



# **A System Dynamics Analysis of Policies to Relieve an Urban Traffic Congestion Problem**

A thesis submitted in fulfilment of the requirements for the degree of Master of Science

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## **Declaration**

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis/project is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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## ABSTRACT

In the last decade, the continual growth of air transport has resulted in overwhelming traffic congestion in most international airport access roads. This problem is a bottleneck in the development of airports which are regarded as vital contributors to the economic sustainability of their respective cities. Many studies have been done to relieve the problem of congestion in access roads to airports. However, few of these studies have investigated the implications of these strategies on the different stakeholders in the system. In this study, a System Dynamics model is formulated to provide an understanding of some of the wider consequences of congestion-mitigating strategies in a system comprising airport access for a hypothetical city.

This System Dynamics modelling approach offers an assessment platform for policy makers to study the short and long term system behaviour resulting from congestion-mitigation strategies. In particular, the implication of these strategies on the taxi industry livelihood is investigated, which besides the people involved in the industry, makes a significant contribution to an airport's business. The model is composed of three sectors: passengers and travel demand, taxis and private cars, and train. It deals with the congestion level in the road, the growth of passengers, investment in taxis, and the service availability of taxis. Simulations are performed under four policy scenarios aimed at alleviating congestion.

The results indicated that, all policy interventions will have some undesirable effects on the taxi industry in terms of reduced profit and loss of jobs, each having a different level of impact. In addition, it was found that the timing of policy interventions has a significant effect on the magnitude of those outcomes. An earlier policy intervention to tackle the congestion leads not only to better conditions for the road in terms of traffic flow, but also less unfavourable effects on the livelihood of taxi drivers and operators. Accordingly, careful attention should be paid to the particular timing of policies and the timing of their implementation.

The sensitivity analysis suggests that most parameters are insensitive to variations in parameters, except for one parameter; changes in this parameter had a big impact on

the supply and demand for taxis and this in turn has a considerable impact on the viability of the taxi industry. The proper controlling of this variable will allow the amplitude of a shortage or surplus of taxis to be minimized.

This thesis focused on certain socio-economic aspects of a transportation system and yielded insights into some aspects of the system which usually is neglected in solving transportation problems. It is hoped that the insights gained by the simulation results will lead to further understanding by decision makers about some of the wider implications of their proposals in solving transportation problems. Finally, the model in this study demonstrates the ability of System Thinking and System Dynamics methodology in the analysis of the dynamic behaviour of socio-economic systems which include complexity and multiple feedbacks.

# Chapter 1

## INTRODUCTION

### 1.1 Overview

Today the congestion of transportation networks is an important challenge in urban transportation planning (May and Nash, 1996). Many urban areas in the world are experiencing serious traffic congestion that causes significant economic losses to their societies. There are also concerns regarding the negative impacts of congestion on air quality and other environmental considerations (Armah et al., 2010). In the last decade, the continual growth of air transport demand has resulted in unacceptable levels of traffic congestion in existing airport access roads of most global cities (Rhoades et al., 1994, Czerny, 2010). This problem is a bottleneck in the further development of airports which is regarded as a vital contributor to the economic sustainability of their corresponding cities (ATAG, 2005).

Many metropolitan areas in the world have examined various policies to resolve congestion problems on airport access roads such as extending or building highways, developing transport demand management strategies, utilising intelligent vehicles and intelligent highways (Slack, 2014). However, due to the rapid growth of air travel, congestion problems are expected to increase in the future (Czerny, 2010). On the other hand, the implementation of mitigation strategies may result in some unintended short and long-term consequences for different stakeholders of the airport access system. For example, congestion-alleviating strategies could cause socio-economic problems for the taxi industry and its workforce. Accordingly, it is important to consider the social implications of the proposed policy options in these systems before any policy intervention, and therefore to look for ways to minimise the undesirable effects on different stakeholders within the system. In the following section, the problem of traffic congestion in several international airports is outlined.

## 1.2 A Worldwide Problem

A review of airport problems by the US Federal Aviation Administration (FAA) found that 23 of 41 major metropolitan airports in the US are suffering from capacity constraints imposed by landside congestion or a lack of adequate access to the airport (FAA, 2011). Brief examples of congestion problems at a number of international airports are now presented.

### *Los Angeles International Airport (LAX)*

One of the best known examples of the effect that landside access can have on airport operations is at Los Angeles International Airport (LAX). LAX is one of the busiest airports in the world in terms of the number of airplane passengers served and the size of the ground transportation necessary to serve those passengers. Because of the limited capacity of airport circulation roads and the inability of the freeways and city streets near the airport to absorb a greater volume of automobile traffic, regional transportation authorities imposed a cap on aircraft operations and the annual passenger volume permitted at the airport (Mahmassani et al., 2000).

### *New York, John F. Kennedy International Airport (JFK)*

JFK currently has over 50 million passenger movements a year and a 3.37 per cent passenger growth rate, the highest of the top 30 busiest US airports. This greatly accelerates the congestion problem in air traffic and ground access to the airport. The concept of a new dedicated rail service for air travellers between the World Trade Centre and JFK Airport has been proposed to ease traffic congestion on airport access roads (The Port Authority of New York And New Jersey, 2013).

### *Texas, Dallas Fort Worth (DFW) International Airport*

Roadside access to DFW Airport has become strained, extending travel times for both public and private transport. Journey times can double or even treble when compared to free-flow traffic conditions. The airport is surrounded by a number of Texas's most congested roads, with delays costing more than \$109.6 million annually. To address this problem, the Dallas Area Rail Transit (DART) light rail network is currently being extended to the airport (TTF, 2013)

### *London, Heathrow Airport*

A new survey conducted by the Board of Airline Representatives in the UK (BAR UK), reveals that chronic congestion at Heathrow Airport is driving international airlines away from the UK (Wilson, 2014). Landside access to the airport is highly congested, especially in peak hours. Consequently, congestion charges have been introduced to reduce traffic congestion and improve air quality for local communities, while also raising money for public transport improvements. Heathrow is currently failing to meet air quality standards and is under pressure to cut emissions and minimise traffic on surrounding roads. There is also a national debate about an additional airport in London versus expanding the existing airport to meet the growing air travel demand.

### *Melbourne International Airport (Tullamarine Airport)*

Rapid growth in the number of passengers travelling through the Melbourne Airport, combined with rising traffic volumes across greater Melbourne, has constrained access to the airport. Congestion along the major access to the airport (Tullamarine Freeway) is reaching critical levels, impacting the reliability of airport services. Travel times for SkyBus services, the only public transport mode between the CBD and the airport, often reach 40 minutes during peak times and can be as long as 51 minutes in the morning and 59 minutes in the afternoon peak compared to 20 minutes for off-peak times (TTF, 2013). To tackle this problem, the Tullamarine Freeway widening project has been developed. In addition several studies such as Melbourne Airport Rail Link Study (PTV, 2013) and Melbourne Airport Landside Access Strategy (PTV, 2012) have been conducted to ensure appropriate landside transport access is maintained to the airport in anticipation of the expected growth in activity.

### *Sydney International Airport*

Sydney Airport is Australia's largest airport, servicing 35 million passengers in 2010-11 and acting as a major freight hub. Road congestion getting to and from Sydney Airport has substantially increased over the past decade due to a lack of investment in roads, buses and rail by the NSW government outside the airport's boundaries. The NSW Government and Sydney Airport are jointly investing almost \$500 million to improve traffic flow in and around Sydney Airport, as part of a suite of ground transport solutions and airport facility upgrades (Productivity Commission, 2011).

It is clear that many cities worldwide have similar problems related to road capacity and congestion on airport access roads. These problems may limit the growth of airports and airline services, and therefore threaten the economic sustainability of their respective metropolitan areas. Accessibility has been shown to influence travellers' decisions among competing airports in a region (Gelhausen, 2011). Consequently, many cities have responded by implementing traffic congestion-mitigation strategies such as increasing road capacity, travel demand management strategies, using intelligent vehicles and intelligent highways. Nevertheless, each of these policy interventions will have some socio-economic implications for different stakeholders of the system. Therefore, one key challenge is to evaluate the impacts of a policy intervention within a specific metropolitan area before and after it is implemented.

### 1.3 Problem Statement

Based on common properties of the cities discussed earlier, in this study a hypothetical city will be considered with the properties described below. To provide more realistic magnitudes and behaviours of the system, the properties of the system being modelled along with some of the required input data for the model have been taken from the Melbourne Airport Rail Link Study (PTV, 2013). Other data are based on elucidated expert knowledge or sensible and reasonable assumptions by the author. Therefore, in this study a Melbourne-like city and its international airport will be assumed. Currently, access to Melbourne Airport is entirely road-based, with a major highway carrying 75 per cent of airport traffic. Transport to Melbourne Airport is dominated by cars and taxis. Currently almost 20 per cent of airport users travel on taxis. The airport has 28 million passenger movements a year and this figure is expected to double by 2033.

Road access to the Melbourne Airport is already reaching capacity. The freeway and connecting roads do not have the capacity to meet this increasing demand. Already, the freeway is heavily congested in peak periods causing excessive delays and risk of traffic incidents. Accordingly, to improve transport connections to the Melbourne Airport, the Tullamarine Freeway widening project has been developed with the aim of easing congestion now and providing for future growth. In addition, a State

Government study has examined the viability of a rail link to the airport and has identified four route options to and from the airport (PTV, 2012, PTV, 2013).

However, despite the considerable efforts to tackle the congestion problems, there has been little discussion about the socio-economic consequences of these interventions on stakeholders of the airport access system, such as the taxi industry and people who are involved in it. It is believed that any policy intervention in a social system will have some unintended consequences on some system components (Merton, 1936). Therefore, it is necessary to evaluate the impacts of policy proposals on different components of the system. Accordingly in this study it is assumed that the number of passengers in the proposed airport will double in 20 years, similar to the problem experienced in the Melbourne Airport access road.

One important stakeholder in any airport access system is the taxi industry and its workforce. Taxis play important roles in providing ground transportation to travellers arriving and departing the airport, and thus make significant contributions to an airport's business (Melbourne Airport, 2014). In addition, the taxi industry makes considerable economic contributions to metropolitan areas, especially in international cities. It directly and indirectly generates jobs. Furthermore, the taxi industry has an important role in connecting people, promoting social inclusion and supporting economic activity (Deloitte Access, 2013). Hence it is important to consider socio-economic impacts on the taxi industry and its workforce before any policy intervention, and to explore whether policies to alleviate congestion can be implemented with the least unfavourable impacts on this particular group of people. These socio-economic consequences which are often ignored in addressing airport access traffic congestion problem are the focus of attention in this thesis.

## 1.4 Aims and Objectives

The aim of this study is to examine the socio-economic problems in taxi industry and its workforce on a hypothetical airport access road, arising from congestion-mitigating strategies. To do so, a System Dynamics model will be built and the structure of the proposed airport access road will be organized into the model. This modelling approach offers an assessment tool for decision makers to study the short- and long-

term system behaviours resulting from policies to relieve the congestion problem. Therefore investigating the efficacy of System Dynamics for analysing the socio-economic problems is a secondary component of this study. The decision makers thus may have a better understanding of the dynamics of the system by testing their assumptions and scenarios. In particular, the socio-economic implications of these policies on the taxi industry and its workforce will be examined. It is hoped that the insights gained by the simulation results will make policy makers aware of some of the wider consequences of their proposals to alleviate a congestion problem.

The research objectives for this study are as follows:

- To investigate the short- and long-term implications of congestion-mitigating strategies for the taxi industry and its workforce.
- To explore the effect of timing of the congestion-mitigating strategies.
- To explore the efficacy of System Dynamics methodology to understand the wider implications of policies to solve transportation-related problems such as above.

## 1.5 Thesis Outline

This thesis is organized in six chapters. The first chapter, as was presented in the preceding sections, provided an overview of the background to the problems arising from congestion in airport access roads and aims and objectives of the research.

Chapter 2 focuses on a review of the literature related to planning in transportation in general and applications of System Thinking and System Dynamics to transportation modelling. It also explains System Dynamics methodology and the reasons for using SD methodology in this study.

Chapter 3 details the formulation of the System Dynamics model which outlines the structure of the hypothesised airport access system.

Chapter 4 presents the model implementation and analysis of the simulation results of four policy scenarios for solving the congestion problem. The effect of each scenario on the taxi industry and its workforce is examined. Further, a series of sensitivity analyses have been conducted to examine the system's responses to variations of some



of the input parameters and the most influential parameters of the model have been identified.

Chapter 5 represents the conclusions and recommendations related to the problem being addressed in this research and the reflections on the study.

## Chapter 2

### LITERATURE REVIEW

#### 2.1 Introduction

This chapter reviews literature related to planning in transportation and applications of System Thinking and System Dynamics to transportation modelling. The history of the development of System Dynamics methodology is explained briefly with one application example of this method in the context of social science; *Urban Dynamics* (Forrester, 1969).

In addition, review of specific applications of System Dynamics (SD) in transportation modelling is presented which will serve as a foundation for building a model in Chapter 3. Finally, the rationale for using SD methodology in this study is explained.

#### 2.2 Transportation Planning

Urban planning or city and regional planning, and transportation planning in particular is a dynamic process which is essential to develop new structures (such as cities, suburban areas, highways, airports, bridges) and improve existing structures. Transport planning focuses on the public provision and financing of transportation assets, particularly roads and public transit systems (Black, 1981, Slack, 2014).

Planners often use logic or simulation models to present their visions of the future to the decision makers. These models range from simple logical or mathematical models to complicated socio-political models (Shirazian, 1981). However, all of them are developed for two main purposes. The first is to provide a better understanding of how transportation systems operate. The second is to utilise models for prediction of future conditions, and policy analysis.

##### 2.2.1. Traditional Transport Planning

For a long time transport planning was dominated by traffic engineers who gave it a distinctly mechanistic character, in which the planning process was seen as a series of

rigorous steps which are undertaken to measure likely impacts and to propose engineering solutions (Slack, 2014). This approach regards transport problems as isolated problems with technical solutions.

There are four major steps in traditional transport planning: trip generation, trip distribution, modal split, and route selection (Zhao et al., 1997, Ahmed, 2012). They involve the use of mathematical models, including regression analysis, entropy-maximizing models, and critical path analysis (Putman, 1975). The predictions of future traffic flows produced by the four stage sequence are then used to identify planning options. Usually the most common prediction of the modelling is that present capacities will be unable to cope with traffic growth (Rodrigue et al., 2013). Therefore the tendency has been to produce planning solutions that call for an expansion of capacity, which has been referred to as ‘predict and accommodate’. This solution has resulted in the massive growth of highway construction that fortifies the dominance of the automobile (Slack, 2014). But this approach has an important flaw. Solutions to one problem often intensify other problems, particularly if they increase total vehicle travel. In the long run, increasing roadway capacity tends to increase traffic volume, due to induced travel demand (Noland and Lem, 2000, Litman, 2001).

### 2.2.2 Contemporary Transport Planning

Traffic problems in cities have increased significantly since the 1970s, despite considerable efforts made towards urban transport planning. This indicates that in developing transport systems governments have acted to meet immediate requirements rather than planning for the future (Black, 1981, Slack, 2014). There is a growing realization that rather than estimating traffic increases and then providing capacity to meet the expected growth, better management of the transport system by new approaches to planning is required. Whilst urban planning requires the inputs of many specialists, transport planning is beginning to utilize multi-disciplinary teams in order to broaden the scope of the planning process.

#### *Transport Demand Management*

In response to the failure of the previous paradigm of increasing capacity, transport planners have turned to managing both demand and the transport system. Transport

demand management (TDM) strategies use various mechanisms to change travel patterns, including facility design, improved transport options, pricing, and land use changes. These affect travel behaviour in various ways, including changes in trip scheduling, route, mode, destination, and frequency, plus traffic speed, mode choice and land use patterns (Victoria Transport Policy Institute, 2014).

Table 2-1: Examples of TDM travel impacts  
Source: (Victoria Transport Policy Institute, 2014)

<b>Travel Demand Management Strategies</b>	<b>Mechanism</b>	<b>Travel Changes</b>
Traffic Calming	Roadway redesign.	Reduces traffic speeds, improves pedestrian conditions.
Flextime	Improved transport choice.	Shifts travel time (when trips occur).
Road/Congestion Pricing	Pricing	Shifts travel time, reduces vehicle travel on a particular roadway.
Distance-based charges	Pricing	Reduces overall vehicle travel.
Transit improvements	Improved transport choice.	Shifts mode, increases transit use.
Rideshare promotion	Improved transport choice.	Increases vehicle occupancy, reduces vehicle trips.
Pedestrian and bicycle improvements	Improved transport choice, facility improvements.	Shifts mode, increases walking and cycling.
Car sharing	Improved transport choice.	Reduces vehicle ownership and trips.
Smart Growth, New Urbanism	More efficient land use, improved travel choices.	Shifts mode, reduces vehicle ownership and trip distances.

Table 2-1 provides nine typical travel demand strategies. The mechanisms by which different travel demand management strategies affect the improvement of the traffic situation are listed in the second column. The third column describes the impacts of implementing these strategies. Each strategy uses alternative mechanisms, and thus causes different travel changes. For example, road/congestion pricing, uses pricing mechanisms to shift travel demand from peak to off-peak periods or reduces vehicle travel demand on a particular roadway.

In this study, it is assumed that the demand for air travel and therefore travel in the airport access road will increase regardless of factors that may affect the number of

passengers. Passenger population is modelled in a simple way to mimic the projections used by planners (the number of passengers will double in 20 years). Nevertheless, this study does not seek to find the best solutions to reduce traffic congestion on a road; rather it aims to study some of the socio-economic consequences of several congestion-mitigating strategies. Hence, strategies that utilize mechanisms to change travel demand are not considered as congestion-mitigation strategies in this research.

## 2.3 System Dynamics Methodology

System dynamics is a simulation tool for modelling, understanding, and discussing the dynamic behaviours of complex systems. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. The field was developed initially by Jay W. Forrester from the MIT Sloan School of Management in 1950s (Kirkwood, 2013).

“System Dynamics deals with how things change through time, which includes most of what most people find important. It uses computer simulation to take the knowledge we already have about details in the world around us and to show why our social and physical systems behave the way they do. System Dynamics demonstrates how most of our own decision-making policies are the cause of the problems that we usually blame on others, and how to identify policies we can follow to improve our situation.”

(Forrester, 1993)

The early work *Industrial Dynamics* (Forrester, 1961) presented the concepts and methodology in the context of inventory systems and the growth of industries. The methodology was then extended to *Urban Dynamics* (Forrester, 1969). This model is the first application of System Dynamics (SD) in the context of social science that simulates the behaviour of a city over short and long time horizons. In this model, the city is defined as a system in which industries, housing and people interact within defined boundaries. Urban dynamics dealt with the process of growth and stagnation in a city and examined several policies to implement revival in an old city.

Starting with *Urban Dynamics*, and followed by *World Dynamics* (Forrester, 1971b) and *The Limits to Growth* (Meadows et al., 1972), the System Dynamics methodology has been widely used throughout the public and private sector for policy analysis and design such as urban and regional planning, education, economics, business, industry, environmental management and so forth (Ghaffarzadegan et al., 2011).

### 2.3.1 The Structure of the System Dynamics Model

A system dynamics model describes the relationship amongst the individual system variables. This is usually represented using a stock and flow diagram.

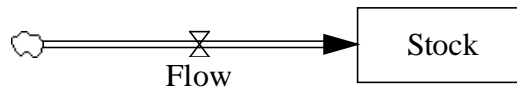


Figure 2-1: A basic stock and flow diagram

As it can be seen in Figure 2, the building blocks of system dynamics models are stocks and flows which are defined as follows:

- Stock which is the value or amount of something at a point in time.
- Flow which is an element affecting the amount of stock.

Input data and stock and flow diagrams can be constructed with System Dynamics software. The most commonly used software programs are *Vensim*, *Dynamo* and *Stella*. These programs use nonlinear, first-order differential equations coupled with inputted parameters (boundaries) and goals to simulate dynamic models. In Equation 2.1, variable  $x$  is a vector of stocks, variable  $p$  is a set of parameters, and variable  $f$  is a nonlinear vector-valued function (the variable  $f$  contains the flows into or out of the stock  $x$ ) (Richardson, 2013):

$$dx/dt(t) = f(x, p) \tag{2.1}$$

The steps of the modelling process are as follows (Sterman, 2000):

- Define the problem
- Describe the system

- Develop the model
- Build confidence in the model
- Use the model for policy analysis
- Use the model for public outreach

## 2.4 Transportation as a Dynamic Complex System

Urban transportation systems are complex, including various stakeholders; with many feedbacks and time delays between the responses of users, developers, operators and policy makers (Shepherd and Emberger, 2010). That is, the effects of any action in the transport system can appear at a distant point in time and space, including unintended consequences. In large-scale systems like transportation, dynamics is essentially caused by the internal feedback structure of the system. That is, provided the system boundaries are well chosen, problems are rooted in the internal structure of the system (Sterman, 2001, Meadows, 2008). The structure of a system is the totality of the relationships amongst system variables. It operates over time so as to produce the behaviour patterns of the system variables over time (Barlas, 2007).

For a real system, the structure is not exactly known. For a model of a real system, the structure consists of those aspects of the real structure that the modeller has hypothesized to be important for the problem of interest (Forrester, 1961). The structure of a system in social science field of study can become subject to controversy since perspectives on a problem and perceptions therefor may differ widely (Forrester, 1971a). For example in the model built in this study, while the taxi industry supports a policy of increasing the road capacity, environmentalists may oppose such a policy. Similarly, transportation planners might propose policy options different from engineers. This variety in the goals of system components leads to policy resistance, which is one characteristic of complex systems (Meadows, 2008). Thus keeping sub-purposes and overall system purposes in harmony is an essential function of successful systems.

