
Switch FL2c	0	0	0	0	0	0	0	0	0
Switch FL3	0	0	0	0	0	0	0	0	0
TIME STEP									
Total Daily Trips	3.598.860	3.714.489	3.833.898	3.957.095	4.084.129	4.215.067	4.349.987	4.488.970	4.632.100
TpV decrease[TW]									
TpV decrease[Car]									
TpV increase[TW]									
TpV increase[Car]									
Travel Time[TW]	26	26	26	27	28	30	33	39	50
Travel Time[Car]	35	35	36	36	38	40	45	53	69
Travel Time[PT]	32	32	32	33	34	37	41	49	62
Trips per Vehicle[TW]	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19	1,19
Trips per Vehicle[Car]	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24
Urban Density	8.677	8.759	8.844	8.933	9.026	9.123	9.225	9.330	9.439
Vehicle Fleet[TW]	1.203.361	1.223.731	1.242.171	1.258.214	1.271.475	1.281.620	1.288.353	1.291.407	1.290.554
Vehicle Fleet[Car]	437.874	488.571	544.488	605.990	673.435	747.161	827.486	914.692	1.009.022
Vehicle Ownership[TW]	0,390	0,385	0,380	0,374	0,367	0,359	0,351	0,342	0,332
Vehicle Ownership[Car]	0,142	0,154	0,166	0,180	0,194	0,209	0,225	0,242	0,259
Vehicle Quota[Car]									
Vehicle Substitution factor	0,52	0,53	0,53	0,54	0,55	0,55	0,56	0,56	0,57
VO Adjustment Time	3	3	3	3	3	3	3	3	3

Time	2023	2024	2025	2026	2027	2028	2029	2030	2031
VO Discrepancy[TW]									
VO Discrepancy[Car]									
VO Growth[TW]	-0,005	-0,005	-0,006	-0,007	-0,008	-0,008	-0,009	-0,010	-0,011
VO Growth[Car]	0,012	0,013	0,014	0,014	0,015	0,016	0,017	0,017	0,018
Ref population									
Ref Vehicle Fleet[TW]									
Ref Vehicle Fleet[Car]									

A-7: VENSIM Source Code for DUTM-i (Indore, excl. Lookup Tables)

```
Quota Decrease[Car]=
        STEP(5000,25) - STEP(5000,30)
        ~               |

Switch FL2c=
        0
        ~       STEP (1,20)
                        |

Quota Increase[Car]=
        0
        ~               |

Vehicle Ownership[TW]= INTEG (
        VO Growth[TW],
                0.26) ~~|
Vehicle Ownership[Car]= INTEG (
        IF THEN ELSE(Switch FL2c = 1, Quota Growth[Car] , VO Growth[Car]),
                0.027)
        ~               |

Vehicle Quota[Car]= INTEG (
        Quota Increase[Car] - Quota Decrease[Car], 75000)
        ~               |

Quota Growth[Car]=
        (Vehicle Quota[Car]-Vehicle Ownership[Car]*Population Growth)/(Population+Population
        Growth )
        ~               |

Switch FL2a=
        1
        ~               |

VO Growth[TW]=
        IF THEN ELSE(
        VO Discrepancy[Car]=0,((Expected VO[TW]-Vehicle Ownership[TW])/2)*Private VO Fractional
        Decrease Rate[TW], VO Discrepancy[TW]/VO Adjustment Time
        ) ~~|
VO Growth[Car]=
        IF THEN ELSE(
        VO Discrepancy[Car]=0,((Expected VO[Car]-Vehicle Ownership[Car])/2)*Private VO Fractional
        Decrease Rate[Car], VO Discrepancy[Car]/VO Adjustment Time )
        ~       (Expected VO[TW]-Vehicle Ownership[TW])/2
        |
```

```
Private VO Fractional Decrease Rate[TW]= WITH LOOKUP (
	Congestion Ratio*Switch FL2a,
		([(0,0)-(2,1)])) ~~|
Private VO Fractional Decrease Rate[Car]= WITH LOOKUP (
	Congestion Ratio*Switch FL2a,
		([(0,0)-(2,1)]))
	~		|

VO Adjustment Time=
	3
	~		|

VO Discrepancy[Car]=
	Switch FL2b[Car]*(Acceptable VO[Car]-Vehicle Ownership[Car]) ~~|
VO Discrepancy[TW]=
	Switch FL2b[TW]*(Acceptable VO[TW]-Vehicle Ownership[TW])
	~		|

Acceptable VO[Car]=
	IF THEN ELSE
	(Congestion Ratio <= 0.8,Vehicle Ownership[Car],
	 ((Qmax*Road Length*0.8*10*3.76)-
	  (Vehicle Fleet[TW]*Trips per Vehicle[TW]*Average Trip Length[TW]*(1/Occupancy Rate\
		[TW])*PCU Factor[TW])
	 )/
	 (Population*Trips per Vehicle[Car]*Average Trip Length[Car]*(1/Occupancy Rate[Car])\
		*PCU Factor[Car])
	) ~~|
Acceptable VO[TW]=
	IF THEN ELSE
	(Congestion Ratio <= 0.8,Vehicle Ownership[TW],
	 ((Qmax*Road Length*0.8*10*3.76)-
	  (Vehicle Fleet[Car]*Trips per Vehicle[Car]*Average Trip Length[Car]*(1/Occupancy Rate\
		[Car])*PCU Factor[Car])
	 )/
	 (Population*Trips per Vehicle[TW]*Average Trip Length[TW]*(1/Occupancy Rate[TW])*PCU
		Factor[TW])
	)	~	|

Fractional TpV decrease rate[TW]= WITH LOOKUP (
	Congestion Ratio*Switch FL1,
		([(0,0)-(1.5,1)]) ~~|
Fractional TpV decrease rate[Car]= WITH LOOKUP (
	Congestion Ratio*Switch FL1,
		([(0,0)-(1.5,1)])
	~		|
```

