A Linkage between Travel Demand Models and Road Management Systems

Seyed Reza Ghobad Pour

A Thesis

in the Department

of

Civil, Building and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of

Master of Applied Science (Civil Engineering) at

Concordia University

Montreal, Quebec, Canada

January 2020

This is to certify that the thesis prepared

By: Seyed Reza Ghobadpour

Entitled A linkage between travel demand models and road management systems

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Civil Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

______________________________ Chair
Dr. Ciprian Alecsandru
______________________________ Examiner
Dr. Ursula Eicker
______________________________ Examiner
Dr. Govind Gopakumar
______________________________ Supervisor
Dr. Luis Amador

Approved by Dr.Michelle Nokken
____
Chair of Department or Graduate Program Director

Dr. Amir Asif
____
Dean of Faculty

Date: February 19th , 2020

ABSTRACT

A linkage between Travel Demand Models and Road Management Systems

Seyed Reza Ghobadpour

Road congestion is a widespread problem across the world. While certain socioeconomic stratum responds better to measures to encourage the use of public transportation, others exhibit an inelastic behavior and remain loyal to their automobiles. Maintenance and expansion of transportation networks are costly and require annual investments that escape the financial abilities of most governments. Under this paradigm, there is a need to implement optimal decision support systems able to allocate scarce financial resources to accomplish reduced congestion and travel time, and that encourages the use of public transportation. To that end, the traditional approach used to handle Pavements and Road Management was extended in both cases to support a linkage to travel demand models illustrated through two case studies: first of a developing country where an attempt to alleviate road congestion is implemented. Secondly, in a city with good levels of Public transportation where poor support has been granted to the traditional bus system, although they provide the main mean of access to MRT and LRT stations. The proposed approach schedules investments on bus routes through measures to handle traffic and to optimize the surface condition of pavements in an attempt to encourage higher levels of bus ridership.

DEDICATION

To my father, mother, brother and beloved family

ACKNOWLEDGMENTS

I am so grateful to have so many helpful people during my MASc study. Firstly, I would like to express my deepest gratitude to Dr. Luis Amador for his advice, support, encouragement, and friendship. He really is a friend to me and I have never felt that I am alone in this path. I am very honored to know him and worked with him during my MASc study.

Secondly, I am very grateful to my friend Ms. Jenny Chaverri for her consistent support in every step of the hardship to provide me with datasets from the Costa Rica case study that I know personally how hard was it to collect all those data. I acknowledge the LANAMME (University of Costa Rica) for providing the pavement condition data and the Costa Rica Institute of Statistics and Census (INEC) for the census data.

I also express my appreciation to Dr. Ciprian Alecsandru for his support and helpful comments, also providing me access to the facilities such as software programs. Also, I would like to thank my friends for their understanding, encouragement, and support.

Finally, I must express my very profound gratitude to my parents and my brother who has always been there for me in every situation. There will never be the right word to express my appreciation for their unconditional love, support and encouragement throughout my life and through the process of researching and writing this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
ADT	Average Daily Traffic
APTA	American Public Transportation Association
ESAL	Equivalent Single Axle Load
FHWA	Federal Highway Administration
FHWA	Federal Highway Administration
FSM	Four-Step Modeling
FWD	Falling Weight Deflectometer
GAM	Great Metropolitan Area
GFA	Gross Floor Area
GIS	Geographic Information System
HDM	Highway Design Manual
HBW	Home Based Work Trips
HBO	Home Based Other Trips
ILP	Integer Linear Programming
IRI	International Roughness Index
LOS	Level of Service
M&R	Maintenance and Rehabilitation
MRT	Mass Rapid Transit
NHB	Non-home Based Trips
PMS	Pavement Management System
PPP	Pavement Performance Prediction
RMS	Road Management System
TAM	Transportation Asset Management
TAMF	Transportation Asset Management Frameworks
TAZ	Transportation Analysis Zone
TDM	Travel Demand Management
TMP	Transportation Master Plans
TSM	Transportation System Management
VDF	Volume-delay functions

Chapter 1: Introduction

1.1Background

The world's urban population has more than doubled since 1950, coming to nearly 4.2 billion in 2018. Furthermore, the growth of urban traffic in cities coincided with the advent of faster transport modes, which made possible progressively longer commuting trips. However, the delimiter of city growth is rarely vehicle top speed. As cities grow and sprawl, traffic congestion effectively and inevitably lowers the travel speed and convenience of a private automobile (Unidas, 2003). Which has become a significant concern to city planners, transportation professionals, and policymakers (Unidas, 2003). Hence, nowadays, road agencies of cities like London, Singapore, and Western Australia have changed their primary tasks, from expanding the extensiveness of the network and constructing new infrastructures to managing and maintaining existing road networks in serviceable condition and policies have been shifted towards combatting transport congestion rather than shortening free-flow travel time. Therefore, efficient transportation planning is expected to effectively forecast future changes in socioeconomic characteristics of the users and land use patterns in order to plan maintenance activities on the existing and future road infrastructure assets such as pavement, since maintaining pavement surface conditions at acceptable levels is offers many benefits, including cost efficiency, reduction in noise pollution and comfort.

However, nowadays, the rising cost of maintenance and reduced resources of municipalities (Horak et al., 2017) it has become necessary to optimize the use of resources and to place more emphasis on maintenance and rehabilitation (M&R) rather than expansion. Such a process started back in the 1980s with Pavement Management System (PMS) (Hass et al. 1994), which assisted engineers and decision-makers in finding cost-effective optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition. Transportation agencies and municipalities often struggle to understand and respond to the travel demand growth and the impact of this growth on the deterioration of assets (Vanier et al. 2001). Many municipalities focus on corrective actions (worst first approach) and initiate to do something when a problem takes place. For example, in terms of pavement condition, they start to do the treatment when there are cracks on the pavement surface instead of having an integrated program capable of taking into account the preventive maintenance needs of their assets effectively and efficiently over their life cycle.

Therefore, travel demand models have been developed in the 1950s for forecasting levels of demand across modes of transportation to link the interaction between infrastructure (assets condition) and user behavior (population growth) to employ as decision support tools for transportation planning over the last several decades.

In this thesis, two case studies have been considered. The first one is the road network of the Great Metropolitan Area (GAM) in Costa Rica, comprising areas of high population density (6,455 people per square kilometer) surrounding the capital Sane Jose. In an area of 2.044 km^2, GAM has a population of 2.2 million (about 50 percent of the population).

The second one is Montreal Island: Montreal is the second-largest city in Canada, with a population of 1.7 million (Statistics Canada, 2016). It is one of the highest population densities (4,517 people per square kilometer) among North American standards and an extensive transit network.

1.2Problem Statement

Many travel plans and transportation strategies included within transportation impact regulations and in Transportation Asset Management Frameworks advocate for the preservation of existing roads rather than building new ones; at the same time, modern Transportation Master Plans (TMP) have been found to contain specific strategies to develop or improve road networks. However, there is a disconnection between TMP and Transportation Asset Management Frameworks (TAMF).