## 2.5 System Thinking and System Dynamics in Transportation Planning

Tran (1979) in his PhD dissertation studied the potential of System Dynamics as a methodology in transportation planning. He investigated various conventional methods in transportation modelling and listed the deficiencies of those approaches as: 1) a lack of consideration of the feedback relations within the considered transportation system; and 2) a lack of consideration of the interactions between transportation systems and other transport related systems such as the urban system and environmental system. Shirazian (1981) also describes the main deficiency associated with conventional planning models as a lack of feedback and time lag consideration between elements of transport systems.

Abbas and Bell (1994) also investigated the applicability of System Dynamics in transportation modelling. They note that forecasting the future visions of transportation systems is the major aim of most models. However, many errors appear in forecasting models. According to the authors, the unreliability of forecasts is mainly due to: 1) the possibility of errors in existing or collected data; 2) the difficulty of modelling human behaviour; and 3) the uncertainty of the future. The impossibility of point prediction in social systems has been discussed extensively by Forrester (1961).

Urban transportation systems are difficult to analyse by using pure mathematical and statistical models alone. In addition, qualitative modelling approaches are needed to identify the overall behaviour of the transportation system. The variety of components and issues associated with transportation problems with various feedbacks between them call for systematic approaches to evaluate and solve those problems. There is a genuine need to develop transport models with the capability of demonstrating the implications of a broad range of transportation options and to help decision makers to gain more in-depth insight about such consequences.

System thinking provides methods and techniques to apply non-linear causal thinking to planning and management problems. In other words, system thinking means the consideration of the whole components integrated to a complex entity rather than the separate consideration of individual components. It aims to understand the system's patterns of behaviour over time, rather than focusing attention on individual events



(Meadows, 2008). Thus, the principles of systems thinking are necessary in solving transportation problems.

System Dynamics (Forrester, 1961, Forrester, 1969, Meadows et al., 1972, Richmond and Peterson, 1997, Sterman, 2000, Sterman, 2001), a member of a family of system approaches, recognises interactions between system components which produce dynamic behaviours over time. The method can thus help urban transport planners to identify problematic trends and their root causes. In SD, qualitative models can be developed relatively quickly and affordably to identify system behaviours, and to provide insights into the root causes of multidimensional transportation problems.

The main purpose of System Dynamics methodology is to understand the causes of undesirable dynamics and develop new policies to ameliorate or eliminate them. Managerial understanding, action and control are at the heart of the method. System Dynamics thus focuses on dynamic problems with a systemic, feedback nature (Barlas, 2007). According to Sterman (1991):

“A model must have a clear purpose, and that purpose should be to solve a particular problem. A clear purpose allows model users to ask questions that reveal whether a model is useful for solving the problem under consideration. Beware the analyst who proposes to model an entire social or economic system rather than a problem. Every model is a representation of a system—a group of functionally interrelated elements forming a complex whole. But for the model to be useful, it must address a specific problem and must simplify rather than attempting to mirror in detail an entire system”.

In the following sections the importance of modelling purpose, and the purpose of modelling in this study, will be discussed. Specific applications of System Dynamics methodology in transportation modelling will then be presented.

### 2.5.1 Modelling Purpose

Modelling is a common scientific tool used to investigate problems and solutions:

"A model can be defined as "a representation of selected aspects of a real system with respect to some specific problem(s)." Thus, we do not build "models of systems," but build models of selected aspects of systems to study specific problems. The crucial motivation, purpose that triggers modelling is a problem".

(Barlas, 2007)

Pidd (2010) has developed an attractive classification of modelling based on four broad types of purpose: modelling for decision automation; for routine decision support; for investigation and improvement; and for generating insights. Modelling for decision automation refers to model use that is "frequent and routine, with, in general no need to prepare the model for each use". With this modelling purpose, there is typically very little tolerance for any inaccuracy, since decisions made by the modeller are used on a continuous basis in a less supervised environment. Therefore, all the model assumptions, parameters, outputs, and their relationships should be examined critically before using the model in a decision making context (i.e. during the model-building stage). In modelling for routine decision support, where models are "used to assist, but not replace, people making routine, repeated decisions". The models for investigation and improvement are supporting "investigations that are relatively unique, which may involve system design, system improvement or just an attempt to gain understanding of a very complex situation". This type of modelling could be employed to develop a decision support model for a new real-world system which may not even physically exist or may be in the process of being designed. The last type of modelling purpose; to provide insights is "not would-be representations of the real-world, it rather attempts to understand and represent how different stakeholders and interest groups see that world".

In transportation planning, SD models are developed for different purposes to answer different questions. The SD model in this study is built to provide an understanding for policy makers about the implications of interventions in a transportation system on a specific stakeholder of that system. Hence the modelling purpose of this research could be regarded as 'modelling to provide insights'.

## 2.6 Specific Applications

System Dynamics methodology has been widely used in transportation modelling. Each of these studies has taken different perspectives to study the behaviour of transportation system. Abbas and Bell (1994) critically reviewed the strengths and weaknesses of the application of System Dynamics in transportation modelling. They concluded that SD modelling can contribute to a better understanding of the relationship between elements of the transport system. They refer to the simplicity of SD models for testing alternative transport policies and the effects that each policy exerts. Moreover, they emphasized that SD models are not built to provide predictions of the system; rather they are developed to gain broad understanding of the transport system and thus help policymakers to make better decisions. The remainder of this section discusses specific applications of System Dynamics in transportation planning.

Tran (1979) investigated the potential of SD in transport planning. His model includes six components related to transportation and urban development: the urban socio-economic activity component; the highway transportation component; the bus transit component; the vanpool component; the air pollution component; and the transportation fuel consumption component. He demonstrated that the SD modelling approach fulfils a need which is not met by the standard planning and programming approaches, namely that of consideration of feedback relations within the considered transportation system and also consideration of the interactions between the socioeconomic system and transportation system. The ultimate aim of this research was to apply system concepts in general and the methodology of System Dynamics in particular to transportation policy planning and analysis.

Hirsh (1977) studied the application of System Dynamics in urban bus transit. The model built in this study consisted of four sections: the transit ridership; the fare price level; the net transit funds; and bus fleets and bus trips. With this model he evaluated the insights gained through the application of SD in urban public transport planning. In addition, he examined various scenarios regarding the urban bus transit operating policies. The author concluded that the model, which does not require the collection of extensive data, permits the evaluation of many alternative policies and greatly reduces the complexity and uncertainty of transit planning and decision-making.

Hansen and Kahne (1975) proposed a conceptual foundation for a general transportation ecology model which represents the environment of transportation systems. The model addressed four major sectors of transportation ecology: the transportation system design sector; the economic sector; the environmental sector; and the energy supply sector. At the end of their appraisal of modelling large-scale systems using System Dynamics modelling techniques, they stated that "the benefit derived from the modelling efforts of large scale systems suggests that the techniques may be beneficially applied to other large-scale systems. Transportation provides many problems of large scale where new and more effective approaches are needed".

System Dynamics is applied to transport energy demand modelling in Australia by Wadhwa (1979) with two major objectives: 1) to investigate the future fuel demand for passenger transportation; and 2) to evaluate the effects of incomes, prices and car ownership on travel demand. The model consisted of two sub-models which are the passenger task sub-model and the energy intensiveness sub model. It incorporated the various determinants of passenger transport task and simulated the effects of income, prices and car ownership levels on travel demand. It also included technological, social and regulatory factors aimed at improving the energy intensity of automobiles e. g. smaller and lighter cars, improvement in auto-fuel efficiency, lower highway speed limit and carpooling. It was concluded that the passenger travel demand is less likely to be contained but a combination of conservation and efficiency measures can significantly reduce the energy intensity, thereby controlling the energy demand in the next 25 years to almost the present consumption levels.

Shirazian (1981) developed a System Dynamics model of transportation planning in his PhD thesis and applied it to the city of Gadsden, Alabama, USA. His model consisted of four sectors: the socioeconomic; transportation; environmental; and energy sectors. The major motivation of this research was to use this model to project future transportation requirements. Analysis of the model simulations were used to test the model for sensitivity toward different policies and parameters. He concluded the results of the modelling supports the development of a methodology that can improve the trip generation phase of transportation planning.

Liu et al. (2010) undertook SD modelling to examine the implications of an area-wide congestion pricing policy along with other congestion-mitigation policies on urban transportation systems, including both the short-term and long-term effects. The research had two major contributions. First, it provided a conceptual framework to explain a qualitative evaluation of a congestion pricing policy in a transportation socioeconomic system. Second it considered the uncertainty of people's perceptions of the impact of congestion on travel mode selection. Within this framework, improved bus and metro capacities contribute to the supply dynamics which in turn affect the travel demand of individuals and their choice of different transportation modes. Work travel and social networking activities are assumed to generate additional travel demand dynamics that are affected by travellers' perceptions of the level of service of the different transportation modes, their perceptions of the congestion level, and the associated traveling costs. It is assumed that population, tourism and employment growth are exogenous factors that affect demand.

Yevdokimov (2002) investigated the possibility of applying System Dynamics in modelling sustainable transportation systems<sup>1</sup>. The author identified three dimensions of sustainable transportation which are the economic, social, and environmental sectors. He concluded that mathematical modelling based on aggregate sustainability criteria, systemic analysis and the System Dynamics approach is the best way to model sustainable transportation systems. The SD approach can simultaneously address all aspects of the transportation's sustainability.

Armah et al. (2010) proposed a SD perspective of the problem of congestion and air pollution in Accra, the capital city of Ghana. In this study, the main drivers and cause-effect relationships of traffic congestion and its attendant air pollution were investigated and analysed using causal loop diagrams. The study explained how fragmented approach to solve traffic problems in city planning in Accra draws

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<sup>1</sup> Sustainable transportation is an aspect of global sustainability, which involves meeting present needs without reducing the ability of future generations to meet their needs (Yevdokimov, 2002)

policymakers to develop short term solutions which serve the interests of political authorities. It demonstrates how the mechanisms used to solve traffic problems of past years have become the traffic problems of today. The authors finally proposed three long term policies to solve the traffic congestion in Accra: 1) government policy and planning (e.g. to implement economic and policy mechanisms to control further increases in car use); 2) travel demand management; and 3) supply management.

Abbas (1990) employed SD methodology as a road management tool to assist managers of a network of highways to make more informed decisions in regard to fund allocation. The model simulated the effect of different road investment strategies and maintenance options in the road networks. The main purpose of this study was to construct a dynamic, simulation model to serve as a management tool for designing, testing and assessing strategies that support the decision making process in the field of highway planning. The model was then used to analyse the impacts of proposed changes in the funding levels, as well as in the structure of the properties involved in the allocation of road funds.

In a study conducted by Swanson (2003), a model was built to simulate the interaction between transport, land use, population and economic activity in an urban area. The model was constructed on ideas from Forrester's original Urban Dynamics work and extended to a fully zonal model with road and public transport networks. He studied the relationship between the economy and the transport system and concluded that the changes to the economy will lead to interventions in the transport system of a metropolitan area.

Failla (2013) adopted a systemic perspective in investigating the dynamic of passengers' satisfaction with respect to airports' landside congestion. In this preliminary research, a System Dynamics model was built to support airport managers to outline alternative policies to improve passenger satisfaction. The analysis was carried out in an Italian international airport. Simulated results showed unexpected side effects and counterintuitive behaviours. For example, while it was expected that greater investment in airport cleanliness and security staff training hours would lead to positive effects in terms of quality of service, the results indicated that after a certain value of security staff training hours, it negatively affects the overall quality of service

level. The results obtained facilitated decision makers learning and encouraged examining of the project by focusing on the areas affecting passenger service quality.

Wang et al. (2008) developed a SD model to examine the effects of vehicle policy intervention on urban development and population, GDP, and environment aspects, and applied it to a case study of Dalian, China. The model was developed based on the cause-and-effect analysis and feedback loop structures in the system and comprised 7 subsystems: population, economic development, number of vehicles, environmental influence, travel demand, transport supply, and traffic congestion. The coefficient of the intervention policy of vehicle ownership is chosen as the control variable for simulation, and the impacts of different policy scenarios on urban development and transportation system are analysed. The suggestions made by the authors to improve the sustainability of the transportation system to the policy on vehicles in Dalian included three aspects: (i) restrict the ownership and use of vehicles in an acceptable way; (ii) restrict private vehicles and simultaneously improve the service level of public transport; (iii) implement the restriction policy and simultaneously put emphasis on the research and development of emission-reducing technologies.

Shen et al. (2009) developed a SD model to evaluate low/high density land use policies for Hong Kong. In the distant long term they show that compact high density scenarios are more sustainable with investment in rail-based transport over car infrastructure which is seen to be more prominent in the low density case. The simulation results indicated that the growth in population in the very long term can be accommodated only in the high density scenario. The authors conclude: “that only by means of a planning policy scheme to support compact and high-density development could Hong Kong meet the environmental, social and economic requirements of sustainable land use and achieve a perfect balance among them”.

To study the US highway system sustainability problem, Egilmez and Tatari (2012) employed a System Dynamics modelling approach. The objective of the research was to reduce CO<sub>2</sub> (in the USA) and meet the Liberman and Warner Climate Act’s targets by 2050. Three potential policy making strategies, namely fuel efficiency, public transportation and electric vehicle usage were tested in the model. The results indicated that hybrid implementation of individual policies has a crucial impact on the success of

policy making. Hence, to have sustainable highway transportation, the cooperative policy making is inevitable and the policy makers should consider the dynamic cumulative impact of individual policies during the scenario generation.

Similarly, Raux (2003) constructed a model architecture based on System Dynamics and econometrics to simulate the medium- and long-term effects of urban transport policies with reference to sustainable travel. Three sub-models were examined in his research, which are public transport finance, modal split, and combined assignment and time of departure choice. In particular, the results of the model simulations indicated that increasing car ownership results in an increase in car trips, in spite of the increased congestion it generates: this congestion is counterbalanced by a spreading out of departure times. Conversely, an increase in road capacity will permit the car to retain its advantage over public transport, and result in more uniform travel times by car. Finally the models in this research provided a sound basis for the achievement in the future of an urban trip simulation system based on a systems dynamics approach.

Haghani et al. (2003) employed a System Dynamics approach to model simultaneous land use transportation system performance. The model consisted of 7 sub-models: population, migration of population, household, job growth-employment-land availability, housing development, travel demand and traffic congestion level. The model designed by the authors was based on the causality functions and feedback structure between a large number of physical, socioeconomic and policy variables. The results of the model analysis indicated that the proposed method is a promising approach in dealing with complex urban land use-transportation modelling.

Lei et al. (2012) built a SD model of urban low-carbon transportation and explained the complex dynamic relationship among the urban economy, urban population, urban vehicles (civilian traffic and public transportation), urban transportation infrastructure, city traffic management level and urban transportation carbon emissions. The applicability of the model was tested on Shanghai city. The model results demonstrated that the major reasons of increasing carbon emission are urban private car possession and expansion of the scale of urban population. So, it is important to strengthen urban transport demand management and improve the urban transport structure in building urban low-carbon transport.



Qian et al. (2006) constructed a System Dynamics model to demonstrate the consequences of massive road construction in Shanghai, China. The modelling results showed that road congestion will become more severe in the future by only increasing road supply. The author then suggested that alternative policies, such as promoting public transportation, should be considered. A SD model for transportation planning of Bangkok Metropolitan Area, Thailand was presented by Tanaboriboon (1979). Two major activities were considered in this application, socioeconomic activity (urban/rural population, pollution, industry, residences) and urban bus transit activity. In this research, the author tried to use System Dynamics to evaluate different policies associated with the transport and urban development.

## 2.7 Conclusion

One merit of System Dynamics methodology in transportation modelling in comparison with statistical transportation models is that the construction of a SD model is relatively simple compared to common transport models (Abbas and Bell, 1994). A SD model can be used with less numerical data; therefore its results are not as detailed as the usual simulation models. However, this broader systems perspective complements the available static and narrowly defined optimization studies. SD models do not provide statistically valid estimates; rather they provide demonstrations of the unpredictable consequences of the actions that arise due to the feedback loops and time lags in the system (Sterman, 2000, Collins et al., 2013). For example, the most common response of urban planners to congestion is to expand the road infrastructure in order to increase highway capacity. In this case while the short term result is a relief in congestion, as information about the improved and attractive road begins to affect people's choice of transport mode and the places to live, the congestion can return and even be worse than before. This phenomenon refers to induced travel demand in the transportation planning literature.

System Dynamics modelling has the ability to provide important and often counterintuitive insights into the behaviour of the feedback structure of the system. These insights can then be easily understood by policymakers (Ghaffarzadegan et al., 2011). This approach has the ability to represent multiple and concurrent interactions among variables that are incorporated in multiple feedback loops. It therefore allows

one to easily understand and interpret these interactions (Sterman, 2001). SD is a behaviour-oriented simulation discipline in which behaviour patterns of model variables are more important than their numerical values (Barlas, 2007). That is, it emphasizes on system behaviour, rather than events or system states at specific time points. SD models help trace the patterns of behaviour of a dynamic system to its feedback structure. It should be noted that this study, does not provide accurate predictions of the future, rather it presents a broader understanding of the behaviour of the transportation system under several congestion-mitigating strategies.

Examining certain policy scenarios on a System Dynamics model can greatly aid in understanding how the system behaviour changes over time. It will thus enable the investigation of both the short and long term implications of different policies and strategies. These insights could be helpful in making more informed and justified decisions. Considering all above factors, it is realized that, the aim of this study is best addressed by this methodology.

In conclusion, SD methodology has been applied into a wide area of transportation research including but not limited to; sustainable transportation systems (Yevdokimov, 2002, Yevdokimov and Mao, 2004, Raux, 2003, Egilmez and Tatari, 2012) traffic congestion problems (Raux, 2003, Qian et al., 2006), transportation energy demand (Wadhwa, 1979, Shirazian, 1981), urban buss transit (Hirsh, 1977), transportation infrastructure management (Abbas, 1990, Kim, 1996), urban transportation policy evaluation (Tran, 1979, Haghani et al., 2003, Liu, 2007, Wang et al., 2008, Liu et al., 2010), transportation ecology (Hansen and Kahne, 1975), economic and transport planning (Wadhwa and Demoulin, 1978, Tanaboriboon, 1979, Swanson, 2003), low carbon transportation (Armah et al., 2010, Lei et al., 2012, Egilmez and Tatari, 2012), the interactions between transportation and land use (Shen et al., 2009, Pfaffenbichler et al., 2010). However no specific application of System Dynamics that evaluates the socio-economic consequences of congestion-mitigation policies on the taxi industry of an airport access road system was found in the literature. In current study, a System Dynamics model has been developed that evaluates how different congestion-mitigation scenarios affect the average level of traffic congestion and the viability of the taxi industry and its workforce as a stakeholder of the system. Formulation of the model will be explained in the next chapter.

## **Chapter 3**

### **FORMULATION OF THE MODEL**

#### **3.1 Introduction**

This chapter details formulation of the model which represents assumptions about the dynamic relationships between the variables of the proposed airport access system. Three sectors are defined in formulating the model; namely Passenger, Taxi and Train sectors. All variables of the model can be classified under one of these sectors.

The model is formulated in the following order: first the stock and flow diagram is constructed and then the associated mathematical equations will be developed. This is followed by specifying initial values for the parameters in the simulation which are based on assumptions about the hypothetical airport access road of the city being modelled. These assumptions are described in detail in Chapter 1.

The stock and flow diagram of the passenger sector is illustrated in Figure 3-1. In the proceeding sections the process of formulating mathematical equations for all variables of the model are described.

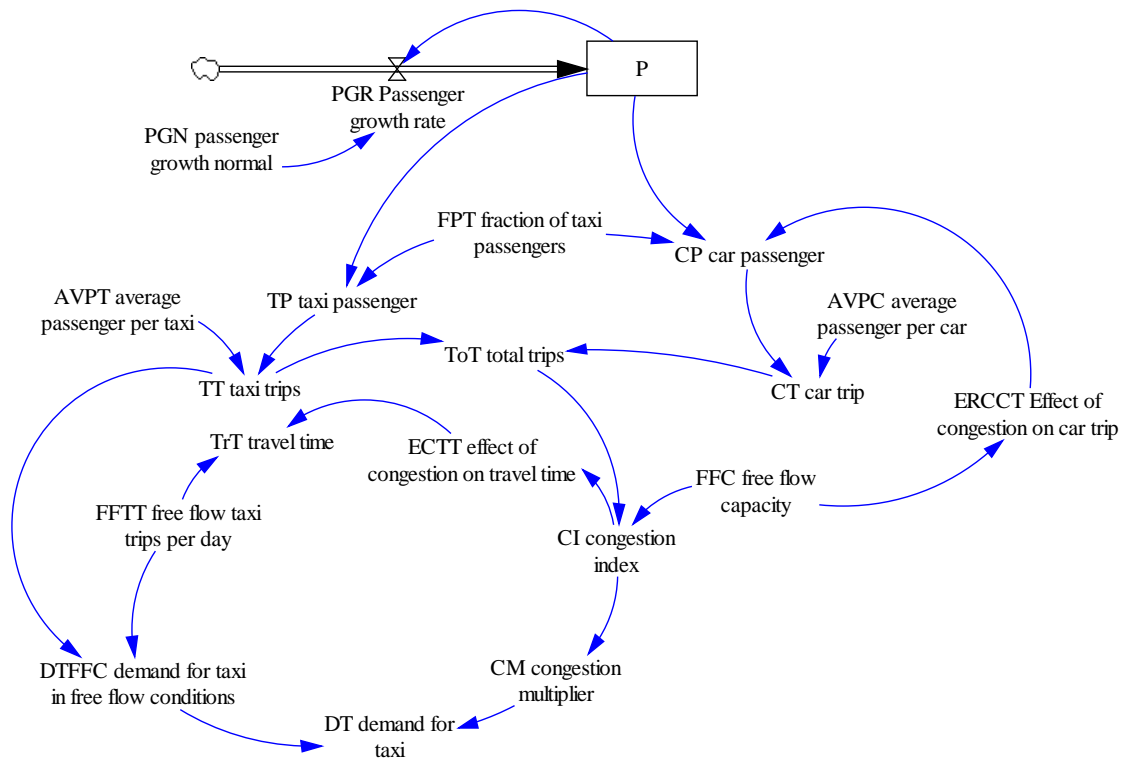


Figure 3-1 Stock and flow diagram of the passenger sector

### 3.2 Passenger Sector

The intention in the passenger sector of the model is to imitate changes in passenger numbers in the proposed system at particular times. The method of calculating passenger numbers for the simulation is explained below.