Fractional TpV increase rate[TW]=
Congestion Ratio*0 ~~|
Fractional TpV increase rate[Car]=
Congestion Ratio*0
~ |

TpV decrease[TW]=
Trips per Vehicle[TW]*Fractional TpV decrease rate[TW] ~~|
TpV decrease[Car]=
Trips per Vehicle[Car]*Fractional TpV decrease rate[Car]
~ |

Trips per Vehicle[TW]= INTEG (
TpV increase[TW]-TpV decrease[TW],
1.19) ~~|
Trips per Vehicle[Car]= INTEG (
TpV increase[Car]-TpV decrease[Car],
1.24)
~
~ Assumption = Vehicle Trips/Vehicle Fleet in the reference (CMP) Year
TW = 10190000/854332 = 1.19
Car = 149705/120495 = 1.24
|

TpV increase[TW]=
Trips per Vehicle[TW]*Fractional TpV increase rate[TW] ~~|
TpV increase[Car]=
Trips per Vehicle[Car]*Fractional TpV increase rate[Car]
~ |

PCTR=
0.55+(Motorised Trip Rate*0.7615)
~ |

Motorised Trip Rate=
(1.01+0.32*LN(Vehicle Ownership[TW]+Vehicle Ownership[Car]))
~ |

Expected DPPKM=
Daily motorized trips[PT]*Average Trip Length[PT]
~ |

Expected DRPKM[TW]=
Daily motorized trips[TW]*Average Trip Length[TW] ~~|
Expected DRPKM[Car]=
Daily motorized trips[Car]*Average Trip Length[Car]
~ |

Motorized mode share=
SUM(Daily motorized trips[Transport Mode!])/Total Daily Trips
~ |

PT Trip rate=
Motorised Trip Rate-(Private Vehicle Trip Rate[TW]+Private Vehicle Trip Rate[Car])
~ |

Private Vehicle Trip Rate[TW]=
Vehicle Ownership[TW]*Trips per Vehicle[TW] ~~|
Private Vehicle Trip Rate[Car]=
Vehicle Ownership[Car]*Trips per Vehicle[Car]
~ |

Daily motorized trips[TW]=
Population*Private Vehicle Trip Rate[TW] ~~|
Daily motorized trips[Car]=
Population*Private Vehicle Trip Rate[Car] ~~|
Daily motorized trips[PT]=
Population*PT Trip rate
~ |

Ref population:=
GET XLS DATA(' , ')
~ |

Ref Vehicle Fleet[TW]:INTERPOLATE::=
GET XLS DATA(' , ') ~~|
Ref Vehicle Fleet[Car]:INTERPOLATE::=
GET XLS DATA(' , ')
~ |

Average Trip Length[TW]=
14.14-0.789*LN(Urban Density) ~~|
Average Trip Length[Car]=
16.65-0.789*LN(Urban Density) ~~|
Average Trip Length[PT]=
15.33-0.739*LN(Urban Density)
~ |

JS Discrepancy=
Switch FL3*(Desired JS - Average Journey Speed)
~ |

Switch FL3=
0
~ |

Switch FL1=
1
~ |

Switch FL2b[Transport Mode]=
0
~ |

New Road Development=
IF THEN ELSE(
JS Discrepancy <= 0,STEP(6,15) - STEP(6,20) + STEP(10,21)-STEP(10,28),
40/JS Adjustment Time)
~ |

JS Adjustment Time=
3
~ |

Desired JS=
15
~ |

DPPKM Growth=
(Expected DPPKM-Daily Public Passenger km)/2
~ |

Private Modal Share=
(Daily Road Passenger km[TW]+Daily Road Passenger km[Car])/Daily Total Passenger km
~ |