Planners do not take into consideration the need to sustain road networks (pavement) in a good level of condition, also most importantly, to consider dynamic traffic volume load data (travel demand). TAMF is limited and likely inaccurate because they base their forecast over average daily traffic (ADT) estimates and constant traffic growth neglecting the dynamics of the economic development of urban sprawl and other circumstances explicitly considered by travel demand models.

Road agencies rarely use travel demand results to predict future deterioration. Instead, they adopt the common practice of using estimates of future equivalent single axle load (ESALs) during the pavement design of a new or rehabilitated facility without considering the possible acceleration (deceleration) of pavement wear related to higher (lower) than anticipated traffic volumes. Therefore, sustainable tactical plans are required to balance the allocation of resources from long term analysis into a shorter period of time to be able to conduct a trade-off between asset condition, travel demand and cost.

1.3Research Objective

1.3.1 Overall Goal

The overall goal of this research is to introduce a procedure able to support decision-making strategies to alternate congestion and encourage bus ridership by linking travel demand to road management systems.

1.3.2 Research Tasks

Two tasks were identified to address the main goal of this research:

Task 1

The motivation of this task was to explore the feasibility of using the output of travel demand models within transportation infrastructure management. As such this task illustrates a simple way to simulate traffic volume and use it as an input to allocate actions and strategies to accomplish consistent cost-benefit analyses for the entire road network.

Task 2

This task takes further steps to use the linkage established in task 1 to support the decision making of strategies oriented towards improved public transportation services. As such, this task accomplished the allocation of travel demand management strategies (TDM) within the decision-making system.

This is particularly important for congested cities as it seeks to provide adequate road network capacity that matches user's demand in a way that users experience shorter travel times and smoother network surface. This is achieved using goal optimization to deal with conflictive objectives pursuing a trade-off between overall cost, road deterioration, road congestion and travel time.

1.4 Scope and Limitations

In this thesis, the integrity of datasets was one of the main challenges. Some datasets were collected from different sources in different file formats. In order to be able to aggregate the data into one dataset, spatial and temporal consistency was required (same location and same year). As part of this converting and merging separate data files into one dataset that matched the given geographic boundaries was challenging and required months of work to properly fix boundaries and reallocate data proportionally. In addition, the segment's length from the demand model was different from the segment size of the optimization model. This further produced limitations when linking both models.

The output from optimization produced an allocation of actions across space and time that disregarded logical grouping of segments into corridors to facilitate the implementation of interventions or strategies; as such future research should look into ways to take the results and coordinate them to create corridors.

The next limitation was the ability to produce a real-time feedback loop between the demand model and optimization model since, in this thesis, the outcome from the demand model was extracted manually and used as an input into the optimization model for the road management system, but for future research, both models must adjust through a feedback loop.

The lack of calibration data was another challenge. In this thesis for the demand model, the calibration has been done from a trial and error approach to match the estimated values with observed values; however, in the future, there is a need for a more automated approach for the calibration.

In addition, there were segments with missing data for pavement condition indicators and casual factors within the deterioration model. Finally, the current budget levels for the optimization were unknown. To overcome this problem a specific budget level to achieve minimum levels of improvement was assumed in the optimization framework.

1.5Research Significance

The objective of this thesis is to develop a novel linked travel demand and road management system to enhance the decision-making process for improved mobility. The trip-based travel demand and traffic assignment-modeling framework (VISUM) was linked to the transportation asset management system (REMSOFT). The model was shown applicable for cars and buses within the road network.

This thesis serves as a guide for future research or practical implementation of connected travel demand models to road management systems. Future researchers will be able to follow the same procedure to upload the datasets into the required format of VISUM and use the optimization algorithm to expand the model with other characteristics such as environmental factors, road safety, frequency of public transportation services and to include investment on public facilities. In this thesis, the case studies illustrate the development of initial models facing data gaps that often impede their implementation.

1.6Organization of the Thesis

This thesis is presented in six (6) chapters as follows:

- Chapter 1 - Defines the problem statement and presents the objectives and structure of the thesis.
- Chapter 2 - Consists of a review of the state of practice and concepts related to travel demand modeling and decision support systems.
- Chapter 3 - presents the methodology employed for analyzing and processing the data and building strategic plans considering the travel demand.
- Chapter 4 – is a self-contained paper
- Chapter 5 – is a self-contained paper
- Chapter 6 - summarises the most important conclusions of the thesis

The work described in Chapters 4 and 5 has been written as self-contained journal papers and as such, each chapter has its own abstract. Chapter 4 and Chapter 5 will be submitted soon, as follow:

Chapter 4**:** Ghobad Pour, R., Amador-Jimenez, L., (2020). Investment planning to handle road congestion while waiting to implement public transit: a case study of costa Rica.

Chapter 5**:** Ghobad Pour, R., Amador-Jimenez, L., (2020). Adapting road management systems to support traditional bus transit: a case study of Montreal.

Chapter 2 Literature review

2.1 Introduction

Urban centers around the world are experiencing increasing transport demand, and many are unable to handle due to inexistent road and rail infrastructure. Many developing and low-income nations relying solely on roads have responded by building new roads or lanes; however, such a solution only accommodates demand in the short term, triggering land development, which produces more traffic in the medium term, hence returning to a congestion state. At the same time road agencies at many developed countries had changed their main tasks, from projecting and constructing new infrastructures to managing and maintaining existing networks.

Traffic congestion arrives when travel demand exceeds the capacity of the road network. More traffic is often associated with detriments in road safety and pavement deterioration. According to the Federal Highway Administration (FHWA), congestion can be expressed as the resultant delay compared to the amount of time it takes to make a trip under ideal conditions. The most reliable congestion measure focuses on the travel time faced by road users. Highway congestion is caused if there are more cars on the roads, or if traffic demand approaches or goes beyond the existing highway system capacity. Congestion is also the product of abnormal circumstances such as inclement weather, presence of animals, or fallen objects on the road and road collisions. The traffic demands vary considerably depending on the season of the year, the day of the week, and even the time of day. Capacity can also adjust due to weather conditions, work areas traffic incidents, or the combination of drivers and vehicles on the road. Every municipality has its way of tackling this problem. One of the often-encountered strategies is to shift the demand from single-occupancy automobiles towards car-pooling or transit ridership, which requires enabling facilities that encourage such alternatives. Programming of investments to build and maintain such facilities requires the use of the most cost-effective solutions to squeeze funds out of limited budgets and across systems.

Henceforth transportation asset management (TAM) can be thought of as the solution to this dilemma. TAM is a strategic and systematic process of operating, maintaining, and improving physical assets. TAM appears to have developed from a Pavement Management System (PMS), with an emphasis on engineering and financial analysis based on information of high quality, to recognize systematic measures which will achieve and maintain the desired level of good repair at a minimum cost over the life cycle of the assets.

However, to date, practical implementations of TAM has faced many drawbacks (NCHRP 2005): (1) Modeling of static output which does not understand the dynamic nature, of the transport networks (i.e., condition, safety, and capacity) that respond to demand changes in the transportation system from upgrades and expansion or the development of urban patterns and the creation of new industry and economic development in general. (2) Analytical tools that have limited ability to integrate various objectives across modes of transportation.