*Passenger (P)*: Passenger P, in equation (3.1) defines the stock of passengers, which represents all passengers travelling throughout the airport. The number of the passengers determines the scale of this system. The rate of change of passengers, P, is equal to the passenger growth rate (PGR). Thus:

$$\dot{P}(t) = PGR \tag{3.1}$$

where,

$$P = \text{Passenger (person)}$$

$$P(0) = PN = \text{Initial Passenger (constant, person)}$$

The initial number of passengers per day has been set to 100000.

*Passenger Growth Rate (PGR)*: This rate variable defined in equation (3.2) is the annual increase in the number of passengers. Simple exponential growth is assumed for the simulation period. Thus the value of PGR depends on the size of the current passengers P and passenger growth normal (PGN) and is given by:

$$PGR = Passenger * PGN \quad (3.2)$$

where,

$$PGR = Passenger Growth Rate (person.year^{-1})$$

$$Passenger = Passenger (person)$$

$$PGN = Passenger Growth Normal (constant, year^{-1})$$

*Passenger Growth Normal (PGN)*: it is assumed that the number of air passengers will double in the next 20 years, thus PGN is determined as follows:

$$P(t) = PN * e^{PGN.t} \quad (3.3)$$

where

$$P = Passenger (person)$$

$$PN = Initial Passenger (constant, person)$$

$$PGN = Passenger Growth Rate (person.year^{-1})$$

$$t = Time (year)$$

The resulting value for PGN is roughly equal to 0.035. This value implicitly reflects various factors other than the number of passengers that affects passenger growth rate. Tourism industry, aviation system, economic activity of a city and so forth, all influence the passenger growth rate which are all aggregated into PGN.

In fact the stock of passengers has been considered as an exogenous variable to the system. It has no feedback structure to limit or stimulate growth and is assumed to

grow at a constant fractional rate. In some real systems the number of passengers may change in response to internal conditions of the system.

*Taxi Passengers (TP)*: The taxi passengers indicates the number of passengers that use a taxi to move from or into the airport and is given by the number of passengers at any point in time multiplied by the proportion of passengers that use a taxi (FTP). It has been assumed that 20 percent of the passengers use taxis for their transportation to or from airport, thus FPT is set to 0.2.

$$TP = Passenger * FTP \quad (3.4)$$

where

$$TP = \textit{Taxi Passengers (person)}$$

$$Passenger = \textit{Passenger (person)}$$

$$FTP = \textit{Fraction of the Passengers that use Taxi (constant, dimensionless)}$$

*Car Passengers (CP)*: Passengers not using taxis are assumed to use private cars to and from the airport. Thus:

$$CP = Passenger * (1 - FTP) \quad (3.5)$$

where:

$$CP = \textit{Car Passengers (person)}$$

$$Passenger = \textit{Passenger (person)}$$

$$FTP = \textit{Fraction of the Passengers that use Taxis (constant, dimensionless)}$$

*Taxi Trips (TT)*: Indicates the number of trips made by taxis and is calculated by the number of passengers which use taxis divided by average passengers per taxi trip (AVPTT).

$$TT = TP/AVPTT \quad (3.6)$$

where:

$TT = \text{Taxi Trips (trip)}$

$TP = \text{Taxi Passengers (person)}$

$AVPTT = \text{Average Passenger per Taxi Trip (constant, person.trip}^{-1}\text{)}$

*Average Passenger per Taxi Trip (AVPTT)*: This variable indicates the average number of passengers who are carried by each taxi under normal condition (free flow condition). Considering that the maximum number of passengers that can be carried by each taxi is 3 and the minimum is 1, the average number is set to 1.4.

A more precise formulation might consider AVPTT as a variable increasing under conditions of high congestion and low taxi availability. However for model simplicity it has been set as a constant.

*Car Trips (CT)*: Car trips refer to all the trips to or from airport which are made by private cars. It is given by the number of passengers that use a private car divided by the average number of passenger per car (AVPC) multiplied by the effect of road capacity on car trips (ERCCT) as per following equation:

$$CT = (CP/AVPC) * ERCCT \quad (3.7)$$

where:

$CT = \text{Car Trips (trip)}$

$CP = \text{Car Passengers (person)}$

$AVPCT = \text{Average Passenger per Car Trip (constant, person.trip}^{-1}\text{)}$

$ERCCT = \text{Effect of Road Capacity on Car Trips (dimensionless)}$

It is assumed that some passengers with a return air travel drive their own cars to the airport and park their cars at long term car park. Other passengers are transported with a member of family or friend. Thus AVPCT varies between 1 & 4. Hence in this model the average number for this value has been set to 2.

*Effect of Road Capacity on Car Trips (ERCCT)*: This variable refers to the *Induced Traffic*; a term that has been widely used to describe the observed increase in traffic

volume that happens due to the increase in the capacity of a congested road or after a new road is opened (Litman, 2001).

In urban areas when travel time increases, to avoid congestion some travellers may divert to alternative routes, change the time they make their trips, switch to different travel modes, travel to other destinations, or decide not to make a particular trip at all. The new or widened road facility can carry significantly more traffic before it becomes congested. Many travellers who previously took other routes or travelled at other times may switch to the new facility to take advantage of decreased travel times. These travel decisions can result in additional vehicles on the new road system.

Road construction or extension lead to the above travel behaviour changes that feed back in to the system, and cause unexpected side effects. This phenomenon is known as *Induced Travel Demand* in urban transportation planning literature (Noland and Lem, 2000). Ignoring long term feedbacks of policies can result in unanticipated side effects which are delayed or defeated by the system (Collins et al., 2013).

The underlying theory behind induced travel is based on the simple economic theory of supply and demand. Any increase in road capacity (supply) results in a reduction in the time cost of travel. Travel time is the major component of variable costs experienced by passengers using private vehicles for travel. When any good (in this case travel) is reduced in cost, demand for those goods increases.

In the real world, the relationship between increases in road capacity and traffic is very complex, involving various travel behaviour responses, residential and business location decisions, and changes in regional population and economic growth. Several studies have been conducted to evaluate and quantify the effect of road capacity improvements on traffic volume. In a study by Noland and Cowart (2000) the effect of an increase in road capacity on *Vehicle Mile Travel* (VMT) growth in US urban areas has been forecasted and founded to account for about 15% of annual VMT growth in short term. In another work by (Noland, 2001), assuming historical rates of growth in the road capacity, about 25% of VMT growth is estimated to be due to capacity additions. This trend grows over time as Hansen and Kahne (1975) pointed out in their analysis results that a capacity expansion increased traffic on the improved facility and that the effect occurred over an extended period and grew over time.



Based on the aforementioned studies an aggregate average value for travel growth rate, indicated by the effect of road capacity on car trips (ERCCT) in the model, has been assigned. This value is defined in the following way: First values for traffic growth over time have been estimated through comparisons with similar cases in (Hansen and Huang, 1997, Noland, 2001) as shown in Table 3-1.

Table 3-1 Estimations for the effect of induced traffic demand

Time (year)	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Traffic (Percentage growth)	0.04	0.05	0.07	0.09	0.12	0.13	0.15	0.17	0.19	0.22

Then a regression equation method was used (by the exponential equation) to estimate the effect of induced traffic for a particular time period, with the coefficient of determination ( $R^2$ ) at 0.9663. This method provides the equation as shown in Figure 3-2.

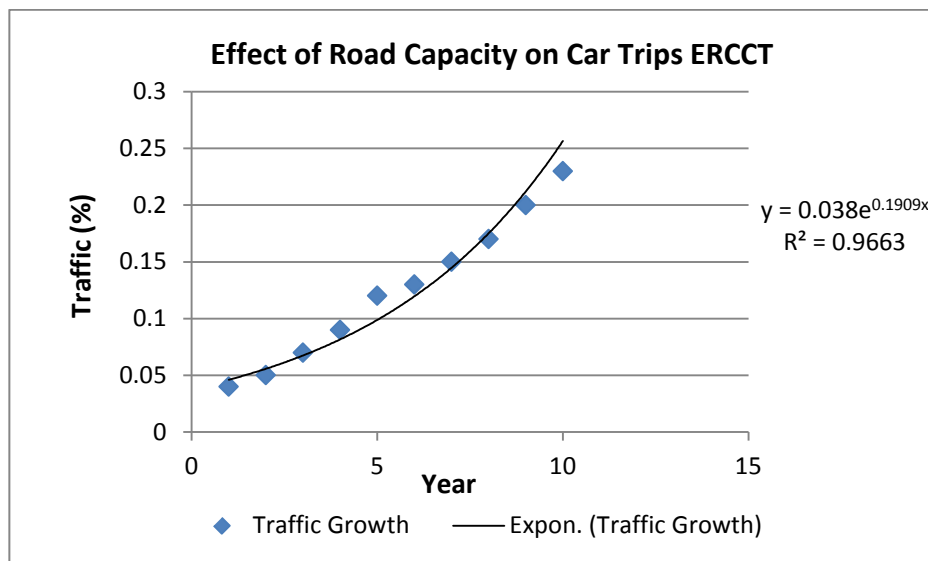


Figure 3-2 Estimations for the effect of induced traffic demand

Accordingly the equation for ERCCT is defined as per follows:

$$ERCCT = \begin{cases} 0.038e^{0.1909*Time}, & \text{if } FFC > 50000, & (a) \\ 1, & \text{if } FFC \leq 50000, & (b) \end{cases} \quad (3.8)$$

where:

*ERCCT = Effect of Road Capacity on Car Trips (dimensionless)*

*FFC = Free Flow Capacity (constant, trip)*

*Time = Time (year)*

This formula suggests that any increase in the road capacity, indicated by free flow capacity (FFC) in the model, will increase the traffic volume over time.

*Total Trips (ToT):* Is simply the sum of taxi trips and car trips.

$$TOT = TT + CT \quad (3.9)$$

where:

*ToT = Total Trips (trip)*

*TT = Taxi Trips (trip)*

*CT = Car trips (trip)*

*Congestion Index (CI):* Congestion index (CI) is defined as a measure to represent the level of congestion in the airport access road. This value is defined by total trips divided by free flow capacity of the road. It should be noted that CI is an average measure in this model and does not capture variations in the congestion level during the day.

Congestion is usually defined as excess demand for road travel: when the travel demand is greater than the capacity of the available road space, congestion occurs and traffic is prevented from moving freely, quickly and reliably (May and Nash, 1996, OECD/ECMT, 2007). Congestion is characterised by slower speeds, longer travel times, unstable travel times and increased queuing and has a number of costs, including travel delays, driver stress and frustration, increased accident risks, wasted fuel, greater air pollution, reduced community amenity and higher costs to business.

$$CI = ToT / FFC \quad (3.10)$$

where:

$CI = \text{Congestion Index (dimensionless)}$

$ToT = \text{Total Trips (trip)}$

$FFC = \text{Free Flow Capacity (constant, trip)}$

*Free Flow Capacity (FFC)*: Is a constant which indicates the total number of vehicle trips that can be made in free flow conditions in a common day on the proposed airport access link. This number has been estimated according to the number of total trips (ToT) at the beginning of the simulation time which is equal to 48717. To start the simulation of the model in free flow conditions and remain in that condition for a while, the value of FFC is set to 50000.

$$FFC \cong ToT(0) + FFCC \quad (3.11)$$

where:

$FFC = \text{Free Flow Capacity (constant, trip)}$

$ToT(0) = \text{Total Trips at start of the simulation time (trip)}$

$FFCC = \text{Free Flow Capacity Control (trip)}$

*Free Flow Capacity Control (FFCC)*: This variable is defined to control the value of FFC, in the following way:

$$FFCC = STEP(\text{height, time}) \quad (3.12)$$

The term *height* implies the value of increase in the number of free flow capacity of the road and *time* suggests the year in which the road is extended.

*Demand for Taxi in Free Flow Condition (DTFFC)*: Is the number of taxis which are needed to transport passengers in normal conditions each day. This value is derived simply by dividing taxi trips by free flow taxi trips (FFTT) per Day.

$$DTFFC = TT/FFTT \quad (3.13)$$

$FFTT = 45$

where:

$DTFFC = \text{Demand for Taxi in Free Flow Condition (dimensionless)}$

$TT = \text{Taxi Trips (trip)}$

$FFTT = \text{Free Flow Taxi Trips (constant, trip)}$

*Free Flow Taxi Trips per Day (FFTT)*: Indicates the number of trips made by each taxi per day. In this model it has been assumed that the airport has a curfew free operation. Accordingly the number of trips in a free flow condition has been set to 30, implying a travel time approximately equal to 45 minutes in free flow conditions. This value for travel time includes the time needed to enter and leave the airport and the taxi queuing time.

*Demand for Taxi (DT)*: Demand for taxi (DT) is the product of demand for taxi in free flow condition (DTFFC) multiplied by the congestion multiplier. This variable indicates the varying effect of congestion on demand for taxi via the congestion multiplier (CM) which will be described in the following equation.

$$DT = DTFFC * CM \quad (3.14)$$

where:

$DT = \text{Demand for Taxi (dimensionless)}$

$DTFFC = \text{Demand for Taxi in Free Flow Condition (dimensionless)}$

$CM = \text{Congestion Multiplier (dimensionless)}$

*Congestion Multiplier (CM)*: CM in equation (3.14) is an auxiliary variable that modulates the number of taxis needed under different congestion conditions. This multiplier represents the variable effect of congestion on the number of taxis. Hence it is a function of the congestion Index (CI).

It is assumed that in this system the only access way to the proposed airport is ground access and the number of passengers will grow exponentially regardless of the effect of road congestion and other factors. Thus the demand for taxis and private vehicles will

increase continually. This trend will increase the congestion level and consequently travel time and thus passengers' waiting time in the airport. In this situation many taxis are stuck in traffic while passengers are waiting at the airport to take a taxi. The unavailability of taxis to meet passengers' demand will increase the demand for taxis consistently with the increase of congestion level. This effect of congestion on the demand for taxi is represented by the congestion multiplier (Fig 3-3).

$$CM = CMF (CI) \tag{3.15}$$

where,

$CM =$  Congestion Multiplier (dimensionless)

$CI =$  Congestion Index (dimensionless)

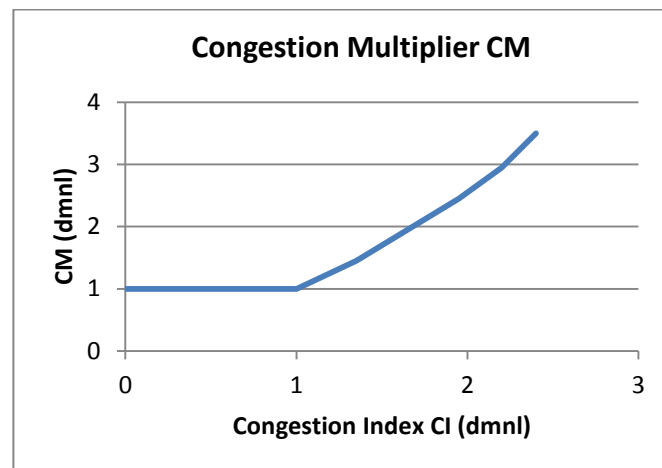


Figure 3-3 Congestion multiplier

A CI less than or equal to 1.0 indicates free flow conditions for vehicles. In this condition the number of taxis needed proceeds at the normal rate equal to the demand for taxis in free flow condition (DTFFC). As congestion takes effect; which is indicated by values of CI greater than one, the demand for taxis increases.

When the number of vehicles on the road is double the free flow capacity, the number of taxis needed is estimated to be 2.5 times the free flow situation. This implies; a 25% increase in taxis needed.

*Travel Time (TrT):* Travel time TrT is defined in the following way:

$$TrT = (24/FFTT) * ECTT \quad (3.16)$$

where:

*TrT = Travel Time (hour)*

*FFTT = Free Flow Taxi Trips (constant, trip)*

*ECTT = Effect of Congestion on Travel Time (dimensionless)*

The first term on the right hand side of the equation (3.16) represents the travel time under free flow conditions. This is then multiplied by the, effect of congestion on travel time (ECTT) to determine the actual travel time.

*Effect of Congestion on Travel Time (ECTT):* This auxiliary variable modulates the value of travel time in response to the traffic flow on the road. Obviously, congestion will have a direct relationship with the number of trips; as congestion increase travel time will increase and then the number of trips by each taxi will decrease.

According to research conducted by Victoria Transport Policy Institute (VTPI, 2013), congestion is a non-linear function of travel time, so as a road approaches its maximum capacity, small changes in traffic volumes can cause proportionately larger changes in congestion delays. In that study traffic congestion impacts was measured based on roadway volume to capacity ratios (V/C). A V/C less than 0.85 is considered under-capacity, 0.85 to 0.95 is considered near capacity, 0.95 to 1.0 is considered at capacity, and over 1.0 is considered over-capacity.

The findings revealed that a 10% increase in traffic volume in a mild over-capacity situation, reduces traffic speeds about 30%. This effect is even more in greater congestion. This trend indicates that on a congested roadway, small increases in traffic volumes can provide relatively large increase in travel times. It should be noted that, these numbers are average measures. For example in that study, traffic volumes are measured as annual average daily traffic and speeds are generally measured for the 85th percentile (the speed below which 85% of vehicles travel).

Travel time depends on various factors other than the capacity such as driving behaviour, weather condition, road geometry, and so forth. However, for simplicity only road capacity and number of vehicles on the road has been considered as the influencing factors of travel time in this model.

$$ECTT = ECTT(CI) \tag{3.17}$$

where,

*ECTT = Effect of Congestion on Travel Time (dimensionless)*

*CI = Congestion Index (dimensionless)*

According to the findings in that research, the lookup table is calibrated as Figure 3-4.

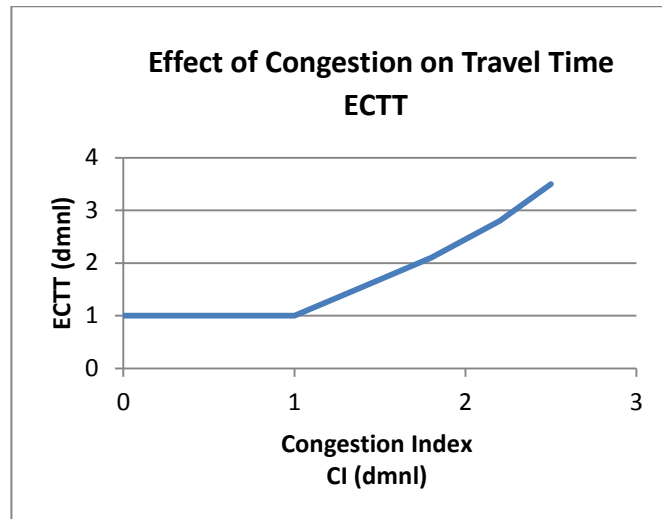


Figure 3-4 Effect of congestion on travel time

This table function has similar properties to the congestion multiplier (CM) described in equation 15. However the effect of congestion on number of taxi trips (ECTT) is slightly more than that on demand for taxi (DT).

*Taxi Trips per Taxi per Day (TTT):* Is the number of trips made by each taxi in actual condition, whether congested or not. The value of TTT is given by the number of taxi trips per day (TT) divided by the number of taxis (T).

$$TTT = TT/T \tag{3.18}$$

where:

$TTT = \text{Taxi Trips per Taxi per day (trip/taxi)}$

$TT = \text{Taxi Trips (trip)}$

$T = \text{Taxi (taxi)}$

### 3.3 Taxi Sector

Taxi sector consists of a single stock of taxis (T) and two flows regulating it and auxiliary variables to modify the rate of flows. The flows determining the rate of change in the number of taxis in this model are the taxi buying rate (TBR) and the taxi selling rate (TSR). The taxi subsystem and the passenger subsystem are joined via taxi availability index (TAI), the auxiliary variable in the stock and flow diagram which implies the supply and demand for taxis in the system and is determined later in this section (Figure 3-5).