Public Transport Modal Share=
Daily Public Passenger km/Daily Total Passenger km
~ |

Congestion Ratio=
Average Daily Traffic Flow Q/Qmax
~ |

Travel Time[TW]=
(Average Trip Length[TW]*60)/Average Journey Speed ~~|
Travel Time[Car]=
(Average Trip Length[Car]*60)/Average Journey Speed ~~|
Travel Time[PT]=
(Average Trip Length[PT]*60)/Average Journey Speed
~
~ minutes
|

Average Journey Speed=
16.4/(1+0.5*Congestion Ratio^9.5)
~ |

Average Daily Traffic Flow Q=
((Daily Car Equivalent Vehicle km[TW]+Daily Car Equivalent Vehicle km[Car])/(10*Road Length*3.76))
~
~ Assumption: average Capacity: 500 PCU/h*10h*3.76 lanes = 18.800 PCU/day
CMP_1 p.64
|

Qmax=
500
~ |

alpha=
-5.897
~ |

Expected VO[TW]=
Vehicle Substitution factor - Vehicle Ownership[Car] ~~|
Expected VO[Car]=
gamma*EXP(alpha*EXP(beta*Per Capita Income/1000))
~ |

gamma=
0.683
~ |

beta=
-0.24
~ |

Daily Total Passenger km=
Daily Public Passenger km+Daily Road Passenger km[TW]+Daily Road Passenger km[Car]
~ |

Daily Car Equivalent Vehicle km[TW]=
Daily Vehicle km[TW]*PCU Factor[TW] ~~|
Daily Car Equivalent Vehicle km[Car]=
Daily Vehicle km[Car]*PCU Factor[Car]
~ |

Fractional Population Growth Rate=
0.0292
~ |

Population Growth=
    Fractional Population Growth Rate*Population
    ~ |

Real Income Growth=
    Fractional Income Growth Rate*Per Capita Income
    ~ |

Fractional Income Growth Rate=
    0.04
    ~ |

Daily Vehicle km[TW]=
    Daily Road Passenger km[TW]/Occupancy Rate[TW] ~~|
Daily Vehicle km[Car]=
    Daily Road Passenger km[Car]/Occupancy Rate[Car]
    ~ |

Total Daily Trips=
    PCTR*Population
    ~ |

Vehicle Fleet[TW]=
    Vehicle Ownership[TW]*Population ~~|
Vehicle Fleet[Car]=
    Vehicle Ownership[Car]*Population
    ~ |

Vehicle Substitution factor= WITH LOOKUP (
    Time,
        ([(0,0)-(50,1)],(0,0.3),(5,0.4),(10,0.46),(20,0.51),(30,0.57),(50,0.6)))
    ~ |

Daily Road Passenger km[TW]= INTEG (
    DRPKM Growth[TW],
        3.4e+006) ~~|

Daily Road Passenger km[Car]= INTEG (
    DRPKM Growth[Car],
        480000)
    ~ |

DRPKM Growth[TW]=
    (Expected DRPKM[TW]-Daily Road Passenger km[TW])/2 ~~|
DRPKM Growth[Car]=
    (Expected DRPKM[Car]-Daily Road Passenger km[Car])/2
    ~ |

```
Transport Mode:
	TW,Car,PT
	~		|

New Land Development=
	STEP(14,5) - STEP(7,20)
	~
	|

PCU Factor[TW]=
	0.5 ~~|
PCU Factor[Car]=
	1 ~~|
PCU Factor[PT]=
	3
	|

Area= INTEG (
	New Land Development,
		132)
	~		|

Per Capita Income= INTEG (
	Real Income Growth,
		2507)
	~
	~	Monthly Avg Income: CMP_1 p.188: 7524 INR (2003), Avg HH Size CMP_1 p.186 = 3.7
	|

Occupancy Rate[TW]=
	2.3 ~~|
Occupancy Rate[Car]=
	2.6
	~
	|

Daily Public Passenger km= INTEG (
	DPPKM Growth,
		3.5e+006)
	~		|

Population= INTEG (
	Population Growth,
		1.64e+006)
	~
	~	CMP_1 p.10
	|
```

```
Road Length= INTEG (
	New Road Development,
		270)
	~
	|

Urban Density=
	Population/Area
	~
	~	Pop/km
	|

********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|

FINAL TIME  = 50
	~	Year
	~	The final time for the simulation.
	|


INITIAL TIME  = 0
	~	Year
	~	The initial time for the simulation.
	|

SAVEPER  =
      TIME STEP
	~	Year [0,?]
	~	The frequency with which output is stored.
	|

TIME STEP  = 1
	~	Year [0,?]
	~	The time step for the simulation.
```