A robust Transportation Asset Management System (TAM) generates a systematic and consistent framework for selecting among alternatives for Maintenance, Repair, and Rehabilitation (M, R&R) and should ideally determine priorities and optimal timing for upgrades and expansion by predicting future expected demand levels and networks performance.

In the late 1960s and early 1970s, TAM first became popular as decision support tools for the whole range of activities involved in pavements provision and maintenance (OECD, 1987 and Peterson, 1987). Common decision-making systems for pavement management seek the accomplishment of maximum levels of condition, in the form of surface or structure indicators. Others have added goals related to safety and travel time (Amador and Afghari 2015). Attempts to consider road's operational characteristics (speed, capacity, volume, etc.) within pavement management systems have opened the door for broader management frameworks such as those proposed by the Highway Economic Requirements System (HERS/ST) or the Highway design manual (HDM) of the World Bank.

The increased computing capacity has enabled the use of advanced simulation and optimization methods to solve complex transport and urban planning problems. The most cost-effective solution for allocating resources to competing alternatives was found in methods such as linear programming and heuristic optimization (L. E. Amador-Jiménez, 2011).

The goal of this chapter is to establish the need for an extended decision support framework capable of handling strategies and investments to prioritize resources to reduce the travel time of most travelers and sustain the network condition at reasonable levels.

The chapter is divided into three major sections: 1) the first one (Section 2.2) provides an overview of the state of practice in modeling travel demand, reviewing background, criticizing current models, and establishing the need for a better approach that connects to decision support systems.

2) Section 2.3 reviews common strategies for counteracting congestion since these strategies are input within the road management system model.

3) Next, Section 2.4 discusses and reviews the fundamentals of decision support systems. It summarizes their advantages and limitations for the modeling of travel time and congestion and

focuses on road infrastructure works (M&R actions) and strategies to facilitate traffic movements with an eye those useful to reduce travel time and congestion.

2.2Travel Demand Modeling

2.2.1 Overview of Travel Demand Models

This chapter presents a detailed and comprehensive review of the literature on travel demand modeling. The objective of the literature review is to determine the related work and research already conducted in this field. The literature review will be presented in two sections. First, it will provide detail descriptions of aggregate demand models, i.e., four-step models, and, second, concentrate on the short description of disaggregate models of travel demand at the strategic level (i.e., activity-based). Travel demand forecasting is a key part of transport planning and policy analysis. A travel-demand model is defined as:

"*a mathematical relationship between travel-demand flows and their characteristics on the one hand, and given activity and transportation supply systems and their characteristics*." (Cascetta, 2009)

Since the 1950s, numerous travel demand models have been developed based on various assumptions and with different approaches to forecast future demand. Cascetta, 2009 classified travel demand models according to the level of detail into two broad categories:

a) Aggregate travel demand models

b) Disaggregate travel demand models

The first generation of travel demand models developed in the 1950s was aggregate in nature. In such models, the attributes for a group of users are compiled (for example, the average travel times or costs of all trips between two zones. In disaggregate travel demand models, attributes are viewed at the individual level (e.g. travel times or costs between the actual origin of the trip and the destination points). Based on the sequence of choices, Cassetta, 2009 has also classified the travel demand models into three broad classes:

a) trip-based models (Four Step Modeling)

b) trip-chaining models

c) activity-based models.

Currently, two main techniques for travel demand modeling are being used (Husein, 2017). They include the trip-based, and the activity-based, modeling processes. Trip-based models assume that each origin-destination trip decision is made independently without considering the interrelationship between the various trip selection attributes (e.g., time, destination, and mode). Activity-based models predict the demand for travel as a result of taking part in activities at various space and time points.

To estimate traffic volumes for this research, the Four-Step Modeling (FSM) technique is the best technique because of its simplicity and its ability to produce acceptable results. However, activity-based models have the potential to lead to more realistic and accurate predictions (Castiglione et al., 2014). Many of these models still heavily focus on the static correlation between observed travel behavior and explanatory variables such as income level, Car ownership, land-use, etc. Due to their complexity and extensive data requirements, activity-based transportation models were not adopted at the same pace by practitioners. Despite this limitation, the four-step modeling process is still accepted and used by most Metropolitan Planning Organizations (MPOs) due to the reasonably satisfactory results produced by this model type (MARTIN, MCGUCKIN, & Barton-Aschman Associates, 1998).

To modelers, the benefits of activity-based transport models in capturing individuals ' behavioral realism and their ability to get closer to an understanding of individual behavior are clear and effective. However, for practitioners and decision-makers at the macro level, it often proved to be less valued or misunderstood in the past, since the decisions for transport planning are generally based on aggregate demand forecasts and transport facilities performance (Janssens & Wets, 2005). Thus, the following sections describe in detail the series of choices in aggregate and disaggregate travel demand models.

2.2.2 Aggregate travel demand models

The aggregate model of the travel demand was developed in the 1950s and focused primarily on the zonal system. In a geographical area, various attributes are aggregated as an analysis unit to estimate travel demand. Traditional models have been enhanced and modified since their first development, but in this thesis, we have only focused on the original framework of the traditional model explained in the literature for simplicity.

Factors considered in the four-step travel demand forecasting technique included the time of day analysis, peak-period spreading, mode choice, and trip assignment.

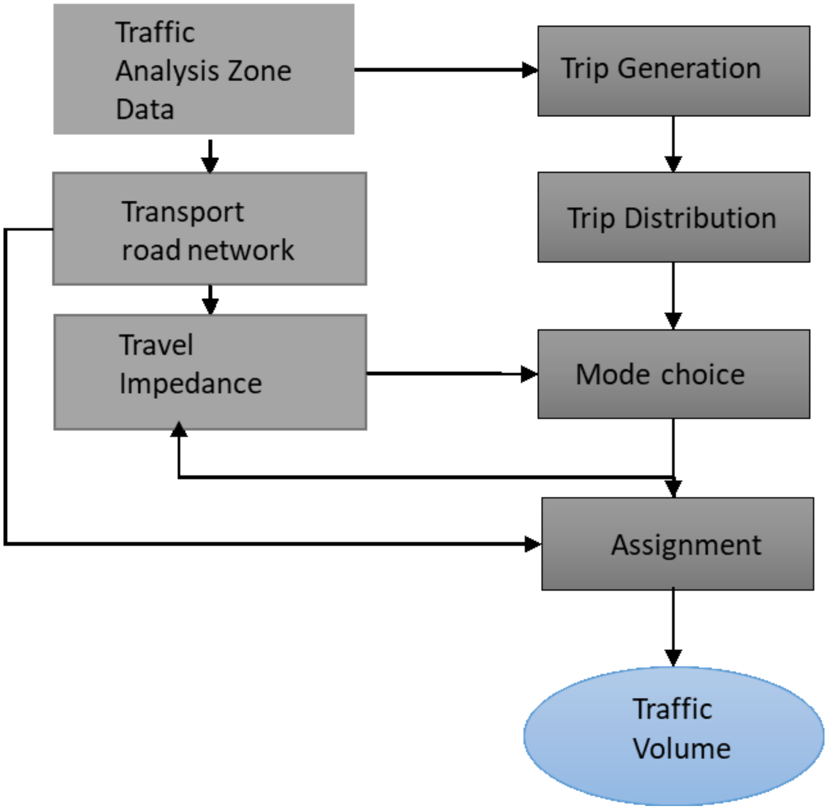


Figure2-1 Four-Step Process Transportation

The four stages are sequentially applied, and each has a different mathematical model to forecast the future demand for travel between pairs of Origin-Destination. A brief description of the four different stages is presented below.