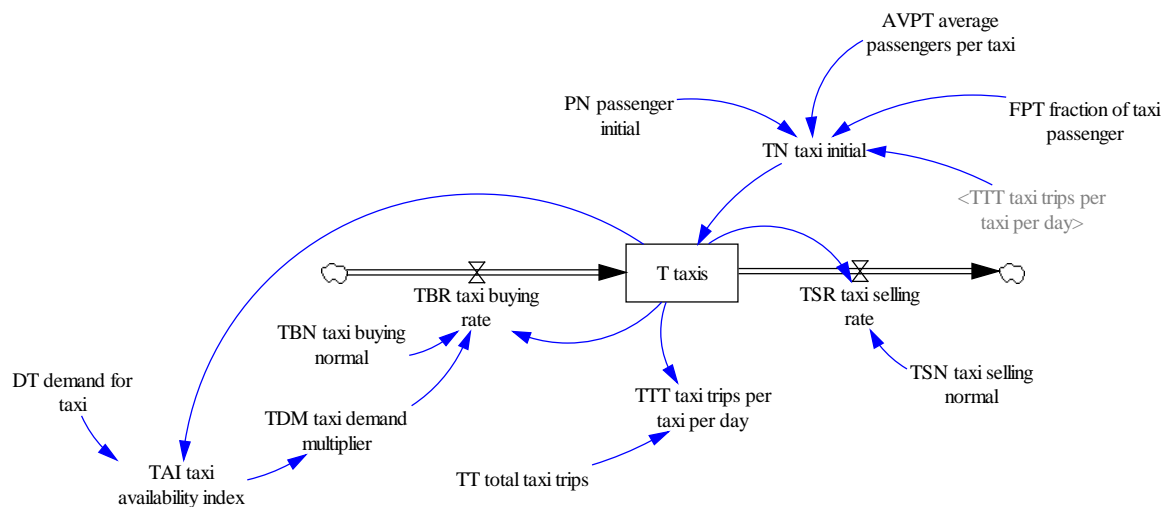


Figure 3-5 Stock and flow diagram of the taxi sector

*Taxis (T)*: The rate of change of the taxi is written as:

$$\dot{T} = TBR - TSR \tag{3.19}$$

where

$T = \text{Taxis (taxi)}$



$TBR = \text{Taxi Buying Rate (taxi. year}^{-1}\text{)}$

$TSR = \text{Taxi Selling Rate (taxi. year}^{-1}\text{)}$

$T(0) = TN = \text{Initial Taxis (taxi)}$

The terms on the right hand of the above equation are derived in the following way:

*Taxi Selling Rate (TSR)*: Specifies the rate at which old taxis are sold to be replaced by new ones. The rate of taxi selling (TSR) represents all factors which might result to sell a taxi, including normal deterioration over time, accidental deteriorations and so forth.

$$TSR = T * TSN \quad (3.20)$$

where:

$TSR = \text{Taxi selling rate (taxi. year}^{-1}\text{)}$

$T = \text{Taxis (vehicle)}$

$TSN = \text{Taxi Selling Normal (1. year}^{-1}\text{)}$

This variable is defined as the product of taxis and a normal fraction; taxi selling normal (TSN). Hence this rate is proportional to the number of taxis.

*Taxi Selling Normal (TSN)*: Specifies the fraction of taxis which are sold each year. To ensure a good first impression of the city for the visitors, most major cities in the world provide high quality ground transport options to airports in terms of comfort and cleanness. A value equal to 0.25 is assigned to taxi selling normal (TSN) implicitly indicates the average age of taxis within the system. A TSN equal to 25% means the average life time of taxi is given as 4 years.

*Taxi Buying Rate (TBR)*: Represents the rate of taxis which are added to the existing taxi stock each year. TBR is defined as the product of taxis multiplied by taxi buying normal (TBN) and buying multiplier (BM).

$$TBR = T * TBN * TDM \quad (3.21)$$

where,

$TBR = \text{Taxi Buying Rate (taxi.year}^{-1}\text{)}$

$T = \text{Taxis (vehicle)}$

$TBN = \text{Taxi Buying Normal (1.year}^{-1}\text{)}$

$TDM = \text{Taxi Demand Multiplier (dimensionless)}$

A growing air travel creates continuing pressures for further growth of the taxi industry which in the model is represented by the taxi buying rate (TBR).

*Taxi Buying Normal (TBN)*: Indicates the fraction of taxis which are added to the system each year under normal conditions. Since the model is intended to represent a growing number of passengers and consequently vehicles, the value for taxi buying normal (TBN) has been assigned slightly more than taxi selling normal (TSN).

*Taxi Demand Multiplier (TDM)*: This multiplier modulates the rate of taxi buying (TBR) in response to the demand for taxis. The value of TDM is a function of taxi availability index (TAI) which is a simple measure of supply of taxis relative to the demand and represents the adequacy of, and demand for, taxis to move the passengers.

$$TDM = TDMF(TAI) \tag{3.22}$$

where:

$TDM = \text{Taxi Demand Multiplier (dimensionless)}$

$TAI = \text{Taxi Availability Index (dimensionless)}$

Figure 3-6 shows the effect of taxi availability index (TAI) on the taxi demand multiplier (TDM). The right side of the graph, where TAI is less than 1.0, corresponds to shortage of taxis; fares are quite high and waiting time in airport to take a taxi is high. This condition suggests to taxi business owners the presence of a demand for additional taxis along with a profitable business. Under such conditions, the value of the taxi demand multiplier stays well above 1.0, and TBR increases consequently. The

value of TDM saturates at around 2. This means that no value of TAI can push TDM above 2 due to the capacity constraints in the system.

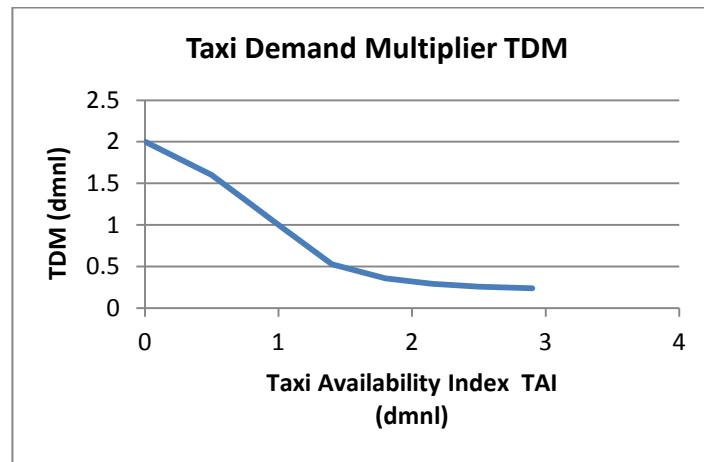


Figure 3-6 Taxi demand multiplier

Under normal conditions ( $TAI = 1.0$ ) the taxi demand multiplier (TDM) equals 1.0. Under conditions of taxi abundance ( $TAI > 1.0$ ), the passenger occupancy rate for each taxi is very low, with many taxis searching at the airport for passengers. This is followed by lower taxi fares, since usually the fares are calculated with a combination of distance and time factors. The taxi market supply is a function of both price and the number of waiting passengers (Wong et al., 2001). Thus lower fares and higher taxi vacancy (lower taxi utilization) will lead to financial losses for the taxi owners and operators. Under such conditions, taxi owners have no incentive to buy new taxis. The value of TDM thus assumes a value less than 1.0 when TAI is above 1.0. However, due to the growing number of passengers the value of TDM never goes to zero to make the TBR zero, even with very high taxi availability.

*Initial Taxis (TN)*: This variable defines the number of the taxis needed to move passengers in the beginning of the simulation period and is given by the number of taxi passengers divided by the number of passengers carried by taxis per day at the beginning of the simulation time as shown in the following equation:

$$TN = (PN * FTP) / (AVPTT * FFTT) \quad (3.23)$$

where,

$TN = T(0) = \text{Initial Taxis}$

$PN = P(0) = \text{Initial Passenger (person)}$

$FPT = \text{Fraction of the Passengers that use Taxi (dimensionless)}$

$AVPTT = \text{Average Passenger per Taxi trip (person. trip}^{-1}\text{)}$

$FFTT = \text{Free Flow Taxi Trips (trip)}$

*Taxi Availability Index (TAI):* This variable provides a simple measure of the adequacy of taxis to meet the passengers demand. It is given by the value of demand for taxi (DT) divided by the value of available taxi stock (T).

$$TAI = DT/T \quad (3.24)$$

where,

$TAI = \text{Taxi Availability Index (dimensionless)}$

$DT = \text{Demand for Taxi (taxi)}$

$T = \text{Taxis (taxi)}$

### 3.4 Train Sector

The next stage of the formulating of the model is to add a train system to the model to examine the dynamics of transition phase from road system to train system. For this purpose, a stock and two flows are added to the previous model. This model extension will allow the investigation of the behaviour of the system under a situation in which passengers change their transportation mode from taxis or private cars to the newly introduced train system. The modified stock and flow diagram encompassing the train sector is shown in Figure 3-7.

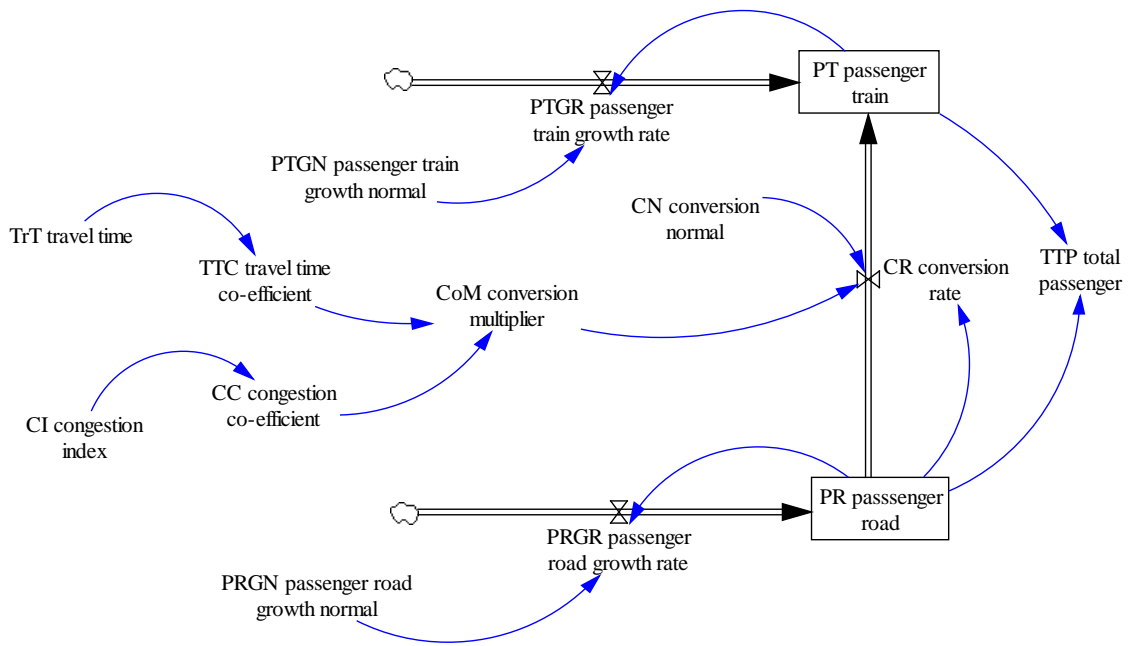


Figure 3-7 Stock and flow diagram of the train sector

Total passengers are divided into two groups, passenger road (PR) and passenger train (PT), each defined as a stock variable. Formulation of the train subsystem is in the following way:

*Passenger Train (PT)*: Is defined as the number of the passengers who will switch their transportation mode to train after the introduction of the train system. The stock of train passengers (PT) accumulates the train passengers' level with the passengers train growth rate (PTGR) and conversion rate (CR) as follows:

$$P\dot{T} = PTGR + CR \quad (3.25)$$

where,

$$PT = \text{Passenger Train (person)}$$

$$PTGR = \text{Passenger Train Growth Rate (person.year}^{-1}\text{)}$$

$$CR = \text{Conversion Rate (person.year}^{-1}\text{)}$$

$$PT(0) = PTN = \text{Passenger Train Initial (constant, person)}$$

*Passenger Train Growth Rate PTGR*: Is defined as the annual increase in the number of passengers which use train to or from airport and is proportional to the number of passengers already using train. This value is defined in the following way:

$$PTGR = PT * PTGN \quad (3.26)$$

$$PTGN = 0.035$$

where:

$$PTGR = \text{Passenger Train Growth Rate (person. year}^{-1}\text{)}$$

$$PT = \text{Passenger Train (person)}$$

$$PTGN = \text{Passenger Train Growth Normal (1. year}^{-1}\text{)}$$

*Passenger Train Growth Normal (PTGN)*: Is the normal fraction of train passengers' growth rate under normal conditions. Normal conditions in this case could be described as a situation in which the road is not congested and vehicles can move freely. A value equal to passenger road normal (PRN) is assigned to PTN.

*Conversion Rate (CR)*: Is the rate of flow of passengers from the road system to the train system. In other words the conversion rate (CR) is the rate at which the passengers change their transport mode from private cars or taxis (road) to the train system. The value for CR is given by the product of road passengers (PR), conversion normal (CN) and conversion multiplier (CoM).

$$CR = PR * CN * CoM + PTP \quad (3.27)$$

where:

$$CR = \text{Conversion Rate (person. year}^{-1}\text{)}$$

$$PR = \text{Passengers Road (person)}$$

$$CN = \text{Conversion Normal (1. year}^{-1}\text{)}$$

$$CoM = \text{Conversion Multiplier (dimensionless)}$$

$$PTP = \text{Passenger Train Programming (person. year}^{-1}\text{)}$$

*Conversion Normal (CN)*: Indicates the proportion of airport passengers which use the train system under normal conditions. The value for CN has been set to 0.025, indicating 2.5 per cent of passengers will switch their transportation mode from road system to train each year.

*Conversion Multiplier (CoM)*: Modulates the rate of change of passenger's transportation mode in regard to traffic flow condition and travel time. CoM is the product of two multipliers which both represent the effect of internal pressures within the system structure on the conversion rate: congestion co-efficient (CC) and travel time co-efficient (TTC).

$$CoM = CC * TTC \quad (3.28)$$

where:

*CoM = Conversion Multiplier (dimensionless)*

*CC = Congestion Co-efficient (dimensionless)*

*TRC = Travel Time Co-efficient (dimensionless)*

*Congestion Co-efficient (CC)*: This multiplier indicates the effect of congestion level on passengers' transportation mode choice.

$$CC = CCF (CI) \quad (3.29)$$

where:

*CC = Congestion Co-efficient (dimensionless)*

*CI = Congestion Index (dimensionless)*

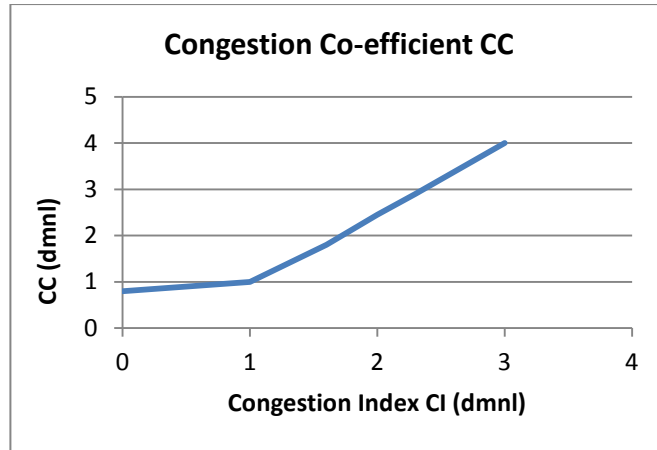


Figure 3-8 Congestion co-efficient

A value smaller than 1.0 for congestion index (CI) indicates free flow conditions on the road. In a such condition due to factors such as strict time constraints, luggage requirements and the relative infrequency of trips made by the train, airport users prefer to take taxis or private vehicles rather than trains. Hence the value of the congestion co-efficient (CC) is less than 1.0. In contrast, values greater than 1.0 for congestion index (CI) will have an incremental effect on the conversion rate (CR). A congested road which is associated with long delays will motivate airport users to change their transportation mode to the train system.

*Travel Time Co-efficient (TTC)*: Indicates the impact of passengers' perception with respect to the travel time on their transport mode choice. Any increase in travel time due to the congestion will stimulate passengers to switch from road system to train system.

$$TTC = TTCF(TrT) \tag{3.30}$$

where:

*TTC = Travel Time Co-efficient (dimensionless)*

*TrT = Travel Time (minutes)*

The average travel time in free flow condition in this system has been set at 45 minutes. The amount of travel time will affect the switching behaviour of passengers from taxis or cars to trains monotonically. This effect is depicted in Figure 3-9.



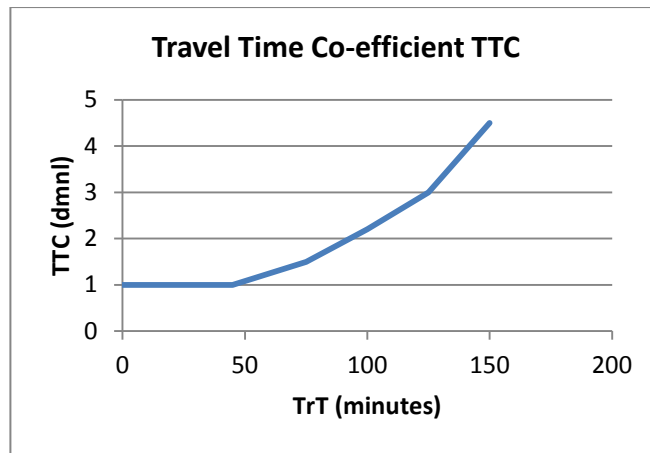


Figure 3-9 Travel time co-efficient

*Passenger Train Programing (PTP)*: This variable is an exogenous variable defined to control the number of passengers which change their transport mode to train after opening the train system. To define this variable a STEP function is used as following:

$$PTP = STEP (height, time) \quad (3.31)$$

where,

$$PTP = \text{Passenger Train Programing (person.year}^{-1}\text{)}$$

The term *height* implies the number of passengers which immediately switch their transport mode to train by introducing the train system and *time* suggests the year in which the train system is established.

### 3.5 Chapter Summary

This chapter explained how the model used in this research was derived. The process of formulation is described step by step and data used were based on assumptions about a hypothetical city. The model variables were selected based on what is necessary to understand the effects of congestion-mitigation strategies on the taxi industry and the traffic conditions on the proposed road. In addition, where needed, evidence from the literature review was used to develop the conceptual idea for this model.

The complete stock and flow diagram including all variables of the model is presented in Figure 3-10. All the equations used in this model were also shown and explained in detail. The list of the symbols used in the model with their meaning can be found in Appendix 1. Also the complete formulae documentation listing in Vensim is located in Appendix 2. In the next chapter this model will be used to study the behaviour of the system under different policy scenarios and effects and consequences of each of them.

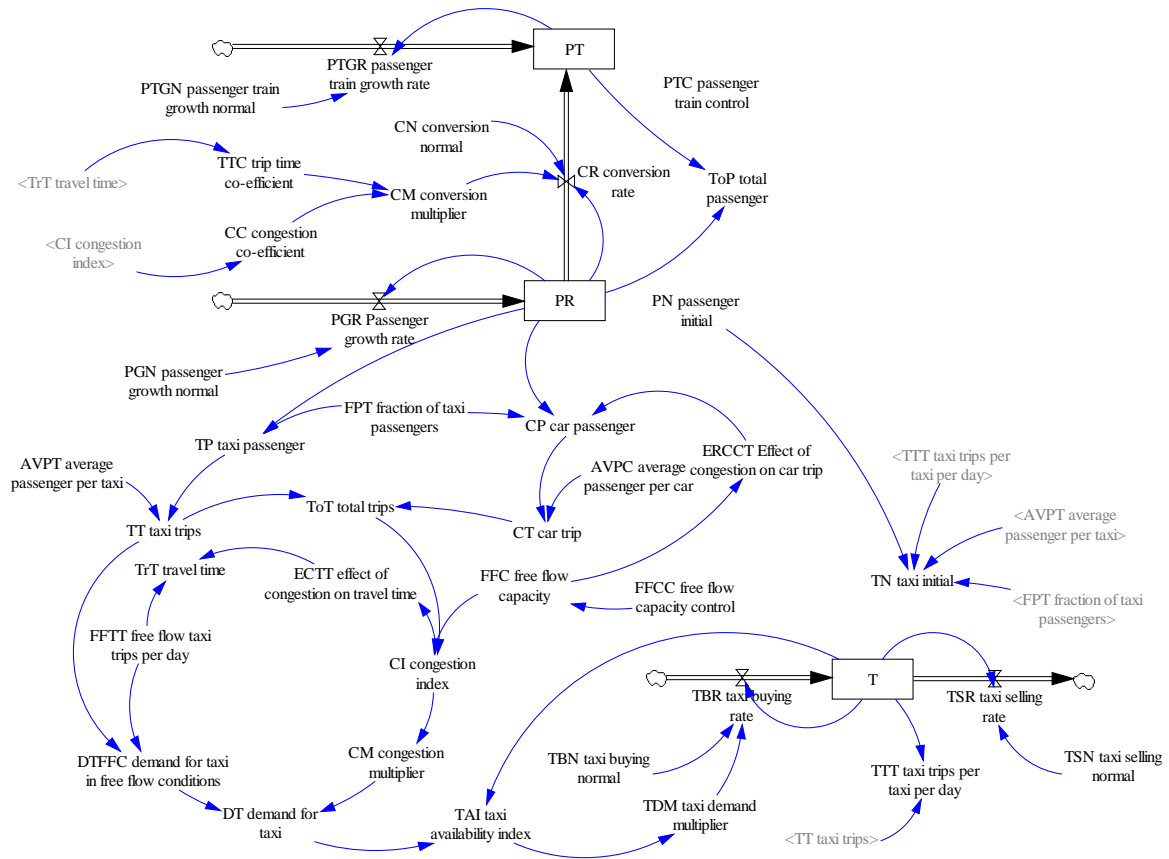


Figure 3-10: The complete stock and flow diagram

## Chapter 4

### MODEL IMPLEMENTATION AND POLICY ANALYSIS

#### 4.1 Introduction

The model formulated in chapter three outlined the structure of the proposed airport access system. In the following sections, the initial values of the levels and other parameters will be assigned and then the model will be solved using these values. The model outputs and a discussion of the results will then be presented.

Further, in order to explore and illustrate the dynamic consequences of congestion-mitigating strategies, four policy scenarios proposed by authorities, will be examined using the model. It is assumed that these policy options are proposed by local governments. Then the simulation results are analysed to gain more in-depth insights into the socio-economic consequences of each policy for the taxi industry and its workforce.

Finally, in order to examine the system's responses to variations of input parameters, a series of sensitivity analyses were conducted.