2.2.3 Trip Generation

The first stage of the traditional 4-stage model is trip generation. In this stage, the models estimate the total number of trips produced and attracted in each zone using the zonal information from land use, population and economic forecasts of the area for different trip purposes, such as work trips that begin or end at home, home-based non-work trips (shopping trips, school trips) and trips that neither begin nor end at home. The trip generation process uses household travel surveys and land use data such as population, households, housing units, and employment to calculate trip productions and attractions in the study area for each Transportation Analysis Zone (TAZ).

The trip production is typically estimated based on household characteristics, namely household size, and the number of vehicles available in a household. Trip attractions are generally estimated based on different criteria for each land use type, such as floor areas. For commercial, retail, and industrial land uses, for instance, the Gross Floor Area (GFA) of the development is considered for estimating the rates. Although this approach results in an accurate estimation of the trip generation, it is considered an expensive practice and is not feasible for traffic zones with larger scales.

Therefore, other policies and guidelines are commonly being used to estimate trip generation. Some of these common guidelines can be found in Mousavi, Bunker, and Lee (2012). In Australia, the most common guideline for trip-generation estimation is the RTA Guide to Traffic Generating Developments (Rasouli, 2018). Another international guideline for estimating the traffic generation of different land uses is the Trip Generation Handbook, which contains the standard guidelines for the United States (US) and includes a wide range of information for various land uses (Trip Generation Manual, 10th Edition © 2018).

The total number of trips produced and attracted is estimated by different mathematical models, namely linear regression models, cross-classification models, or trip rate models (Ortúzar & Willumsen, 2011a; Roorda & Miller, 2005). The output of this first stage is the number of trips produced and attracted by each zone, which is used in the trip distribution stage to make a trip matrix.

2.2.4 Trip Distribution

Trip distribution is the second step of Four-Step Modelling (FSM). The central concept of trip distribution is to calculate the number of trips generated among the destination TAZs. The primary purpose of this step is to create trip linkage or interaction between the zones for commuters. The inputs to a trip distribution model are the zonal productions (Pi) and attractions (Aj), and the output is the Origin-Destination matrix (OD) or, in other words, the production attraction (P/A) matrix). It should be noted when the trip distribution phase precedes modal split analysis; the results include trips by all modes. In actual practice, however, multimodal trip distribution models are seldom, and in most cases, highway-oriented models have been used to distribute trips of all modes; however, in actual practice, the model should have the distribution model for each mode of transport and each trip purpose. Since the trip maker decisions related to destination and travel mode usually are made simultaneously, it is believed that ideally trip distribution should be combined with modal split analysis.

Distributing trips are usually based on the function of time and distance and are dependent on how many trips are anticipated to occur between the two zones. Among the various methods to model trip distribution, the gravity model adapted from Newton's gravity theory is commonly used in the trip distribution process. This method works on the basis that allocates the produced trips of a zone to others for different trip purposes based on some friction variables between pair of zones (McNally, 2007). These frictions can be different such as travel time, distance, and travel cost. As a rule of thumb, people are willing to make longer trips to work from where they live if alternatives for the trip purpose are available.

NCHRP 365 provides the use of gamma-function coefficients of several samples for urban areas as synthetic friction factors. Other calibrated models for similar communities can also provide friction factors. Between the traffic assignment step and the trip distribution stages of the model, an iterative feedback loop can be set to use the congested travel time as an input into the distribution process.

2.2.5 Mode Choice

This step is most important for urban models of alternate modes of travel, such as walking, biking, or driving any motor car or preferring public transportation to drive from one place to another. The main aim of this stage is to transform productions-attraction trips in different modes into origins and destinations.

Mode choice can be defined as the intention of travelers in choosing their mode of transport for their trips. Mode choice is highly dependent on a traveler's personal intentions to choose the means of travel. It divides the production attraction (P / A) matrix into separate matrixes for every travel mode from the trip distribution stage. Modal split models mainly link the likelihood of transit use to mathematically explaining variables or factors. The mode choice models are very data-intensive; one possible source of data is home interview surveys. O-D surveys are usually used to develop mode choice models. The analysis involves the processing of a variety of data for both demand and supply. In developing these models, there is an assumption that needs to be taken, which is the variables that explain the present level of transit usage will do so in much the same manner in the future. Ashalatha, Manju, & Zacharia (2013) researched Thiruvananthapuram, India they describe the method-choice step as a process of arriving at decisions on a particular mode of transport in certain circumstances.

Several factors are affecting mode choice models; these factors can be group into three levels: trip makers characteristics such as income, car-ownership, car availability, and age. trip characteristics such as trip Purpose - work, shop, recreation, and trip length. Transportation Systems Characteristics such as waiting time, speed, cost, and access to a terminal or transfer location.

The mentioned characteristics can be used to estimate the mode choice models. The most common mathematical form is logit models. The logit model is a mathematical formulation that estimates the probability of choosing a specific mode based on attributes from trip characteristics such as cost and level of service. The NCHRP Report 365 outlines the procedure to develop a model based on incremental logit formulation. It uses variables such as in-vehicle travel times, out-of vehicle time (walk, wait, and transit time) and the cost of travel to calculate the probability of choosing a mode of transport (Chiou, Jou, & Yang, 2015; Shen, Chen, & Pan, 2016).

2.2.6 Trip Assignment

The last step in four-step modeling is traffic assignment, which allocates the loadings, or user volumes, on each segment of the road network and transit trips onto the model transportation network. The unit for this user volume can be a number of vehicles, the number of total persons, or the number of transit riders. Depending on the software and the type of analysis, the trip assignment is different. There are two main types of assignments: the car assignment, which handles car routing, and the other one is public transport (transit) assignment that deals with routing of linked passenger trips.

Popular traffic assignment models include the User Equilibrium model, Stochastic Equilibrium model, and Incremental Assignment model. A mathematical algorithm is used in models for the traffic assignment to links between origination destination zones. The final output of the estimate is, for example, the volume of vehicles on each road and the number of passengers on each link, taking two modes into account, i.e., car and public transit. Different methods are used for traffic assignments in the network such as "all-or-nothing" assignment, equilibrium assignment and so on (McNally, 2007; Ortúzar & Willumsen, 2011a). In the all-or-nothing method, all trips between two pairs of zones will be assigned to a single route based on the available capacity. The Equilibrium assignment distributes the demand according to Wardrop’s first principle as follow: Every road user selects his or her route in such a way, that the impedance on all alternative routes is the same, and that switching to a different route would increase personal travel time (user optimum)." The underlying assumption of that action is that every road user is fully informed of the network situation. This theory is accepted by transport planning with a fundamental methodical advantage of equilibrium assignment – the existence and uniqueness of the assignment outcome are guaranteed with very general specifications (expressed in network object volumes).