##### 4.1.1 Policy Options

It is assumed that the authorities will consider the following strategies to be implemented in order to relieve the congestion problem on the proposed airport access road:

- Scenario 1: Increasing the road capacity at year 10
- Scenario 2: Introducing the train at year 10
- Scenario 3: Increasing the road capacity at year 5 and opening the train system at year 10
- Scenario 4: Opening the train system at year 5 and increasing the capacity of the road at year 10

The model is simulated for 20 years under the above 4 scenario options and the effects of each scenario on the taxi industry and its workforce will be evaluated. It should be

noted that, both scenarios 1 & 2, as described in detail later in this section, are not able to solve the congestion problem on the road throughout the simulation time. Under these scenarios, the road experiences a very short period of free flow conditions and after a few years congestion will be even greater than the intervention time. Hence in scenarios 3 and 4, a combination of two strategies will be examined on the system.

#### 4.1.2 Measures of Taxi Utilization and Taxi Industry Viability

To address the aim of this study, three variables of the model are defined as measures of taxi utilization and therefore indicators of viability of the taxi industry. These three variables; taxi availability index (TAI), travel time (TrT) and taxi trips per taxi per day (TTT), determine the working conditions and possible disruptions in the taxi industry as a result of any intervention in the system.

According to Wong et al. (2001) taxi utilization is a direct measure of taxi market profitability. Average taxi utilization is defined as the ratio of the total occupied taxi time to the total taxi service time. This is mainly because most taxi fares are comprised a combination of travel time and distance travelled. There are two opposing impacts of congestion on taxi utilization in this system. First, as congestion increases travel time increases and hence taxi occupancy time and taxi utilization also increase. Second, as congestion increases, due to the longer travel times, the number of trips by each taxi reduces which is another measure of taxi utilization. On the other hand, when congestion reaches an unbearable level, despite the higher taxi occupancy time, increased stress and fatigue and also excessive fuel and maintenance costs make the taxi industry inefficient.

The combined effect of these opposing forces leads to either higher or lower taxi utilization, depending on the amount of increase in the congestion level. In this model the taxi industry conditions will be evaluated and analysed by incorporating varying combinations of these opposing factors. These varying effects have been aggregated to TrT and TTT variables in the model in this study.

Travel time (TrT) is a direct measure of taxi utilization. A longer travel time is meant to increase the taxi utilization due to increasing the taxi occupancy time and thus taxi fares. However it will have a counter effect on taxi utilization when it is higher than an

acceptable level, with a reduced number of taxi trips per taxi per day (TTT). As described earlier when TrT exceeds an acceptable level, the number of taxi trips per taxi per day reduces dramatically. Hence TrT alone does not necessarily correspond to taxi market utilization and in order to study the efficiency of the business, the combined effect of TrT and TTT must be taken into account.

Taxi availability index (TAI), is a simple measure of demand for taxis relative to the supply and represents the adequacy of, and demand for, taxis. In this study, TAI is used in an aggregate sense to include such measures of the taxi industry conditions as taxi fares, employment conditions, job satisfaction etc. A value higher than 1.0 for TAI means that the taxi fleet is bigger than the demand for taxis, indicating relatively unfavorable working conditions for the taxi industry such as lower fares, long waiting times and circling of taxi drivers at airports in search of passengers. In such conditions, some taxi operators or drivers can be expected to leave the industry due to the market inefficiency. Conversely, when the TAI falls under 1.0, implying the demand for taxis is higher than the supply, relatively favorable conditions for the taxi industry are indicated. Hence hereinafter taxi utilization and in general the taxi industry conditions will be evaluated based on TAI, TrT and TTT. It should be noted that generally, TAI provides more insight into taxi market conditions compared to the latter variables which reflect the effects of congestion.

It is worth mentioning that while the oversupply of taxis ( $TAI > 1.0$ ) is desirable for passengers due to low waiting times and lower average fares per taxi trip, it reduces taxi utilization with lower taxi occupancy time and thus leads to loss of profits for taxi owners and operators and the taxi industry as a whole. On the other hand, a shortage of taxis ( $TAI < 1.0$ ) resulting in higher taxi utilization will lead to high passenger waiting times and therefore will reduce the satisfaction of passengers and the airport's competitiveness (Chmura Economics&Analytics, 2008).

Additionally, 56% and 19% of airport managers state the circling of taxis due to excess supply as a problem of some degree and a serious problem, respectively in the airport system (Chmura Economics&Analytics, 2008). Increased taxi supply may also result in changes to taxi regulations which is politically challenging due to multiple stakeholders in the taxi industry (Yang et al., 2010). Furthermore, the excess taxi

supply results in competition for passengers amongst drivers and waste of valuable taxi service time. However, since the focus of this study is studying the viability of the taxi industry, a value equal to or slightly below 1.0 for TAI implies more favourable conditions for those involved in the industry.

## 4.2 Model Implementation

In this section, specific values for the initial values and other parameters will be assigned and then the model will be simulated with these values. This will be followed by a presentation of the model output and a detailed discussion of the results.

The Euler method with a time step of 0.5 is used in VENSIM to solve the system equations. Further simulations were undertaken with the Runge–Kutta method to check for qualitative behaviours of the system which were not affected by the choice of integration method. Moreover, experiments were conducted with different time steps to ensure the qualitative aspects of the solution were not affected by the choice of time step.

### 4.2.1 Input Data

Information and data shortages are considered a major barrier to socio-economic modelling (Forrester, 1975). However, System Dynamics is concerned with behaviour patterns rather than the precise values. The overall model behaviour does not depend on precise input values or on the exact shape of the multipliers. Forrester (1975) says: “So you have first of all the non-availability of data. But more important, you have the question of whether you in fact need data?” System Dynamics models are not derived statistically from time-series data. Instead, they are statements of system structure. They contain the assumptions being made about the system. In fact, the ability to build a model structure and relationships which properly represent the system under study determines the utility of the model (Forrester, 1971a). For example in *Urban Dynamics* to guess the values for parameters and initial values, Forrester assumed that the model outcomes are insensitive to the values assigned, insisting data do not matter. Alfeld and Graham (1976) believe knowledge about a real process can be used to specify parameter values directly. The model is easier to explain, sell or have confidence in if

each parameter and each equation stands individually as a plausible and realistic representation of some real processes.

The proposed airport access system in this study is within a hypothetical city. However, to provide more realistic magnitudes and behaviours of the system, some of the required input data for the model such as initial values for levels or constant parameters have been taken from the Melbourne Airport Rail Link Study (PTV, 2013). Other data are based on sensible and reasonable assumptions by the author. Values for the 8 parameters and the initial values of 3 level variables are required as input for the model. The detailed explanation of the selection of initial value and the shape of the multipliers is provided in chapter 3. Table 4-1 displays the initial values and parameters used in the model.

Table 4-1: Initial values and parameters as input data

<b>Variable Name</b>	<b>Variable Definition</b>	<b>Variable Type</b>	<b>Initial Number/ Parameter Value</b>	<b>Unit</b>
PRN	Passenger Road Initial	Initial Value	100000	person
PGN	Passenger Growth Normal	Constant	0.035	1/year
FPT	Fraction of Taxi Passenger	Constant	0.2	1/year
AVPT	Average Passenger Per Taxi Trip	Constant	1.3	person/trip
AVPC	Average Passenger Per Car Trip	Constant	2.4	person/trip
FFC	Free Flow Capacity	Constant	50000	trip
TN	Taxi Initial	Initial Value	512	taxi
TBN	Taxi Buying Normal	Constant	0.3	1/year
TSN	Taxi Selling Normal	Constant	0.25	1/year
PTN	Passenger Train Initial	Initial Value	0	person

CN	Conversion Normal	Constant	0.025	1/year
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#### 4.2.2 Reference Mode of Behaviour

Using the initial values for level variables and other parameters as presented in Table 4-1, the model is simulated for 20 years. In this section the simulation results of the most important variables are presented in the following graphs and discussed in detail to explain the overall behaviour. Figure 4-1 shows the overall reference behaviour of the model, and Figures 4-2 and 4-3 demonstrate more specific aspects of the reference behaviour. The reference simulation represents as the standard with which other model simulations can be compared.

The model simulation starts at equilibrium in which the road is congestion free and the number of taxis (T) equals the demand for taxis (DT) as displayed in Figure 4-2. In order to illustrate the equilibrium conditions on the road, the reference simulations are performed two years prior to the period of the study which is indicated by year -2 in the reference graphs. The passengers' growth normal (PGN) is set to zero during these two years, and then set to 0.35 from year 0. In addition, the value of taxi buying normal (TBN) has been set equal to the taxi selling normal (TSN) until time zero. All the further simulations will start at year zero.

Figure 4-1 displays that the number of passengers (PR), taxis (T) and consequently congestion index (CI) remain unchanged until year 0, and then grow smoothly during the next 20 years. The stability of these variables within the first two years is due to the passenger's growth normal (PGN) which was assumed to be zero until the onset of the period of the study. While the number of passengers grows smoothly and doubles in 20 years, as assumed for the hypothetical city, the number of taxis doesn't change significantly until year 5. This is due to the delays in the system to adjust the taxi stock to the rapidly growing number of passengers. Then it starts to keep pace with the growing number of passengers. Eventually, after year 10, the rate of growth of taxi stock exceeds that of passengers.

The immediate increase in the number of the taxis after year 10 is mainly due to the rapidly growing congestion level (CI). As congestion increases, vehicle speeds



decrease and thus travel time (TrT) increases. Consequently the number of trips by each taxi (TTT) reduces and hence the demand for taxi and private vehicles becomes higher than that in free flow conditions as shown in Figure 4-2. This higher demand for taxis will increase the taxi purchasing rate via the taxi demand multiplier (TDM). The effect of congestion on the demand for taxis is applied by the congestion multiplier (CM), which in turn affects the stock of taxis through the taxi demand multiplier (TDM) in the model.

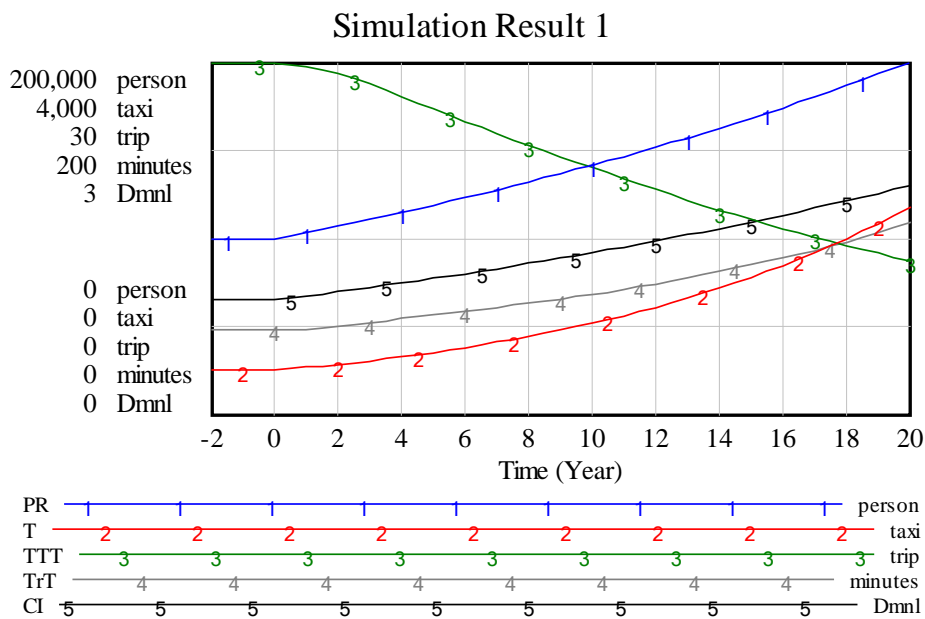


Figure 4-1: Reference behaviour: the growth of passengers’ road (PR) and taxis (T) is stopped until year zero, and thus all variables are unchanged. After this point, all variables; passengers road (PR), taxis (T), travel time (TrT), and congestion index (CI) grow, except for the taxi trips per taxi per day (TTT) which reduces by more than a half.

From the simulation results in Figure 4-1, one can see that without any intervention in the system, at the end of the simulation time, the congestion level is double its initial value. Consequently travel time (TrT) becomes over 2.5 times the initial value, almost 110 minutes, and trips per taxi per day (TTT) falls by more than a half, around 13 trips per day, during this time. Hence it is deduced that a rise in the congestion level on the road, increases the number of taxis and thus the size of the taxi industry. However, when it reaches an unacceptable level, reduces the profit for individual taxi owners and operators due to the increased travel times and less trips per taxi per day.

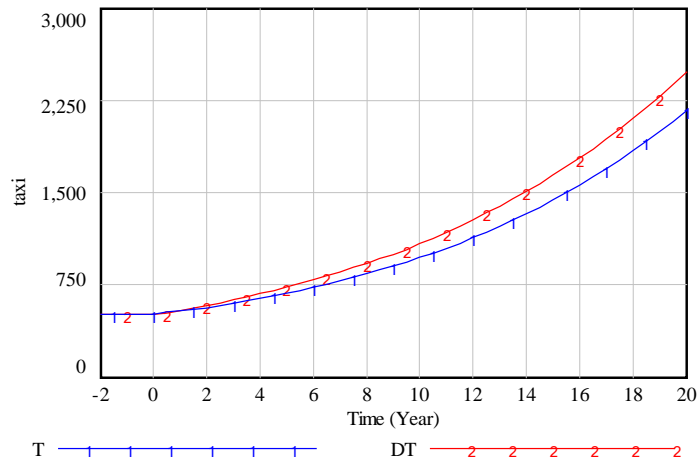


Figure 4-2: The gap between available taxis (T) and demand for taxis (DT) increases over time due to the growing congestion.

Figure 4-2 shows that while the number of taxis (T) and the demand for taxis (DT) are equal at the onset of the simulation, the value of the latter variable exceeds that of the former over time. Therefore at the end of the simulation time, there is a gap between the demand and supply of taxis. The rate of growth of taxis has been higher than that of passengers, and yet unable to meet passenger's demand for taxis. This shortage of taxis implies longer passenger waiting time to catch a taxi at the airport which will negatively affect passengers' satisfaction.

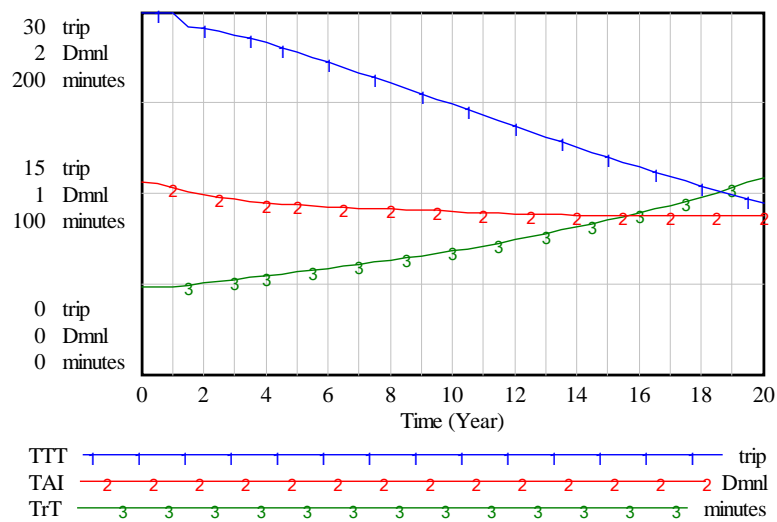


Figure 4-3: Taxi trips per taxi per day (TTT), taxi availability index (TAI) and travel time (TrT) are defined as measures of taxi utilization: At the end of the simulation time, the number of taxi trips per day per taxi (TTT) is less than half and travel time (TrT) is more than

double their initial values. Taxi availability index (TAI) is quite low which implies shortage of taxis.

Figure 4-3 depicts the measures of taxi utilization; TAI, TrT and TTT in the reference case. Towards the end of the simulation time, the road experiences heavy traffic congestion and despite the bigger taxi fleet relative to the number of passengers, a taxi shortage exists which is shown by declining values of taxi availability index (TAI). This is mainly because of the large number of taxis stuck in the traffic and implies long queues of passengers waiting to catch taxis. The number of trips per day per taxi is less than half (13 trips) and travel time is more than double its initial value (110 minutes). From the passengers' perspective, the expected customer waiting time is generally considered as an important value or quality of the taxi service in airports (Yazici et al., 2013). The increased travel time will also result in higher fares per taxi trip due to the time factor. This is a very inefficient mode of transportation from the passenger's point of view, due to longer travel times and higher fares and may affect their choice of airport.

This frustrating traffic congestion is a significant threat to further development of the airport system and is likely to severely impact the economic viability of the city which is highly dependent on tourism industry. Therefore when the congestion level exceeds the capacity of the road, congestion reduction strategies are required to alleviate the traffic congestion to an acceptable level.

### 4.3 Policy Analysis

In this section the model will be utilized to examine the four congestion-mitigating strategies which are explained earlier. The simulation results will then be analysed to gain more in depth insights into the consequences of each strategy on the taxi industry and its stakeholders. Following, analysis of the simulation results, the advantages and disadvantages of each strategy will be described and discussed in detail. Table 4-2 presents the selection and timing of policy options in each scenario.

Table 4-2: Selection and timing of policy scenarios

Scenarios	Train	Road	Timing (Year)
Scenario 1		•	Y10
Scenario 2	•		Y10
Scenario 3	•	•	Road Y5 + Train Y10
Scenario 4	•	•	Train Y5 + Road Y10

### 4.3.1 Scenario 1

One of the most direct solutions to a congestion problem is increasing the road capacity. In this model an increase in road capacity corresponds with an increase in free flow capacity (FFC). Figure 4-4 shows the results of a 40% increase in FFC at year 10 on different variables of the model. After increasing the road capacity at year 10, congestion drops by almost 35% and almost returns to its original value. However, soon after the capacity extension, the growth of the number of passengers coupled with the excess travel demand induced by the road capacity extension, will eventually lead to greater congestion at the end of the simulation time.

Until year 10, due to the growing congestion, the number of taxis has grown faster than the number of passengers. Therefore with increasing the road capacity taxi availability index (TAI) rose by about 27%, to almost 1.22, indicating the supply of the taxis is 1.22 times the demand for taxis. With a lower demand served by a bigger taxi fleet, a surplus occurs, leading to lower revenues for taxi operators. Moreover, due to the shorter travel times, taxi occupancy time and thus fares for each trip are likely to reduce. Consequently, the taxi buying rate (TBR) will reduce through the taxi demand multiplier (TDM) in the model, in response to the lower demand for taxis. Thus the number of taxis remains steady for about three years and the taxi industry does not have any growth in this period.

### Simulation Result (Scenario 1)

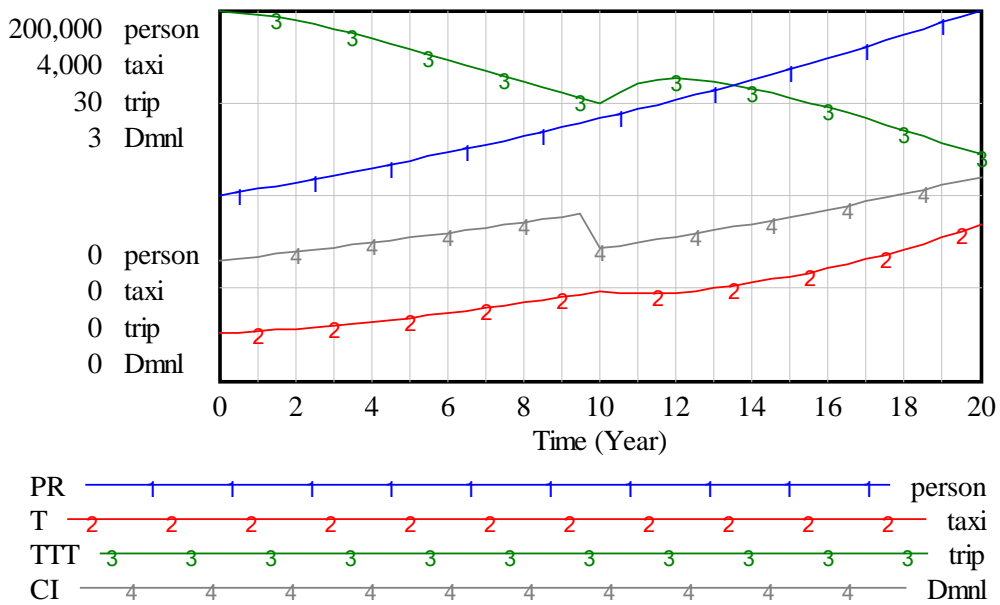


Figure 4-4: System behaviour under scenario 1: the rate of growth of taxis (T) stops growing for 3 years, congestion index (CI) after a 35% drop, increases during the next years and becomes even greater at year 20.

As depicted in Figure 4-5, the number of trips per taxi TTT doesn't increase relative to the congestion reduction and travel time. This is due to the oversupply of taxis relative to the number of passengers. In this situation taxi utilization declines considerably since taxis are not working to their full capacity due to the shorter travel times and spend considerable time searching for passengers. However, due to the unchanged number of taxis and growing number of passengers, TTT grows until year 12.

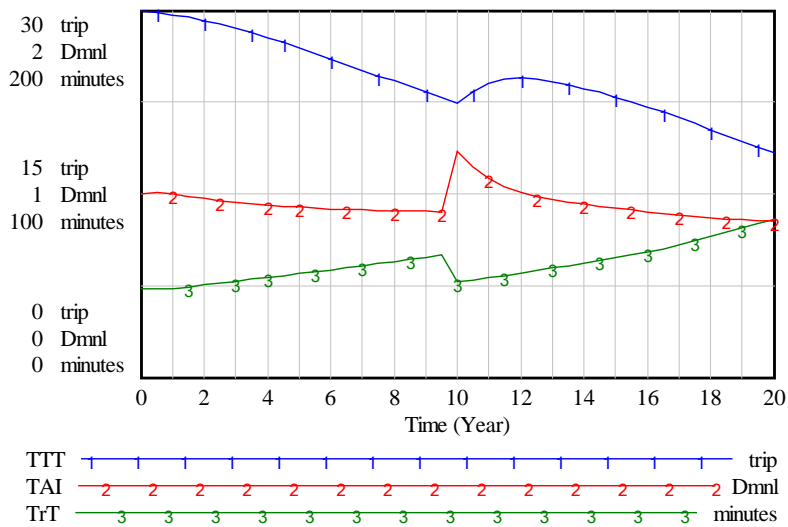


Figure 4-5: Measures of taxi utilization under scenario 1: taxi availability index (TAI) rise by 27% and returns to its previous value by almost 4 years. Taxi trips per taxi per day (TTT) grow until year 12 and then declines over the next years. Travel time (TrT) after a 20% fall, increases over time.

After year 15, as a result of the increased congestion level and hence demand for taxis, the TAI returns to almost its level at year 10, approximately 0.9, which means the demand for taxis exceeded the available taxi stock. Accordingly, the rate of taxi purchasing increases via the taxi demand multiplier (TDM) and the number of taxis grows quicker. In fact, the feedback loop comprised of taxis (T), the taxi buying rate (TBR) and the taxi demand multiplier (TDM) in the model regulates the stock of taxis continually to match up with the passengers demand for taxis. This is shown by the feedback loop in Figure 4-6. A comparison between Figures 4-1 and 4-4 indicates that a 40% increase in the road capacity resulting in 27% excess taxi supply, will reduce the rate at which taxis increase. Therefore the number of taxis at the end of the simulation time (1700 taxis) is lower than the reference simulation (2300 taxis) which implies smaller developments in the taxi industry.

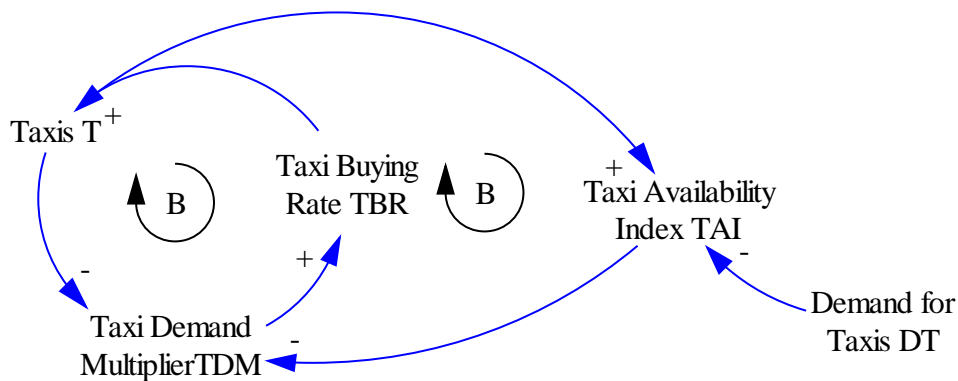


Figure 4-6: Balancing (B) or negative feedback loop regulates the stock of taxis continually via taxi demand multiplier (TDM) to match up the passengers demand for taxis: an increase in the demand for taxis (DT) will increase the number of taxis via TDM. Conversely, oversupply of taxis will reduce the taxi buying rate (TBR) and thus the number of taxis (T).

Whilst an immediate oversupply of taxis occurs after implementing this scenario, the number of TTT is higher than the reference case due to the stabilized number of taxis and shorter travel times. However, taxi occupancy time and thus taxi utilization

reduces due to shorter travel times. This is likely to reduce the fares for each trip and therefore the overall revenue of taxi operators.

### 4.3.2 Scenario 2

In this section, the behaviour of the system after establishing a train system at year 10 will be observed and analysed. It is supposed that immediately some 15% of daily passengers will switch their transport mode to the train system and the number of train passengers' (PT) will increase smoothly to the full capacity of the train system within a couple of years. The gradual increase of train carrying capacity implies increasing the frequency of train services. It is assumed that the train carrying capacity will respond according to the passengers' patronage; a higher patronage will lead to higher frequency of train services.

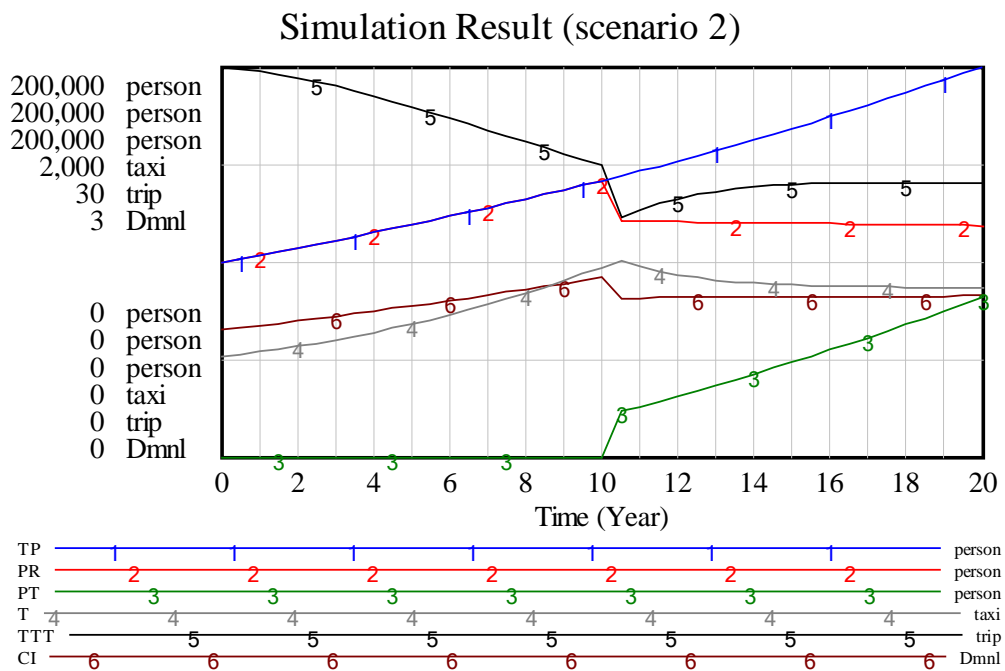


Figure 4-7: System behaviour under scenario 2: Passengers' road (PR) after a 15% drop, decline over time. Passengers' train (PT) after a 15% jump, increase rapidly. The stock of taxis reduces until year 15 and then remains unchanged.

Figure 4-7 shows the effects of introducing a train system at year 10. The number of train passengers (PT) after a sudden jump of around 15% of the road passengers at year 10 continues to rise and reaches approximately 40% of total passengers' number per

day at year 20, after 10 years of service. Conversely, the number of road passengers drops by 15% at year 10 and reduces slightly over the same period of time as shown in Figure 4-7. This suggests that after opening of the train system, its patronage continues to grow while the number of passengers which use the road system declines, despite the continuous growth of the number of the total passengers (TP).

With the introduction of the train system, taxi drivers lose part of their potential customers and therefore the demand for taxis (DT) drops significantly. It then remains unchanged at a lower level than the available taxis. Accordingly the stock of taxis continuously declines until year 15 in response to the reduced demand. It then remains unchanged until year 20, mainly due to the stabilized TAI (refer to Figure 4-8). As a result of the significant reduction of the demand for taxis, the number of trips per taxi per day (TTT) also drops more dramatically; from 22 to 18, and grows slowly until year 15, when it reaches 20 trips per day. The continuous reduced demand for taxis is likely to discourage further investments in the taxi industry which is shown by the reduced number of taxis in the simulation results (refer to Figure 4-7). This indicates that some of the taxi owners will have to sell their taxis and leave the business due to the inefficiency of the business.

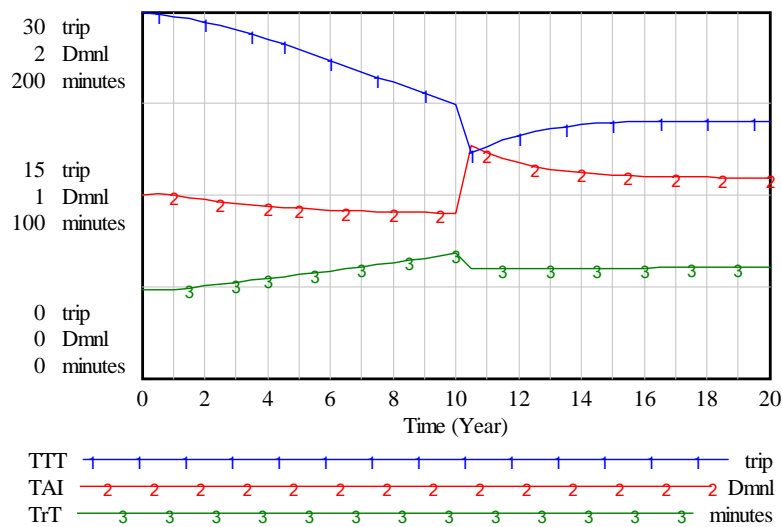


Figure 4-8: Measures of taxi utilization under scenario 2: Taxi trips per taxi per day (TTT) drops from 22 to 18, and then grows slowly to 20 trips per day. Taxi availability index (TAI) rises by almost 40% at year 10 and declines smoothly during the next years. Travel time (TrT) after a decline, remains steady for the next 10 years.



By introducing the train system, TAI rises by almost 40% at year 10 and declines smoothly until year 15. Then the continuous increase of train capacity as a result of the increased frequency of train services (due to the passengers' growth) coupled with the declining taxi stock gives an almost unchanged TAI at about 1.1 for the rest of the simulation time. This indicates that an immediate oversupply of taxis occurs after setting off the train system at year 10. However, due to the declining number of taxis until year 15, TAI reduces during next five years and then remains almost unchanged at 1.1 until year 20. This sudden jump in TAI coupled with reduced number of TTT and also TrT, implies considerable disruptions in the taxi industry for almost two years after the intervention. However, the system experiences minor oversupply of taxis after year 12 since the stock of taxis adjusts its value to the demand for taxis. After a sudden decline, travel time for vehicles also remains steady for the next 10 years. However it is slightly higher than that on free flow conditions.

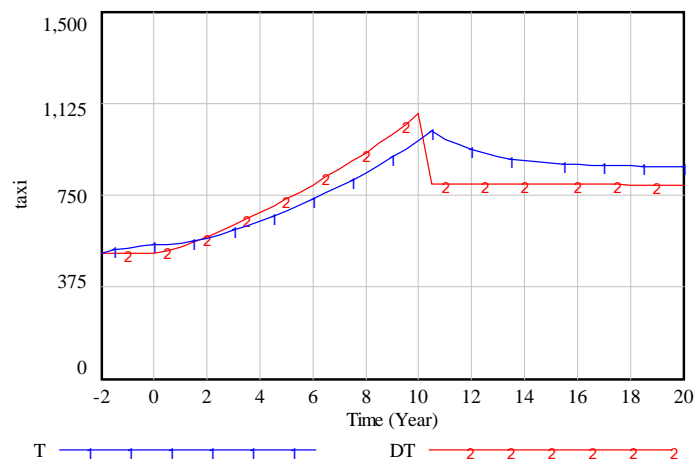


Figure 4-9: Taxis (T) and demand for taxis (DT) under scenario 2: by introducing the train, demand for taxis (DT) drops dramatically below the available taxis (T) and a surplus of taxis occur.

### *Discussion*

From the simulation results of scenarios 1 and 2, one can find that both policies alleviate the congestion for a while. However they have different ultimate effects on the taxi industry and its workforce, especially in the long term. Figure 4-10 shows that in scenario 1, after a sharp fall at year 5, the congestion level continues to rise again and at the end of the simulation time it is even greater than that on intervention time. In

scenario 2 however, the congestion level drops less but then remains steady for the rest of the simulation time.

In the short term, both policy interventions will have some undesirable effects on the taxi industry which is indicated by sudden jumps in TAI and reduced TTT and TrT in the simulation results. These negative externalities include a surplus of taxis relative to the demand and thus lower taxi utilization, lower taxi fares and thus lower revenues, wasteful competition among taxi drivers in search of passengers and therefore substantial waste of valuable taxi service hours which will result in increased stress and fatigue of taxi drivers. All of these factors in turn will discourage further investments in the taxi industry as a whole.

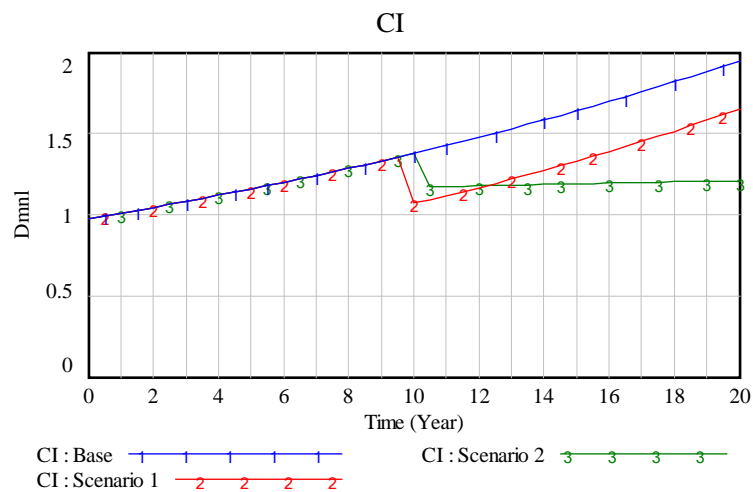


Figure 4-10: Congestion index under scenario 1 and 2: over the long run, scenario 2 has a more sustainable influence on congestion relief compared to scenario 1.

Figures 4-10 and 4-11 indicate that while scenario 2 has a more sustainable influence on congestion relief compared to scenario 1; it does not have the same desirable consequence for the taxi industry. A comparison between measures of taxi utilization in Figure 4-11 reveals that in general, increasing the road capacity seems to be more desirable for the taxi industry and its workforce. The introduction of the train system will cause greater disruption to the industry than increasing the road capacity. The rise of TAI which in scenario 2 is slightly more than the first one, is the main indicator of previously mentioned disturbances in the taxi industry. Moreover, in scenario 1, TAI

returns to its previous level within a few years, while under the latter scenario, TAI remains over 1.0 during the next 10 years.

Figure 4-12 displays TTT which is another indicator of the taxi utilization. It can be seen that under scenario 1, overall, the TTT is higher than in scenario 2. Hence, taking all these factors into consideration, it seems that after a sudden disruption due to the policy intervention, under the scenario 1 the working conditions for taxi owners, operators, and drivers improves over time while in the second scenario it remains poor. The continuous unfavourable conditions in the taxi industry under the second scenario may result in some people leaving the business. This will in turn improve the conditions for those people who have remained in the taxi industry.

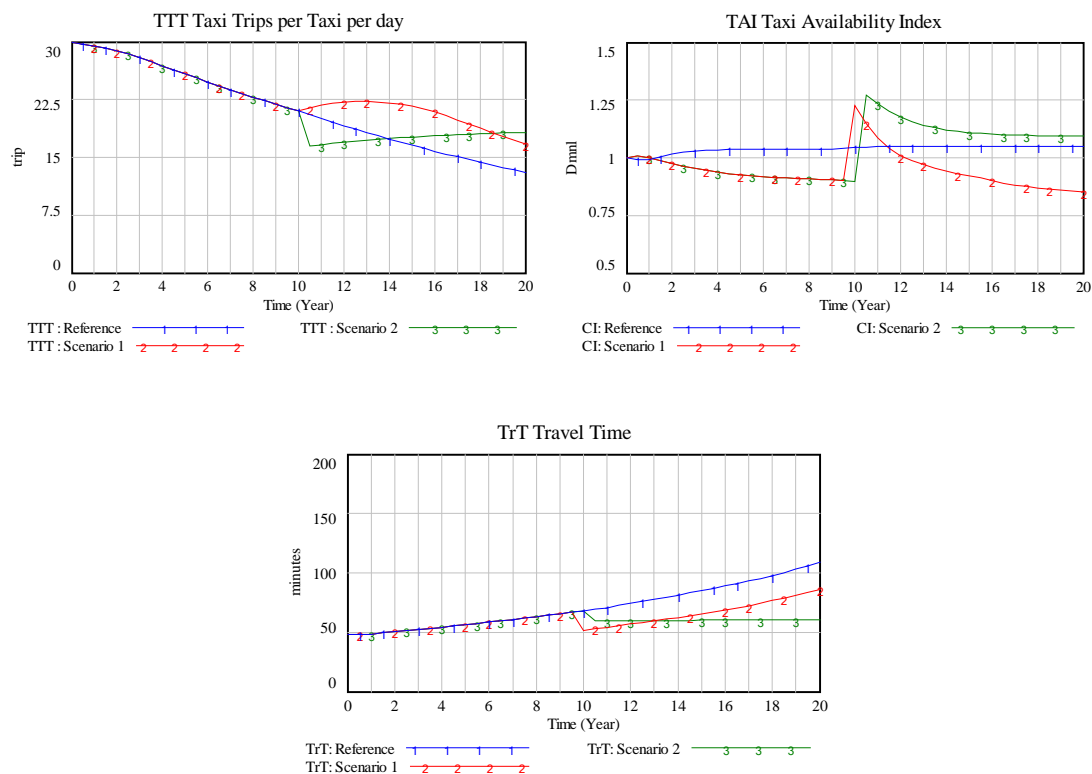


Figure 4-11: Taxi utilization under scenario 1 and 2: The introduction of the train system will cause greater disruption to the taxi industry than increasing the road capacity due to lower TTT and higher TAI.

Usually one major concern for policymakers is the timing effects of interventions in the system. Figure 4-12 indicates that an earlier policy intervention in the system leads not only to a smaller congestion level during the simulation time, but also more sustainable conditions for the taxi industry in terms of employment, revenues and

overall job satisfaction. In both strategies earlier intervention leads to smaller increases in the TAI which corresponds to a smaller reduction in demand for taxis (DT) and therefore more trips per taxi per day (TTT). A later intervention results in a larger taxi fleet due to the combined effect of a growing number of passengers and congestion levels over time. Consequently, a greater oversupply of taxis will occur as a result of a later intervention. It is worth mentioning that, an earlier intervention leads to a smaller taxi industry compared to a later intervention. However, the working conditions for individual taxi owners and operators are better as a result of an early intervention.

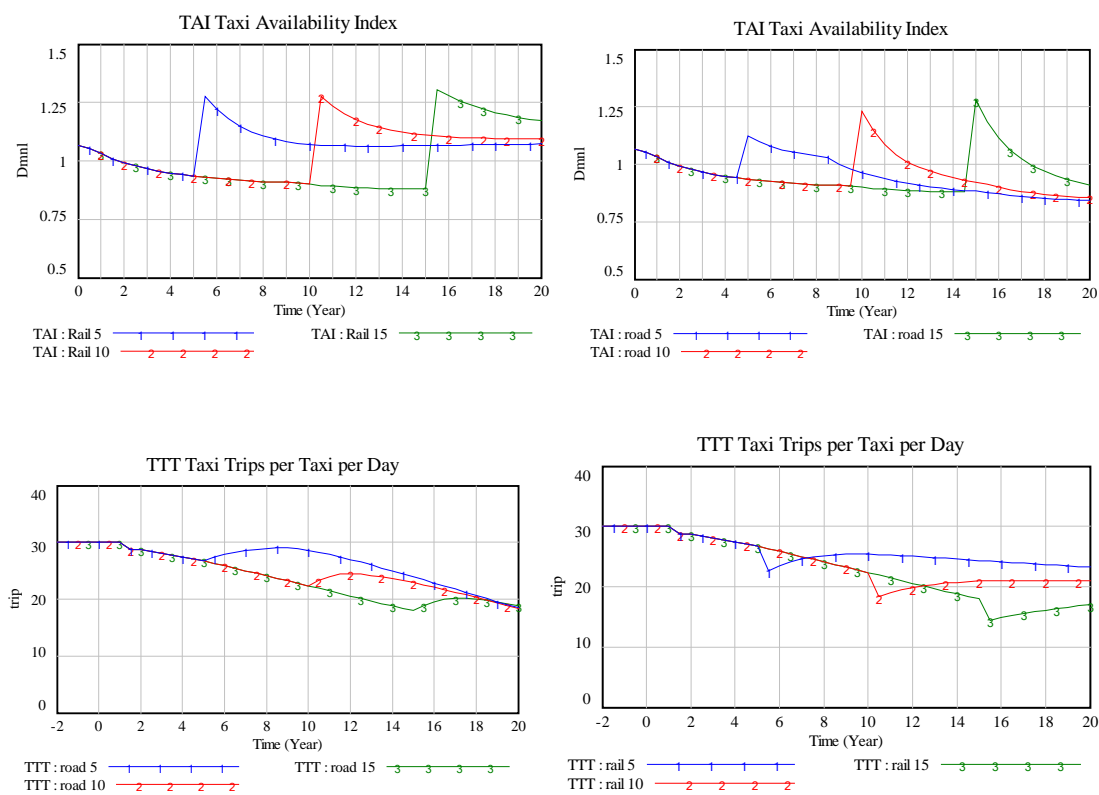


Figure 4-12: The timing effect of policy interventions on TAI and TTT under scenarios 1 and 2: an earlier intervention leads to smaller increases in the taxi availability index (TAI) which corresponds to a smaller taxi surplus and therefore more taxi trips per taxi per day (TTT).

Under both scenarios, however, the road experiences a very short period of free flow condition and after a few years congestion will be even worse than the intervention time. Hence in the following sections a combination of two scenarios proposed by the authorities will be investigated.