In the transit assignment, the line route is one of the main elements regards the assignment, which consists of a set of links called line segments. There are different types of transit assignment depending on time table data and the environment. The most common transit assignment is transport system-, headway- and timetable-based. The transport system-based procedure is used when the aim is to evaluate the whole system instead of analyzing single transit lines. This does not include a transit line and is used to create a public transport network in which passengers choose the shortest routes. The headway-based assignment is based on the optimum strategy theory involving speeds and travel times for the public transport lines involved. Since this form of procedure does not allow exact timetables, it is only useful when the schedules are undetermined for long-term transport planning.

Input data such as network attributes and land use attributes are needed in the previously described four-stage process. Data reflecting travel behavior in the study area is, however, needed to ensure precise estimates at each step. The travel behavior parameters include trip rate tables and vehicle occupancy factors; as mention before, such an approach results in an accurate estimation of the trip generation. Then the estimates are validated and calibrated using actual traffic counts and using past models that were developed for estimating traffic volumes for validation.

2.2.7 Disaggregate travel demand models

One of the significant innovations in the travel demand analysis was the development of disaggregate models using discrete choice methods in the early 1970s; however, in general, these models have focused on modeling individual trips made during the day (Roorda, 2005). The disaggregate approach assumes that aggregate behaviors are the result of numerous individual decisions. The approach models individual choices as a function of the characteristics of the alternatives available and the socio-demographic attributes of each individual. One of the types of disaggregate models called activity-based model contains detailed travel information of individuals (e.g., time/duration of trips/activities, location, frequency, sequence) and required of extensive data, which in turn signifies a high cost for collecting individual data. Given the cost and data securement issues, this thesis rather implements the four-step models as the primary approach to stimulate travel demand.

2.3Common Strategies for counteracting congestion

Travel demand models enable the identification of congestion over a transportation network. Strategies and scenarios are often tested with the same models to counteract congestion.

Traffic congestion arises from many factors, including increased transport and travel demand for intensified economic and leisure activities and a growing population. In some metropolitan areas, because of funding constraints, it is challenging to perform major expansions involving land expropriation or build underground (elevated) structures. Modern solutions seek to accomplish the modal shift from automobile to public transit or towards active transportation to reduce congestion. There is increased world-wide support to public transit (Secretary-general, Group, & Transport, 2016); in fact, many cities are moving towards much stranger support of Transit. Many recent transportation impact assessment regulations include Policies to discourage car travel and support public transportation, as seen in Table 2-1.

Transportation engineers and planners have developed a variety of strategies to manage demand, which are more critical to transport operations than strategies to increase capacity (supply) of facilities and that better use needs to be made of existing and new transport infrastructure. These strategies fall into two general categories: Travel demand management, Transportation System Management (Adamson, Yo, & Hoy, 2005)**.**

2.3.1 Travel Demand Management (TDM)

TDM consists of strategies that foster increased efficiency of the transportation system by influencing travel demand by mode, time of day, frequency, trip length, regulation, route, or cost(Abdul Majid et al., 2015). In other words, these strategies include putting more people into fewer vehicles (through ridesharing, increased public transportation ridership, or dedicated highway lanes for high-occupancy vehicles), shifting the time of travel and eliminating the need for travel altogether.1990s was the end of major highway construction and many planning agencies had shifted to short-term planning to deal with the deterioration of transportation infrastructure and transportation congestion. Moreover, the growth in travel demand was no longer able to be accommodated by increasing supply levels. As a result, integrated TDM strategies, especially those enabled by advanced technology, had a more significant role to play in the revitalized long-term strategic transportation planning process.

2.3.2 Transportation System Management and Operations (TSM)

TSM strategies are improvements intended to utilize the existing transportation system's capacity to the greatest extent possible. These improvements consist of geometric improvements or traffic control strategies rather than increasing the number of general use lanes (Abdul Majid et al., 2015). In recent years, transportation engineers and planners more than just building new infrastructure have embraced strategies that deal with the management of existing roads. Transportation System Management and Operations (TSM&O) aims to reduce the impact of a number of road incidents and control short-term demand for existing road space. This mechanism is the core concept behind Transportation System Management and operations.

2.3.3 Candidate strategies (TDM and TSM) for this thesis

Identification and characterization of actions and strategies intended to reduce demand or increase the capacity of road segments have been previously done (Papageorgiou et al. .2003). Table 2-1shows 24 operational strategies that were selected from an initial list of more than 100 as being particularly useful in enhancing the performance characteristics of links, corridors, and networks (Texas Transportation Institute, 2005) and, therefore useful for the models developed in this thesis. Some of the strategies are applicable only to freeways, some are applicable only to arterials, and others are applicable in both environments.

Table 2-1 Strategies to Improve Capacity (Kittelson et al., 2011)

Freeway	**Arterial**	**Both**
HOV Lanes	Signal Retiming	Narrow Lanes
Ramp Metering	Signal Coordination	Reversible Lanes
Ramp Closures	Adaptive Signals	Truck Only Lanes
Congestion Pricing	Raised medians	Truck Restrictions
Pricing by Distance	Right/Left Turn Channelization	Pre-Trip Information
HOT Lanes	Alt Left Turn Treatments	In-Vehicle Info
Weaving Section Improvements	Access Points	Variable Lanes
Frontage Road	Queue Management	VMS/DMS

Notes: HOV = High Occupancy Vehicle; HOT = High Occupancy Toll; Alt LT = Alternate Left Turn; VMS = Variable Message Sign; DMS = Dynamic Message Sign

2.4Decision support systems for road management system

Road infrastructure is key to a sustainable and competitive economy (Amador-Jimenez & Willis, 2012). Increasing demands and rising financial and human resources render infrastructure planning a dynamic and daunting challenge for governments and agencies. In the face of these challenges, public and private agencies around the world have gradually realized the advantages of implementing asset management systems. Infrastructure asset management is a system and decision-making mechanism which takes into account a range of properties and covers the entire service life of a resource from a technical and economic point of view (Vanier & Rahman, 2004). This seeks to bring a systematic method of cost-effective operation maintenance upgrading and extension of physical assets, a practical strategy for achieving well-defined priorities for both short and long-term planning (AASHTO, 2010).

Infrastructure asset management has evolved from pavement management systems. Since most infrastructure systems matured and demands began to increase rapidly in the mid-1960s. The development of management systems proceeded with bridge management systems and integrated infrastructure management systems (Uddin, 2005). The evolution of decision support and management systems is summarized in Table 2-3.

Pavement Management System (PMS) is relating all the main phases of pavement work together. Such as planning, designing, constructing, maintaining rehabilitating, monitoring, and evaluating pavement conditions (Uddin, 2005). The goal of PMS is to make the best use of available funding to enhance or preserve roadways pavement. PMS finds the best time through the life cycle to apply a particular treatment on a specific pavement segment. These strategies are capable of maintaining existing pavements in good condition and keeping the number of roads in poor condition at a minimum by considering the cost-effectiveness of each treatment. One of the essential components for PMS is a database. This database should include documenting the historical and current road conditions (functional and structural), the pavement structure such as pavement type, thicknesses and traffic information.