### 4.3.3 Scenario 3

Figure 4-13 displays the effects of a 40% increase in the road capacity at year 5 combined with introduction of a train system at year 10. Under this scenario CI varies around 1.0 with minor changes, which means vehicles often travel with free flow speeds during the period of the study. As shown in figure 4-15, travel time also remains stable at its initial value; around 45 minutes, with minor variations. It is worth mentioning that travel time in the train system is a constant number which is not considered in this study. The relief of congestion by an increase in the road capacity at year 5 result in smaller amounts of conversion of passengers from road to train via the congestion co-efficient (CC) in the model. Consequently the number of train passengers (PT) at the end of the simulation is less than that of scenario 2, where only the train system is introduced.

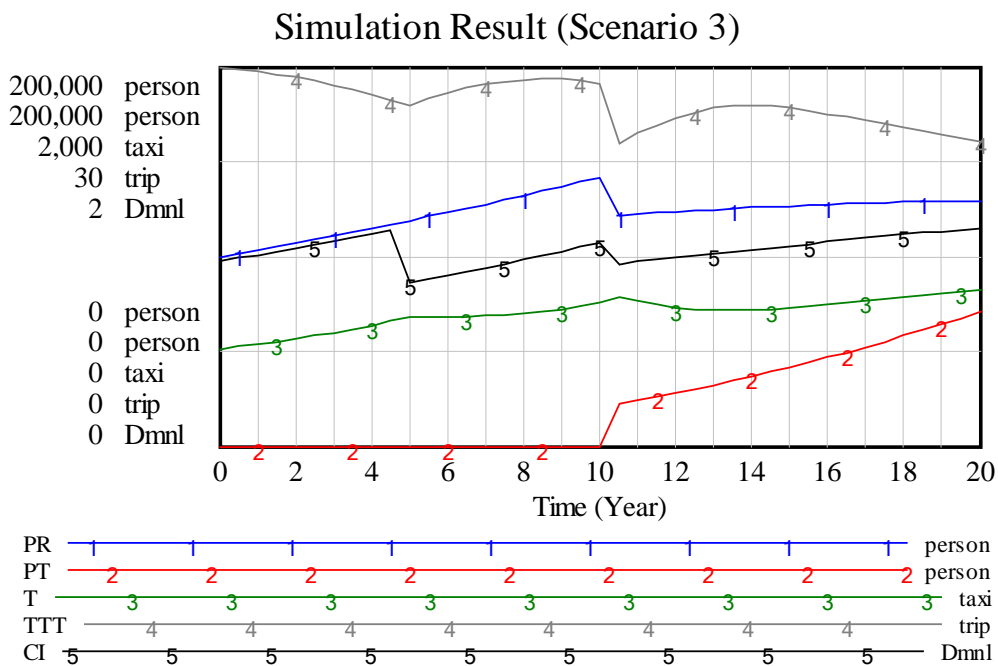


Figure 4-13: System behaviour after scenario 3: with introduction of the train system at year 5, passengers' road (PR) drops by 15% and grows slowly over the next years, passengers' train (PT) increases rapidly over time, and taxis (T) reduces smoothly. Congestion index (CI) is near 1.0 during the next years.

It is assumed that when the road is congestion free, some public transport users will prefer to use taxis instead of trains. Hence the proportion of passengers which use trains when the road is congested will be higher than that in free flow conditions which

is shown by the congestion co-efficient (CC) and travel time co-efficient (TTC). This is also highly dependent on passenger perceptions of the quality of service provided by those options and associated costs. Pricing does represent an important lever in transport mode share (TTF, 2013). However, for simplicity, it is not considered in the model of this study.

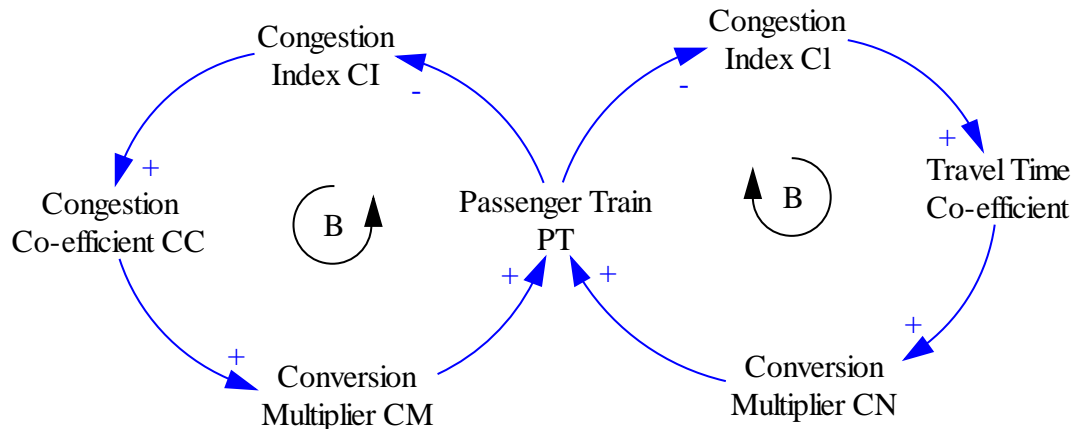


Figure 4-14: Balancing effects of congestion co-efficient (CC) and travel time co-efficient (TTC): an increase in the congestion index (CI) or travel time (TrT) will increase the number of train passengers (PT) via conversion multiplier (CM). This in turn will reduce the congestion index (CI).

After each policy intervention, the rate of growth of taxi stock reduces (through the taxi demand multiplier -TDM), due to the mitigated traffic congestion and reduced demand for taxis in the system (refer to Figure 4-6). It then grows very slowly during the next years, with a lower rate than passenger growth rate. After a 20% increase in TAI due to the road extension, it declines again until year 10, when the train system is introduced. Then it experience a sharp jump of about 30% due to the reduced congestion level and therefore demand for taxis (DT). Nevertheless, it reduces again until year 15 and remains almost stable in the next five years.

From Figure 4-15 it can be seen that both interventions (road extension and train introduction), in the short term result in some undesirable effects in the taxi industry due to immediate rises in TAI. In particular, introducing the train system at year 10 causes a larger disturbance to the industry and its workforce (TAI jumps by 30% and TTT drop by almost 6 trips per day). However, almost two years after the intervention,

the system adapts to the new situation and the working conditions for people involved in the taxi industry improve over the next years.

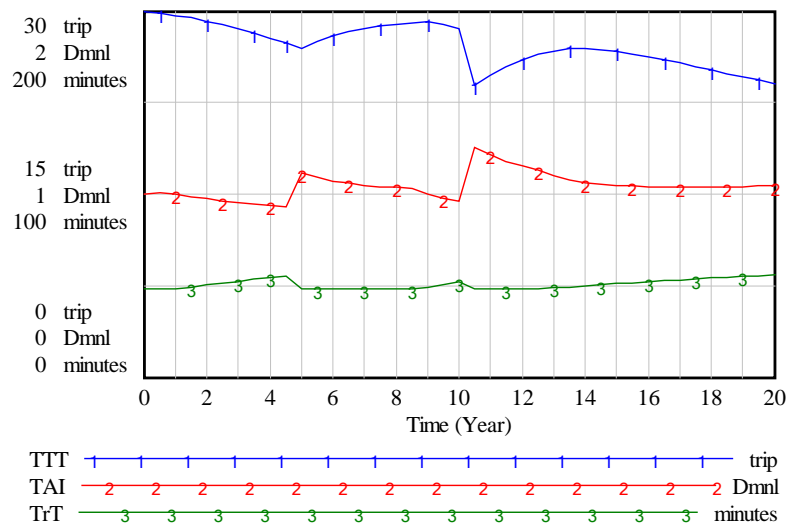


Figure 4-15: Measures of taxi utilization under scenario 3: at year 5, taxi availability index (TAI) increases by 20%, and then jumps of 30% at year 10. Taxi trips per taxi per day (TTT) increases until year 10 and then drops from 27 to 23 trips by introduction of train system

#### 4.3.4 Scenario 4

Figures 4-16 and 4-17 display the overall behaviour of the system under scenario 4. After the introduction of the train at year 5, the number of passengers which travel through the road system (PR) drops by about 15% and then grows slightly until year 20. Conversely, the number of train passengers (PT) after a 15% rise at year 5 grows quickly in the upcoming years. In this scenario, due to the earlier introduction of the train system (year 5), the number of train passengers (PT) at the end of the simulation is higher than that of scenario 3, where the train system has opened at year 10.

Under this scenario, the congestion index continuously remains below 1.0 after introduction of the train system at year 5 with a lower amount than scenario 3. Therefore the road experiences a congestion free situation for a relatively longer period of time. Accordingly, demand for taxis remains lower than available taxis (higher TAI) and thus the rate of growth of taxis declines slowly until year 10 and stabilizes in the upcoming years. While in the former scenario the stock of taxis was growing slightly

during the simulation time, under this scenario no further growth is experienced in the taxi industry after the first intervention in the system at year 5.

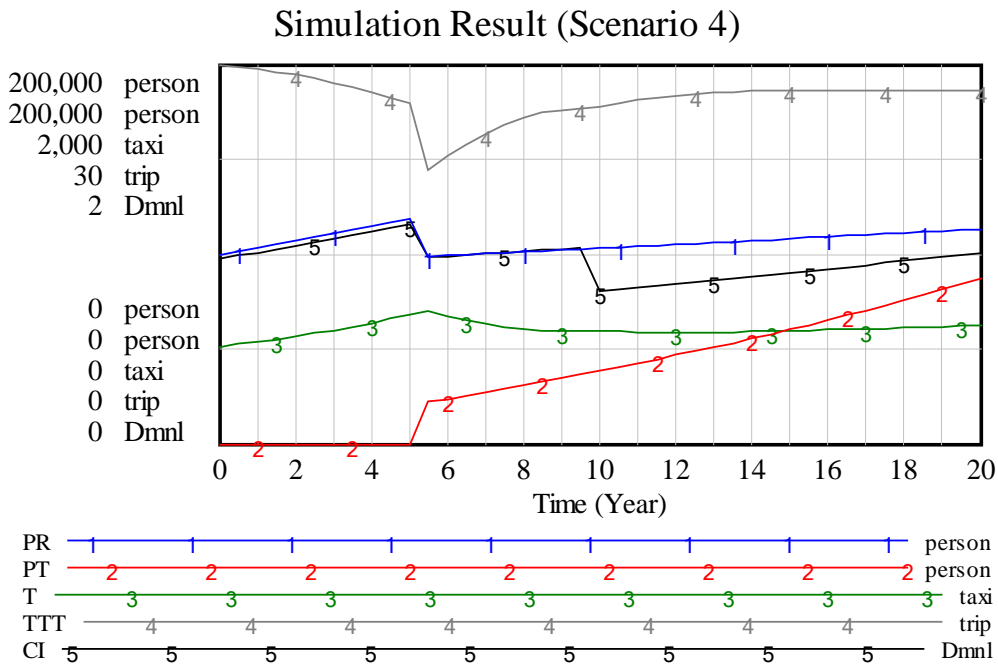


Figure 4-16: System behaviour under scenario 4: with introduction of the train system at year 5, passengers’ road (PR) drops by 15%, passengers’ train (PT) increases rapidly over time, and taxis (T) reduces smoothly. Congestion index (CI) is close to 1.0 during the next years.

Figure 4-17 shows that after opening of the train system at year 5, TAI has a significant jump of about 50% and then declines rapidly until year 10. After this, with the stabilized taxi stock and increasing number of passengers, it remains steady at around 1.1 until year 20. The number of trips per taxi per day (TTT) after a sharp fall from almost 27 trips to 22 trips at year five grows gently in the next few years and accelerates slightly from year 10 to 12 due to the expansion of the road and reduction of travel times (TrT). However, despite the free flow conditions on the road and normal travel times, TTT does not return to its maximum value due to the existence of excess taxis in the system relative to the demand for them.

It is interesting to note that increasing the road capacity at year 10 does not have a meaningful effect on TAI. This is because after the introduction of the train, traffic flow on the road remains below its full capacity (CI remains below 1.0) and hence



demand for taxis does not exceed its supply. Therefore TAI which is a function of demand for taxi does not change considerably due to the road expansion.

Taking into account the combined effects of TAI, TrT and TTT, it can be deduced that despite a large disruption to the taxi industry at year 5, after almost four years, the conditions improve considerably with a higher number of trips per taxi and lower values of TAI. This means that after the policy intervention, the system adjust itself to the new conditions through time mainly due to the effects of feedbacks from TAI, CI and TrT.

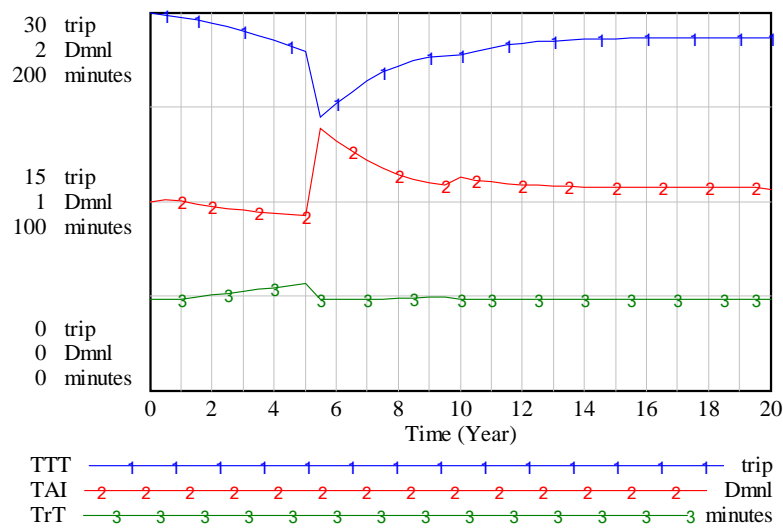


Figure 4-17: Measures of taxi utilization under scenario 4: at year 5, taxi availability index (TAI) jumps of about 50%, taxi trips per taxi per day (TTT) falls from 27 trips to 22. Travel time (TrT) returns to its original value and remains unchanged.

### Discussion

From the simulation results one can find that to ensure an easy and appropriate access to the proposed airport in the long term, a hybrid of two policies is required. This means a choice of two transportation options and improves the possibility of meeting different types of passenger demand and increasing overall satisfaction. Both strategies alleviated the congestion problem during the simulation time; with minor differences. However they vary in terms of their eventual effects on taxi drivers' livelihood and prosperity of the taxi industry as a whole.

It is interesting to note that in terms of maintaining free traffic flows on the road, scenarios 3 and 4 have opposite outcomes. While in the short run scenario 3 reduces the congestion more than the latter scenario, in the long run scenario 4 is more effective in alleviating the congestion (refer to Figure 4-18).

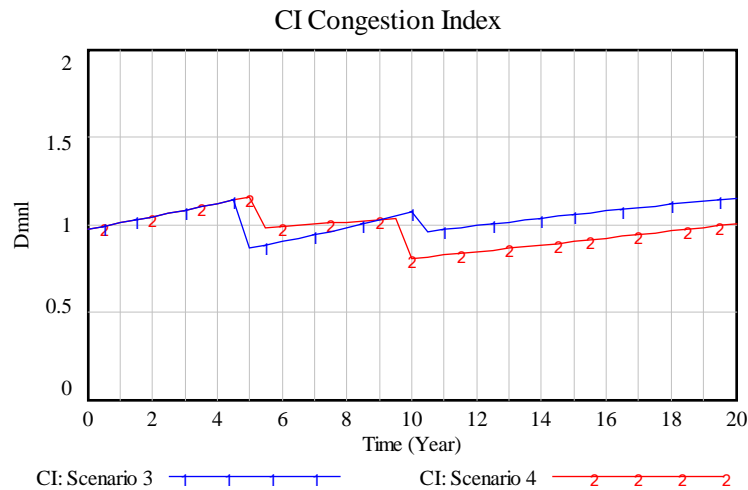


Figure 4-18: Congestion index under scenarios 3 and 4: while in the short run scenario 3 reduces the congestion more than the latter scenario, in the long run scenario 4 is more effective in mitigating the congestion.

Figure 4-19 indicates that the overall behaviour of the system in scenario 3 is more favourable for the taxi industry and its stakeholders compared to scenario 4. This is more evident especially in the short run. Under this scenario, for almost equal values for travel time (TrT) and congestion index (CI), overall, the taxi industry experiences lower values of TAI throughout the period of the study. Additionally, implementing this policy scenario leads to higher numbers of taxi trips per taxi per day (TTT) between years 5 and 10. However, in both scenarios, TTT does not return to its maximum value in spite of the congestion free situation of the road and normal travel times. This is mainly due to the oversupply of taxis and existence of the train system which continuously reduces the demand for taxis.

Under both scenarios, TAI experience immediate increases after the first intervention at year 5. This means that both interventions will cause disruptions in the taxi industry and its workforce. Moreover, implementing these strategies will reduce or even stop

further developments in the taxi industry. Consequently, the suppliers of taxis and taxi licences will also be affected as a result of slower growth in this sector.

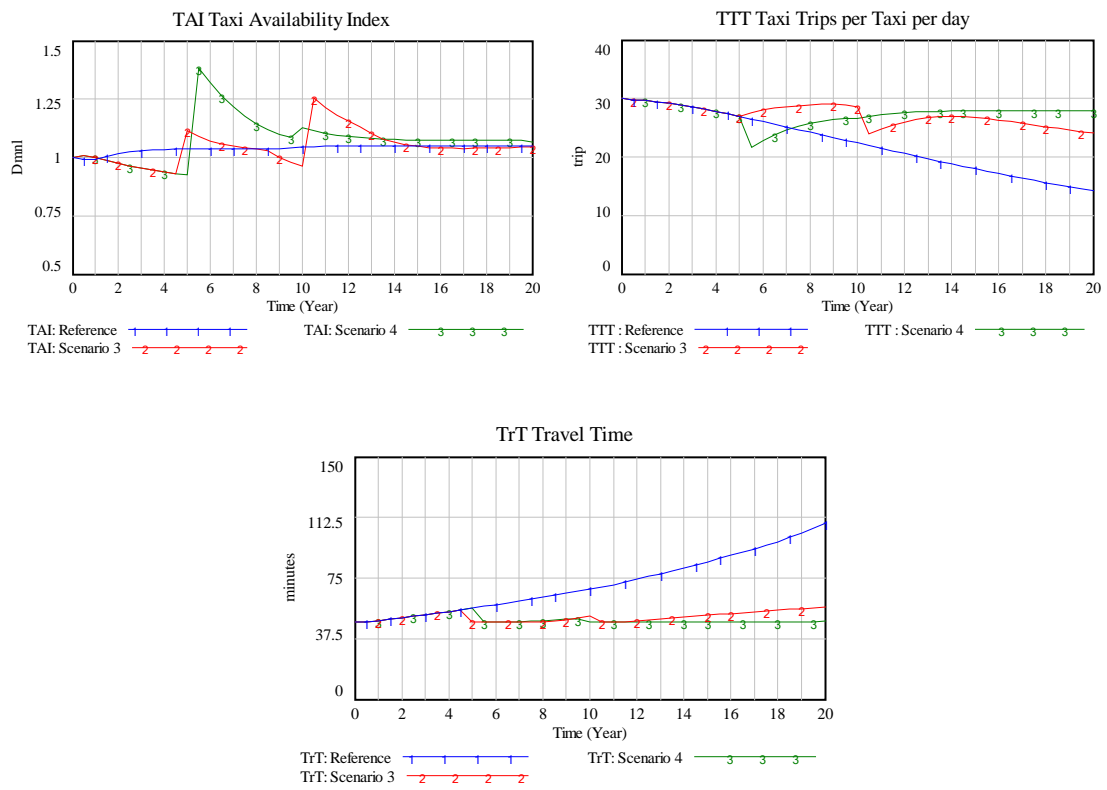


Figure 4-19: Taxi utilization under scenarios 3 and 4: under scenario 3, smaller increases in TAI occur, and the number of taxi trips per day (TTT) between years 5 and 10 is higher than scenario 4.

#### 4.4 Sensitivity Analysis

Parameters of system dynamics models are subject to uncertainty, so sensitivity analysis is an important task for evaluating the reliability of simulation results (Hekimoğlu and Barlas, 2010). System dynamics is a behaviour-oriented simulation field, therefore in order to investigate the effects of parameter uncertainty on the behaviour patterns, sensitivity of behaviour pattern measures, such as equilibrium level or amount of oscillation to the model parameters should be evaluated (Sterman, 2000, Zagonel and Corbet, 2006, Hekimoğlu and Barlas, 2010). Moreover, sensitivity analysis determines the effect of variations in model assumptions on its output and provides insights about the structure of the model. These insights guide the data collection efforts (Sterman, 2000).

Sensitivity analysis could provide important information about the model. The results of sensitivity analysis allow the model builder to determine which of the model parameters are more important for the simulation results. Once the parameters which model output is sensitive to them are identified, more data analysis is required to decrease the uncertainty in the parameter value (Barlas, 2007).

To examine the system's responses to variations of input parameters, a series of sensitivity analyses have been conducted in this study. Analysis of the simulation results are used to test the model for sensitivity toward different parameters.

The sensitivity analysis can be approached in a number of different ways (Ford, 1990, Barlas, 2007, Hekimoğlu and Barlas, 2010). However, the approach adopted depends on the aim of the analyst. The main purpose in formulating the model in this study was to examine the socio-economic problems in the taxi industry and its workforce, arising from congestion-mitigating strategies. A sensitivity analysis of the model in this study should therefore verify whether the understanding of the socio-economic problems gained from the model analysis is dependent on the assumptions about parameter values in the model.

The first step of sensitivity analysis is one-parameter sensitivity analysis which is conducted with "one-at-a time approach" (Saltelli et al., 2000). In this approach only one parameter is changed between two simulation runs. The changes in model output resulting from changes in each parameter value are analysed separately. Then the most influential parameters of the model are estimated.