There has been a shift in the past 30 years toward maintenance and rehabilitation M&R strategies rather than new construction (Birdsall & Hajdin, 2008). The reasons for this shift were; first, there were enough constructed infrastructures like road network, and second, those infrastructures have deteriorated and need to be maintained and rehabilitated in order to deliver an adequate level of service. Therefore, pavement investment policies face essential policy questions regarding the uses of pavement maintenance and rehabilitation (M&R) such as which pavement section to treat, which type of treatment to apply in the current budget period, and when this treatment must be applied.

Insufficient resources and financial limitations lead to the development of new methods in optimization to help asset management decision-makers to program and plan M&R works. Optimization methods such as linear programming (most formal methods of optimization), non-linear programming, integer programming, or heuristic methods are examples of various techniques and decision-making strategies commonly used in the state of practice of transportation asset management. An essential component of the pavement optimization models is the pavement deterioration model, the maintenance decision process, the cost of M&R activities, the available budget, and the functional classification of roads. These models ensure the maximization of the overall condition of the road network, taking into account other important factors such as traffic demand. The development and implementation of a network-level optimization model for pavement M&R have been provided by Gao, et al. 2012, while a project-level optimal framework has been offered by Irfan, Khurshid, Bai, Labi, & Morin, 2012.

Table 2-2 Historical Evolution of Decision Support Systems

System	Authors	Description
Elimination Et Choix Traduisant la Realite (ELECTRE)	Roy and Sussman, in 1966	Multi-criteria decision making of bridges
Weighted Sum Model (WSM)	Fishburn (1967)	Determine an adequate asset management solution for the dam.
Pavement asset management	Developed in the 1970s Rehan et al. 1994	Determine an appropriate asset management approach for pavement
Pavement asset management	Developed in the 1970s Rehan et al. 1994	Comprehensive allocation of pavement-related works including construction, maintenance, rehabilitation, inspection and pavement conditions assessment
The World Bank provided the Highway Design Manual System (HDMS).	Developed in the 1980s Finn, 1998	Fundamentals of road management related to the decision-making progress
Analytical Hierarchy Process (AHP)	Saaty in 1980	Multi-Criteria Decision Makings
The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Hwang and Yoon (1981)	Multi-Criteria Decision Makings
Asset management system (AMS) using capacity-based Approach	In the late 2000s (Xu et al.)	AMS by utilizing the Risk-Return Trade-Off
the municipal asset management system	Howard, R. J., 2001	Avoid the negative effects of declining municipal road infrastructure as it was necessary to maintain a successful and competitive economy
Agent-Based Modeling	Bernhardt et al. 2008	paradigm in order to develop asset optimization
Life-cycle cost approach	Corotis in 2009	Used for the management of Civil Infrastructure Systems
Dynamic Programming Models	In 2011	Management Bridges for improving structural classes (inspection, repair, and rehabilitation)
Infrastructure Performance Rating Models	Mohammed et al.,2014	Models in order to manage wastewater treatment plans
Big Data-Based Deterioration Prediction Models	Kobayashi et al., 2016	To find the best solution to the problem of maintenance

2.4.1 International Roughness Index (IRI)

One of the critical pavement indicators that were employed in a pavement management system is the International roughness index (IRI). The IRI was developed by the World Bank in 1986 and was based on the expansion of the concept of the NCHRP. It shows the smoothness of the pavement surface. It is an indicator of the level of comfort experienced by the traveling public while riding over a pavement surface (FHWA, 2018). Smoothness also has to do with other advantages, including lower fuel and vehicle repair costs (Dam et al.). IRI tests accumulated suspension movement in a vehicle that traverses a given distance.

Traffic conditions especially ESAL, are of the utmost importance in contributing to the IRI performance as ESAL numbers have a significant impact on changes in the pavement surface conditions. Therefore, the IRI value prediction requires a suitable traffic design. Equivalent single axle load (ESAL) is a quantity associated with pavement damage caused by a regular axle load of 80 kilonewtons (kN) (18,000-pound-force lbs) carried by a single axle with dual tires. The IRI units are expressed of slope (m/km, in/mi, mm/m, etc.). The lower IRI means the road is perfectly flat paved such as IRI of 0.0 (m/km) and for the upper limit, there is no theoretical upper threshold although values above 8 (m / km) represent pavement is in the worse condition, and it needs M&R strategies. IRI is an index most widely used in the world to describe longitudinal road roughness for the pavement management system (Múčka, 2017).

The different methods used worldwide to assess road roughness. Using high-speed longitudinal pavement equipment has become the industry standard for measuring road roughness. The different methods used worldwide to assess road roughness. Using high-speed longitudinal pavement equipment has become the industry standard for measuring pavement roughness. Inertial

Profilers are vehicle-mounted instrumentation systems that measure vertical deviations of pavement surface along the direction of travel has been shown in Figure 2-2.

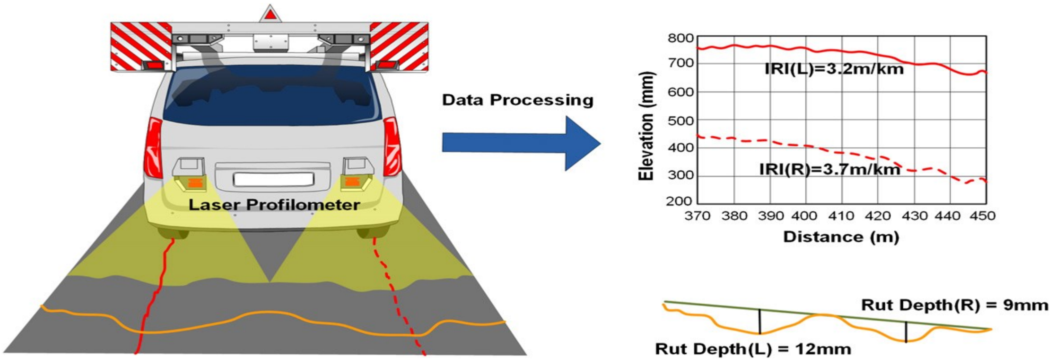


Figure 2-2 Inertial Profiler work principle (Jeong, Lim, Suh, & Nam, 2014)

2.4.2 Deflection Basin area

Deflection measures are used for measuring the pavement structure's reaction to a known applied load. After a load is applied on the pavement Figure 2-3 by Falling Weight Deflectometer test, The AREA Parameter is the index to represent these series of numbers for our simplicity which is normalized area of a vertical slice between the middle of test load and 914 mm (3 feet) away from the test load through a deflection basin. To get the normalized AREA Parameter, we need to divide the slice area by the deflection measured at the center of the test. The area gives information regarding the subgrade soil strength and pavement strength based on the amount of deflection induced by the pavement. The Deflection basin area equation is:

$$\mathrm{AREA} = \frac{6(D_0 + 2D_1 + 2D_2 + D_3)}{D_0}$$

where: AREA = the FWD AREA Parameter. (inches or mm).