From the policy analysis, it is deduced that the overall behaviour of the system in scenario 3 is more favourable for the taxi industry and its stakeholders compared to 3 other scenarios. Hence the sensitivity of some of the model parameters will be tested towards scenario 3 and its simulation results. Perturbations are made in some input variables in order to test their effect on key variables of the model. Taxi availability index (TAI) is identified as the most important measure of taxi market conditions which indicates the supply and demand for taxis. Therefore sensitivity of overall behaviour of TAI, and in particular the amplitude of its drops or rises towards the changes in taxi buying normal (TBN) is examined (refer to Table 4-3).

The next important factor which may impact the TAI is the number of passengers which change their transport mode from the road system to the train system after establishing the train. Conversion normal (CN) determines the rate of passengers' conversion rate and thus the number of passengers who travel by train (PT). Hence the effect of a 20% increase in the value of CN (from 0.025 to 0.03) on TAI is examined. Table 4-3 displays the variations in TAI with respect to perturbations in TBN and CN. Similarly, the effect of a 20% increase in the number of train passengers at year 10 is examined as per Table 4-4. In addition, as shown in table 4-5, the sensitivity of the model towards  $\pm 20\%$  change in the values of taxi demand multiplier (TDM) was tested (20% increase for values ranging from 0 to 1 (below 1.0) and 20% reduction for values ranging from 1 to 5 (above 1.0)).

From the Table 4-3 it can be seen that a 20% reduction in TBN throughout the simulation time, results in a 35% drop of TAI at year 10, when the train system is introduced. This is because until year 10, due to the smaller value of TBN, a higher shortage in the number of taxis occurs. It therefore increases the rate of growth of taxis via TDM. Then as a result of the introduction of the train system, a higher taxi surplus follows. Consequently the drop of TAI is higher in this situation.

The result of sensitivity analysis indicates that the taxi availability index (TAI) is most sensitive to variations in taxi buying normal (TBN). This indicates that TBN is the most influential parameter of the model in regard to supply and demand for taxis and consequently employment conditions in the taxi industry. *This suggests that while developing policies to improve the traffic conditions on the road, the number of taxis and taxi licence provisions should be taken into account. This will allow the amplitude of shortage or surplus of taxis to be minimized.*

It is interesting to note that increasing the conversion normal (CN) by 20% will lead to only 8% increase in the number of train passengers (PT) at the end of the simulation time. Consequently, it doesn't have a meaningful effect on the values of TAI throughout the simulation time. This could be attributed to the resistance of the system to variations in parameters due to the existence of feedbacks in the system. As such feedback is the structure that makes the system variables adapt over time. This implies that feedbacks from the amount of congestion and travel times in the road more

strongly influence the conversion rate than the normal rate considered in the model (refer to Figure 4-14 and Table 4-4). Table 4-5 indicates that a 20% changes in the TDM table function did not have a meaningful effect in TAI as a whole. It only has a minor effect in the amount of drop of TAI due to increasing the road capacity at year 5 and the introduction of the train system at year 10. This also can be attributed to the regulatory effects of the taxi demand multiplier (TDM) in the model.

It is also worth mentioning that the stock variables; passengers road (PR), passengers train (PT) and Taxis (T), are all fairly insensitive to parameter changes.

In general, the results of the sensitivity analysis indicated that most parameters are insensitive to variations in parameters, except for TBN that was identified as the most influential parameter in the model. Changes in this parameter had a big impact on the supply and demand for taxis and this in turn has a significant impact on the economic viability of the taxi industry. Fortunately, the value of this parameter can be controlled by management strategies such as the number of taxi licences issued before and after any intervention in the system. This will allow the amplitude of any shortage or surplus of taxis to be minimized.

Table 4-3: Effects of changes in TBN and CN values on TAI

Time (Year)	Taxi Availability Index (TAI)				
	TBN = 0.30	TBN = 0.25	TBN = 0.35	CN = 0.03	CN = 0.025
0	1.00	1.00	1.00	1.00	1.00
0.5	0.99	1.02	0.97	0.99	0.99
1	0.99	1.04	0.95	0.99	0.99
1.5	1.01	1.07	0.94	1.01	1.01
2	1.02	1.09	0.94	1.02	1.02
2.5	1.02	1.10	0.94	1.02	1.02
3	1.03	1.11	0.93	1.03	1.03
3.5	1.03	1.12	0.93	1.03	1.03
4	1.03	1.12	0.93	1.03	1.03
4.5	1.04	1.13	0.93	1.04	1.04
5	0.86	0.94	0.77	0.86	0.86
5.5	0.87	0.96	0.77	0.87	0.87
6	0.87	0.98	0.77	0.87	0.87
6.5	0.88	1.00	0.77	0.88	0.88
7	0.88	1.01	0.76	0.88	0.88
7.5	0.89	1.03	0.76	0.89	0.89
8	0.89	1.03	0.76	0.89	0.89
8.5	0.90	1.05	0.77	0.90	0.90
9	0.93	1.08	0.79	0.93	0.93
9.5	0.95	1.10	0.81	0.95	0.95
10	0.97	1.12	0.82	0.97	0.97
10.5	0.75	0.86	0.63	0.75	0.75
11	0.76	0.87	0.63	0.75	0.76
11.5	0.76	0.88	0.63	0.76	0.76
12	0.77	0.90	0.63	0.76	0.77
12.5	0.78	0.91	0.63	0.77	0.78
13	0.79	0.94	0.63	0.77	0.79
13.5	0.80	0.96	0.64	0.78	0.80
14	0.82	0.98	0.65	0.79	0.82
14.5	0.83	0.99	0.65	0.80	0.83
15	0.83	1.01	0.66	0.80	0.83
15.5	0.84	1.02	0.66	0.81	0.84
16	0.85	1.03	0.66	0.81	0.85
16.5	0.85	1.03	0.66	0.82	0.85
17	0.86	1.04	0.67	0.82	0.86
17.5	0.86	1.04	0.67	0.82	0.86
18	0.86	1.04	0.67	0.83	0.86
18.5	0.86	1.04	0.67	0.83	0.86
19	0.87	1.04	0.67	0.83	0.87
19.5	0.87	1.04	0.67	0.83	0.87
20	0.87	1.04	0.67	0.83	0.87

Table 4-4: Effect of 20% increase in CN on PT

PT (Passenger Train)

Time (Year)	CN = 0.03	CN = 0.025
10	0	0
10.5	22477	22064
11	24747	24020
11.5	27064	26022
12	29428	28069
12.5	31840	30162
13	34301	32312
13.5	36813	34537
14	39394	36838
14.5	42050	39215
15	44782	41670
15.5	47590	44205
16	50476	46819
16.5	53439	49514
17	56480	52291
17.5	59601	55151
18	62801	58094
18.5	66081	61122
19	69442	64236
19.5	72884	67436
20	76408	70723



Table 4-5: Effect of 20% reduction in TDM slope on T and TAI

Time (Year)	Taxi Availability Index (TAI)		Taxis (T)	
	Scenario 4	20% reduction in TDM slope	Scenario 4	20% reduction in TDM slope
0	1.00	1.00	513	513
0.5	0.99	1.00	532	522
1	0.99	1.01	541	532
1.5	1.01	1.03	555	543
2	1.02	1.04	572	558
2.5	1.02	1.05	590	576
3	1.03	1.05	611	595
3.5	1.03	1.06	633	617
4	1.03	1.06	657	639
4.5	1.04	1.06	682	664
5	1.04	1.06	708	689
5.5	0.69	0.71	735	716
6	0.70	0.72	730	712
6.5	0.71	0.72	725	709
7	0.72	0.73	721	706
7.5	0.73	0.74	717	703
8	0.74	0.75	713	701
8.5	0.75	0.77	711	699
9	0.76	0.78	708	697
9.5	0.77	0.79	707	696
10	0.75	0.76	707	696
10.5	0.75	0.76	704	694
11	0.76	0.77	702	692
11.5	0.76	0.78	701	691
12	0.77	0.78	699	690
12.5	0.77	0.78	699	689
13	0.78	0.79	698	689
13.5	0.78	0.79	698	689
14	0.79	0.80	699	689
14.5	0.79	0.80	699	689
15	0.79	0.80	700	689
15.5	0.79	0.81	702	690
16	0.80	0.81	703	690
16.5	0.80	0.81	704	691
17	0.80	0.82	706	692
17.5	0.80	0.82	708	693
18	0.80	0.82	710	695
18.5	0.80	0.82	712	696
19	0.81	0.82	714	698
19.5	0.81	0.83	717	699

## Chapter 5

### CONCLUSION

The congestion problem in airport access roads is usually addressed with various congestion-mitigation strategies developed by transportation planners, such as increasing the capacity of the road or implementing the travel demand management (TDM) strategies. However, efforts to solve problems in a system may provoke undesirable consequences for some of its components.

This research focused on some of the wider implications of several congestion-mitigating strategies on the taxi industry of an airport access system, which is usually neglected in the transportation planning literature. The taxi industry is one of the important stakeholders in an airport access system. Taxis play important roles in providing ground transportation to travellers arriving at and departing from the airport, and thus make significant contributions to an airport's business. Hence a framework that helps policy makers to understand the impacts of their proposed congestion-mitigation policies on the taxi industry and its stakeholders is necessary.

In this study, the structure of a hypothetical airport access road system has been organized into a mathematical model. The access road is already reaching its capacity and the number of passenger movements is expected to double in 20 years. Consequently, four congestion-mitigating policy scenarios were examined using the model. The objective was to offer an assessment platform for policy makers that focuses on the socio-economic problems in the taxi industry and its workforce, arising from congestion-mitigating strategies.

The focus of the study is at the policy level, hence the specification of system variables are constrained to this level. The model consists of three sectors: passengers and travel demand; taxis and private cars; and trains. It incorporates the congestion level in the road, the growth of passengers, investment in taxis, and service availability of taxis in a hypothetical airport access road of a metropolitan area. All variables of the model along with feedback relationships amongst them interact to produce the system behaviours over time. Three variables of the model were identified as measures of taxi

utilization and viability of the taxi industry. These variables (Taxi Availability Index (TAI), Taxi Trips per Taxi per day (TTT), and Travel Time (TrT)) are indicative of the working conditions and possible disruptions in the taxi industry as a result of any intervention in the system.

The findings regarding the implementation of the proposed policies revealed that any intervention in the system to reduce the traffic congestion on the road will have some short- and long-term undesirable effects on the taxi industry and its workforce. The short term effects include an oversupply of taxis, reductions in the number of taxi trips per day, and thus loss of revenue and loss of jobs for taxi owners and operators. In the long term, the rate of growth of taxis in the system declines and therefore reduces further development of the taxi industry.

However, the system exhibits better behaviours in terms of the road conditions and eventual effects on the taxi industry under a hybrid scenario. This scenario consists of road extension and establishing a train system with the right timing and right prioritizing of those policy interventions (road extension at year 5, train system at year 10). Implementation of this scenario results in a higher number of taxi trips and taxi occupancy time and thus increases taxi utilization. In addition, the taxi surplus is minimised under this scenario. Consequently, better working conditions are provided in the taxi industry, while ensuring free flow conditions on the road.

In addition, it was found that the timing of congestion-mitigating strategies has a significant effect on the magnitude of the disruptions to the taxi industry. An earlier intervention leads not only to better conditions for the road in terms of traffic flow, but also fewer disruptions in the taxi industry and its workforce. Accordingly, careful attention should be paid to the timing of strategies and their implementation.

The results of the sensitivity analysis indicated that most parameters are insensitive to variations in their value, except for one (taxi buying normal-TBN) that was identified as one of the most influential parameters in the model. Changes in TBN had a big impact on the supply and demand for taxis and this in turn has a significant impact on economic viability of the industry. Fortunately, the value of this parameter can be controlled by management strategies such as the number of taxi licences issued before

and after any intervention in the system. This would allow the amplitude of the taxi shortages or surpluses to be minimized.

This thesis applied the System Dynamics modelling method to examine a socio-economic aspect of traffic congestion problem of a transportation system, which is an under-explored application in the SD field, due to the common choice of discrete event simulation and logistic models in transportation planning. While the problem of congestion is typically addressed with the aim of tackling the congestion only, this research focused on the implications of management strategies on other components of the system, namely the taxi industry and its workforce. It provided insights into how and why the implementation of congestion-mitigation strategies may result in unintended consequences for the taxi industry.

Systems Thinking and System Dynamics modelling can help urban policy makers understand the interactions among various interacting sub-systems of a transport system which drive its long-run dynamic behaviour. One significant advantage of System Dynamics compared to the other modelling approaches is that when systems are not too complex, it can help understand the qualitative behaviour of many variables, even before quantitative modelling begins. This in turn facilitates holistic transportation modelling and policy making.

Further, examining certain policy scenarios on a System Dynamics model can greatly aid in understanding how the system behaviour changes over time. It will thus enable the investigation of both the short and long term implications of different policies and strategies. These insights could be helpful in making more informed and justified decisions. This modelling approach also provides a means for decision makers to evaluate the impacts of changes in parameter values and changes in planning policies. This will assist them to identify which parameters play a significant role in the stability and response of the system. These insights will help policy makers to consider the wider consequences of their proposals in solving a traffic congestion problem, and thereby improve their proposed planning strategies.

The model developed in this study illustrates the strength of Systems Thinking and the System Dynamics methodology in the analysis of the dynamic behaviour of socio-economic systems. In particular it shows that small System Dynamics models can

greatly aid the policy making process by utilizing the qualitative, as well as quantitative capabilities of them. It is hoped that this will contribute towards more widespread use of system modelling by urban planners in order to gain improved management practices in their environments, particularly in urban transport systems.

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# Appendix 1

## List of the Symbols Used In the Model

(In the order in which they appear in chapter three)

P = Passenger (person)

PN = Initial Passenger (constant, person)

PGR = Passenger Growth Rate (person, year<sup>-1</sup>)

PGN = Passenger Growth Normal (constant, year<sup>-1</sup>)

TP = Taxi Passengers (person)

FPT = Fraction of the Passengers that use Taxi (constant, dimensionless)

CP = Car Passengers (person)

TT = Taxi Trips (trip)

AVPTT = Average Passenger per Taxi Trip (constant, person.trip<sup>-1</sup>)

CT = Car Trips (trip)

AVPCT = Average Passenger per Car Trip (constant, person.trip<sup>-1</sup>)

ERCCT = Effect of Road Capacity on Car Trips (dimensionless)

FFC = Free Flow Capacity (constant, trip)

ToT = Total Trips (trip)

CI = Congestion Index (dimensionless)

FFCC = Free Flow Capacity Control (trip)

DTFCC = Demand for Taxi in Free Flow Condition (dimensionless)

FFTT = Free Flow Taxi Trips (constant, trip)

DT = Demand for Taxi (dimensionless)

CM = Congestion Multiplier (dimensionless)

TrT = Travel Time (hour)

ECTT = Effect of Congestion on Travel Time (dimensionless)

TTT = Taxi Trips per Taxi per day (trip/taxi)

T = Taxis (taxi)

TBR = Taxi Buying Rate (taxi. year<sup>-1</sup>)

TBN = Taxi Buying Normal (1. year<sup>-1</sup>)

TSR = Taxi Selling Rate (taxi. year<sup>-1</sup>)

TSN = Taxi Selling Normal (1. year<sup>-1</sup>)

T(0) = TN = Initial Taxis (taxi)

TDM = Taxi Demand Multiplier (dimensionless)

TAI = Taxi Availability Index (dimensionless)

DT = Demand for Taxi (taxi)

PT = Passenger Train (person)

PTGR = Passenger Train Growth Rate (person.year<sup>-1</sup>)

CR = Conversion Rate (person.year<sup>-1</sup>)

PT (0) = PTN= Passenger Train Initial (constant, person)

PTGN = Passenger Train Growth Normal (1. year<sup>-1</sup>)

PR = Passengers Road (person)

CN = Conversion Normal (1. year<sup>-1</sup>)

CoM = Conversion Multiplier (dimensionless)

PTP = Passenger Train Programming (person. year<sup>-1</sup>)

CC = Congestion Co-efficient (dimensionless)

TTC = Travel Time Co-efficient (dimensionless)

PTP = Passenger Train Programing (person. year<sup>-1</sup>)



## Appendix 2

### The Model Formulae Documentation Listing In Vesnsim

(01) AVPC Average Passenger per Car= 2.4

Units: person/trip

(02) AVPT Average Passenger per Taxi= 1.3

Units: person/trip

(03) CC Congestion Co-efficient = WITH LOOKUP ( CI congestion index,

(((0,0)(3,4]),(0,0.8),(1,1),(1.66972,1.70175),(2.3578,2.70175),(3,4) ))

Units: Dmnl

(04) CI Congestion Index= ToT Total Trips/FFC Free Flow Capacity

Units: Dmnl

(05) CoM Conversion Multiplier = TTC Travel Time Co-efficient \*CC Congestion Co-efficient

Units: Dmnl

(06) CM congestion multiplier = WITH LOOKUP (CI congestion index,

(((0,0)(2.4,4]),(0,1),(1,1),(1.34588,1.44128),(1.66972,1.94737),(1.94495,2.40351),(2.20183,2.94737),(2.4,3.5) ))

Units: Dmnl

(07) CN Conversion Normal = STEP(0, 10 )

Units: 1/year

(08) CR= PR Passengers Road \*CN Conversion Normal \*CoM Conversion Multiplier  
+PTP Passenger Train Programming

Units: person/year

(09) CT car trips= CP Car Passengers /AVPC Average Passenger per Car

Units: trip

(10) DT demand for taxi per day= DTFFC demand for taxi in free flow condition per  
day\*CM congestion multiplier

Units: taxi

(11) DTFFC demand for taxi in free flow condition per day= TT taxi trips/FFTT ff taxi  
trips per day

Units: taxi

(12) ECTT Effect of Congestion on Travel Time = WITH LOOKUP (CI congestion  
index,([(0,0)(2.5,4)],(0,1),(1,1),(1.41437,1.45614),(1.81176,2.01754),(2.0948  
,2.52632),(2.31651,3.07018),(2.5,3.5) ))

Units: Dmnl

(13) ERCCT Effect of Road Capacity on Car Trips =

IF THEN ELSE(FFC free flow capacity<=50000, 1 , EXP(0.012\*Time))

Units: Dmnl

(14) FFC Free Flow Capacity= 50000+Increase in FFC

Units: trip

(15) FFTT Free Flow Taxi Trips per day= 30

Units: trip

(16) FINAL TIME = 20

Units: Year

The final time for the simulation.

(17) FPT Fraction of the Passengers that use Taxi = 0.2

Units: Dmnl

(18) Gap= DT Demand for Taxi –T Taxis

Units: taxi

(19) Increase in Free Flow Capacity= STEP(0, 10 )

Units: trip

(20) INITIAL TIME = -2

Units: Year

The initial time for the simulation.

(21) CP Car Passengers = (1-FPT Fraction of the Passengers that use Taxi)\*PR  
Passengers Road \*ERCCT Effect of Road Capacity on Car Trips

Units: person

(22) PGN Passenger Growth Normal = 0.035

Units: 1/year

(23) PGR Passenger Growth Rate = PR\*PGN

Units: person/year

(24) PN Initial Passenger = 100000

Units: person

(25) PR Passengers Road = INTEG (PGR Passenger Growth Rate – CR Conversion Rate , PN Initial Passenger )

Units: person

(26) TP Taxi Passengers = FPT Fraction of the Passengers that use Taxi \*PR Passengers Road

Units: person

(27) PTP Passenger Train Programming = STEP(0, 10)-STEP(0, 10.5 )

Units: person/year

(28) PTGN Passenger Train Growth Normal = 0.035

Units: 1/year

(29) PTGR Passenger Train Growth Rate = PTGN Passenger Train Growth Normal \*PT Passenger Train

Units: person/year

(30) PT Passenger Train = INTEG (

CR Conversion Rate +PTGR Passenger Train Growth Rate, 0)

Units: person

(31) SAVEPER = TIME STEP

Units: Year [0,0.5]

The frequency with which output is stored.

(32) T= INTEG (TBR-TSR, TN)

Units: taxi

(33) TAI taxi availability index= T taxis/DT demand for taxi per day

Units: Dmnl

(34) TBN Taxi Buying Normal = 0.25+STEP(0.05, 0)

Units: 1/year

(35) TBR Taxi Buying Rate = T\*TBN/TDM taxi demand M

Units: taxi/year

(36) TDM Taxi Demand Multiplier = WITH LOOKUP (TAI Taxi Availability Index,  
([(0,0)(3,5)],(0,0.5),(0.7506,0.8),(1,1),(1.42588,1.92171),(1.80706,2.84698)  
,(2.14588,3.4),(2.54118,3.98577),(2.99294,4.21708) ))

Units: Dmnl

(37) TIME STEP = 0.5

Units: Year [0,20]

The time step for the simulation.

(38) TN Initial Taxis = (PN Initial Passenger \*FPT Fraction of the Passengers that use Taxi)/(AVPT Average Passenger per Taxi\*TTT taxi trips per taxi per day)

Units: taxi

(39) ToT Total Trips=(CT Car trips+TT Taxi Trips)

Units: trip

(40) ToP Total Passenger= PT Passenger Train+PR Passenger Road

Units: person

(41) TrT Travel Time = (24/FFTT ff taxi trips per day)\*ECTT effect of congestion on ff taxi trip \*60

Units: minutes

(42) TSN Taxi Selling Normal = 0.25

Units: 1/year

(43) TSR Taxi Selling Rate = T Taxis\*TSN Taxi Selling Normal

Units: taxi/year

(44) TT Taxi Trips= TP Taxi Passengers /AVPTT Average Passenger per Taxi Trip

Units: trip

(45) TTC Travel Time Co-efficient = WITH LOOKUP (TrT Travel Time,  
([(45,0)(150,4.5)],(45,1),(76.1468,1.40132),(106.651,2.17105),(126.239,3),(150,4.5) ))

Units: Dmnl

(46) TTT=TT Taxi Trips/T Taxis

Units: trip/taxi