D0 = surface deflection at the test load center
D1 = surface deflection at 12 inches from the test load center
D2 = surface deflection at 24 inches from the test load center
D3 = surface deflection at 36 inches from the test load center

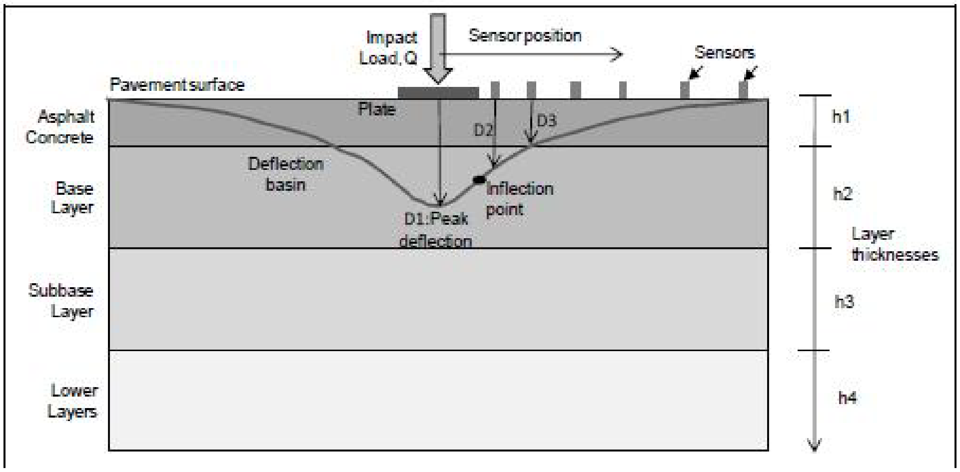


Figure 2-3 Impact load deflection test for Basin Area (Beltrán & Romo, 2014)

The maximum AREA value in theory is 36 inches (915 mm) when D0 = D1 = D2 = D3=1 For all four deflection measurements to be almost identical, the pavement should be extremely rigid, such as rigid pavement or thick hot mix asphalt. The minimum Area value, in theory, should be no less than 11.1 in. (280 mm) under two conditions: same elastic modulus for all pavement layer or no stiffness contribution to the underlying subgrade from pavement layers above it.

2.4.3 Pavement Performance Prediction Models

The acceptable and efficient model of pavement performance prediction (PPP) is the basis for the long-term analysis of PMS. These models are mainly aimed to predict future pavement conditions under specified traffic loading and environmental conditions (Kulkarni & Miller, 2003a). The PPP models have significant features that are essential for the long-range in the process of PMS. These models are used for prioritizing road segment maintenance treatments in the network. Also, these models have been used by transportation agencies to estimate required long-range investment (budget) during the pavement life-span and consequences of budget allocation for maintenance treatments of a particular road segment on the future pavement condition of that road segment (Amin, 2015).

The most commonly employed treatments for pavement preservation, maintenance, and reconstruction, such as crack sealing, micro-surfacing, resurfacing, reconstruction is described below.

1. Crack-sealing: placing materials into developed cracks to prevent water and incompressible materials from intruding through cracks. (California Department of Transportation, (2003).
2. Micro-surfacing: A surface maintenance solution in which a polymer-modified emulsion mixture consisting of graded aggregates, mineral fillers, water, and additives is used to reduce water penetration, provide skid resistance, enhance appearance, and correct weathering, raveling, slight profile defects, and weather damage. (California Department of Transportation (2003)).
3. Resurfacing: A method of installing a new layer of asphalt over the current surface (also known as overlaying) (usually one and a half to two inches). Sometimes, resurfacing can be accompanied by milling, partially removing the damaged, cracked portion of the existing layer before overlaying (Washington State Department of Transportation (2013))
4. Reconstruction: Replacing the whole existing pavement structure by the placement of an equivalent or an increased-strength pavement structure. (FHWA, Office of Asset Management (2005)).

The objective of any Pavement Management System (PMS) is to allow maximum use of the available funding to improve or preserve the roadway pavement. PMS determines the best point through the life cycle of each pavement section to apply a given maintenance treatment. This strategy aims at maintaining existing pavements in good condition and keeping the number of roads in poor condition at a minimum. The PMS consists of two essential components: a comprehensive database and a set of tools and optimization techniques to assist policymakers in establishing cost-effective strategies for the evaluation and maintenance of roadway pavement. The database should contain comprehensive information on historical and current road conditions (functional and structural), pavement structure (pavement type, number and thickness of layers, etc.), traffic and environmental information. The set of tools and optimization methods help in determining the current and future conditions of roadway segments, estimating necessary financial resources, identifying the most cost-effective maintenance treatments, and prioritizing roadway segments for rehabilitation projects.

PMS addresses questions about which pavement section to treat, which type of treatment to apply, and when this treatment must be applied. PMS must integrate three management levels that vary in terms of information detail and complexity of used models in decision making process: strategic, network and project level. At the network level, the primary purpose is the design of the network maintenance program, given overall budget constraints (Torres-Machí, Chamorro, Videla, Pellicer, and Yepes, 2014).

The key elements of an optimization model include the pavement deterioration model, maintenance decision-making process, cost of M&R actions cost, available budget, functional classification of the roadways, and cost-factor associated with the maintenance treatment type. The system ensures that the overall condition of the roadway network is maximized considering other significant factors such as traffic demand and environmental impact. The road maintenance in PMS is a multi-objective optimization problem for several reasons (Saha and Ksaibati, 2017). These reasons are: (1) the objective of engineers or decision-makers is to maximize the overall condition of road network under specific budget limitations; (2) preventive and minor rehabilitation treatments are more cost-effective than reconstruction; (3) budget should be more than a certain amount to achieve maximum benefit to society; and (4) the best mix of roadway segments for rehabilitation should include the segments with high traffic volume.

Chapter 3: Methodology

3.1 Introduction

This chapter presents the methodology employed to develop the models used in this research. The ultimate goal was to obtain long-term plans for interventions and improvements of roads that consider car demand. The chapter is divided into two sections. The first section describes the travel demand model development. The second sections explain the road management system model development. The flowchart of the methodology is shown in Figure 3-1. This study simulates the traffic volume on each road segment through a travel demand model by incorporating the four-step method. An accurate traffic volume is essential for transportation analysis and management, such as pavement management, maintenance schedule, pavement design, and economic evaluations for safety projects (Wang, Gan, & Alluri, 2013).

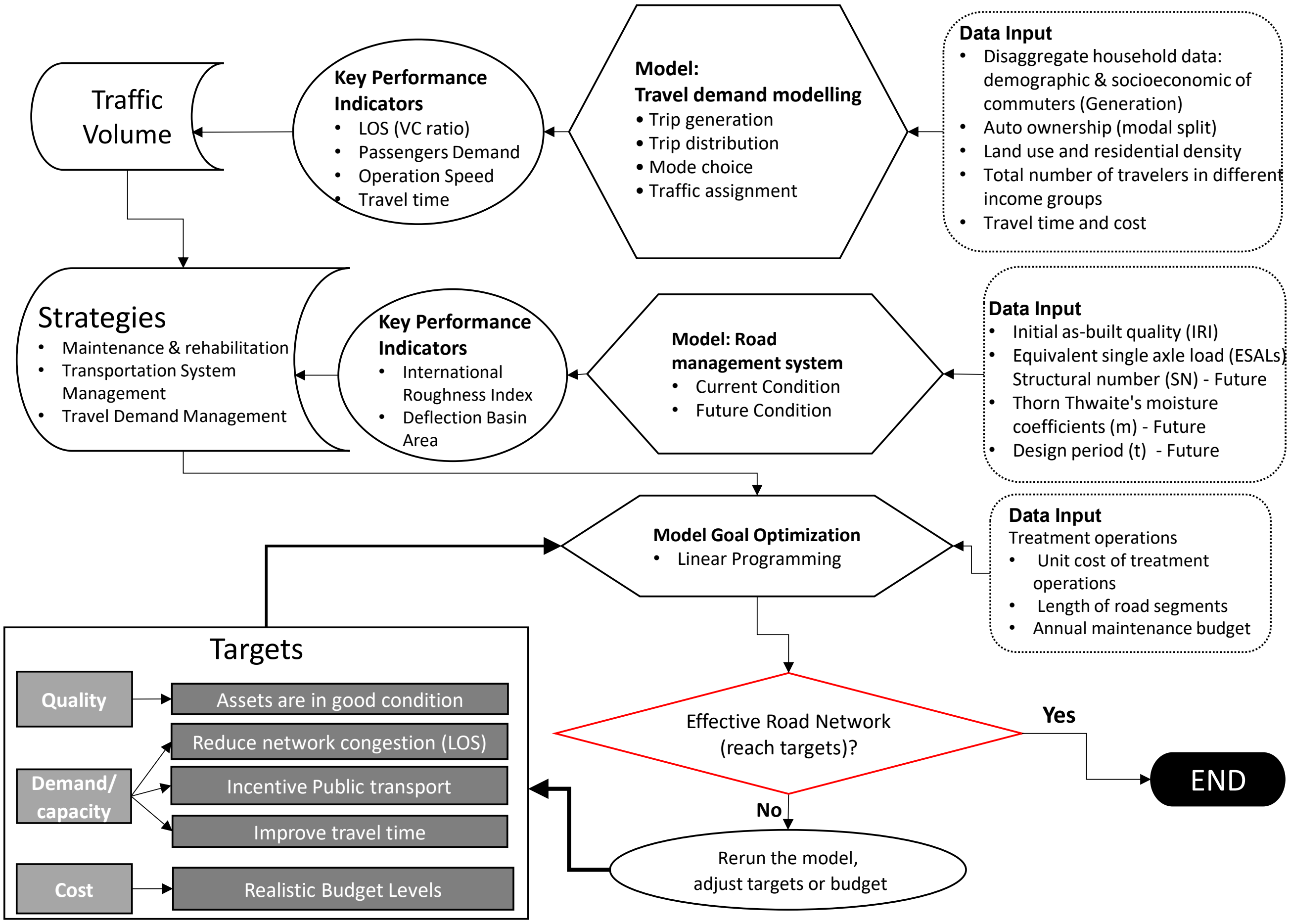


Figure 3-1 Flowchart of the methodology

3.2 Travel demand model development

Developing a TDM model, in particular, is time-consuming and cost-intensive to collect the data needed for a robust model. Therefore, the four-step model approach is used in this study. The reason for using four-step models is that these models represent reality in a simplified way and can be used to analyze the implications of specific policies or strategies. In comparison to field monitoring, the outcome of these models can be obtained quicker and at lower cost and risk. The use of these models in this study is to predict future conditions without a policy intervention or design and find out which road infrastructure, such as pavement, will deteriorate at a future date. Other use of four-step models can be cost-benefit analysis for the new road facilities or new planning proposal in terms of environmental and social impact assessments.

3.2.1 Data sources and description

Development of a travel demand model requires several data types including the following:

1. Transportation road network: with links and nodes. Each link must contain attributes of the posted speed, number of lanes, free flow capacity, whether the carriageway is divided or undivided, etcetera.
2. Population data in transportation analysis zones divided into groups based on relevant socioeconomic characteristics that influence the number of trips made by each household or individual.
3. Aggregated Land use data for each transportation analysis zone in total GFA area or number of employees per land-use type
4. Estimation of travel time cost for each pair of TAZ
5. AADT for control points across the network from recent data counts
6. A dataset that contains pavement surface and structural condition in terms of International Roughness Index (IRI) and Area-basin deflection.

In this study, the transportation road network was obtained from the open street map (www.openstreetmap.org) and also from Open Data Portal for both case studies. The dataset is a GIS file format that contains centers of several road segments, including a unique identifier of each segment of the road, road type, number of lanes, and the length of the segment. Population data are used to get a broader meaning about the population in general by using information from the census data in order to use it in transportation analysis. In the costa Rica case study, population data was provided by the ministry of transportation, and in Montreal, case study data has been obtained from Statistics Canada (http://datacentre.chass.utoronto.ca/census/). The household and individual information such as population, income, and auto-ownership can be derived from O-D surveys and should be aggregated by the TAZ level. Pavement dataset was provided by the National Materials and Structural Models Laboratory (LANAMME) of the University of Costa Rica and an open data portal from the city of Montreal (http://donnees.ville.montreal.qc.ca/dataset/) and was used to develop Pavement Performance Prediction (PPP) models.

3.2.2 Demand model software selection

The selection of tools/packages for travel modeling depends mainly on the following factors: project specifications, cost of acquiring software. Therefore, VISUM from the PTV group was a good choice. VISUM is a detailed, versatile traffic and transport planning software system. The system is used around the world for the preparation of local, national and state-wide infrastructure planning. Its user-friendly interface, it is well-organized command structure and the good user manual made it possible to finish this study.

3.2.3 The four-step model approach in VISUM

A study area needs to be divided into zones, the number of zones and their size is depended on the purpose of the model, and what precision is feasible. Information from land use and population for each zone should be aggregated into zone level. A road network similar to the current conditions is also required for the model, which in VISUM they called links. Residential streets and dead-end streets are typically often ignored because traffic on larger collecting roads is of much greater importance.

The model estimation is done in four stages, which is why we call four-step models. Trip generation (step one), is relating all the data regarding land-use and demographics, and other socio-economic together and trip factors decide the frequency of trip origin or destination in each zone. The trip distribution (step two) measures how much traffic flows between each pair of zones, based on how well links connect the zones. The consistency and quality of the link are often calculated by travel time.

Mode choice (step three) measures the proportion of trips between each zone using a specified mode of transport.

The trip assignment (step four) specifies the flow of traffic through the road network. Techniques of measurement also take account of delays caused by congestions. These delays are calculated to calculate new travel time between zones, and with the new travel time step, two is then repeated. In VISUM there is a feedback loop function that takes care of these repetitions.

The idea of production and attraction is an essential element of four-stage models. Each trip happens between two points where trip intentions are to do a specific activity such as going to work, school, and others.

3.2.4 Matrix corrections in VISUM

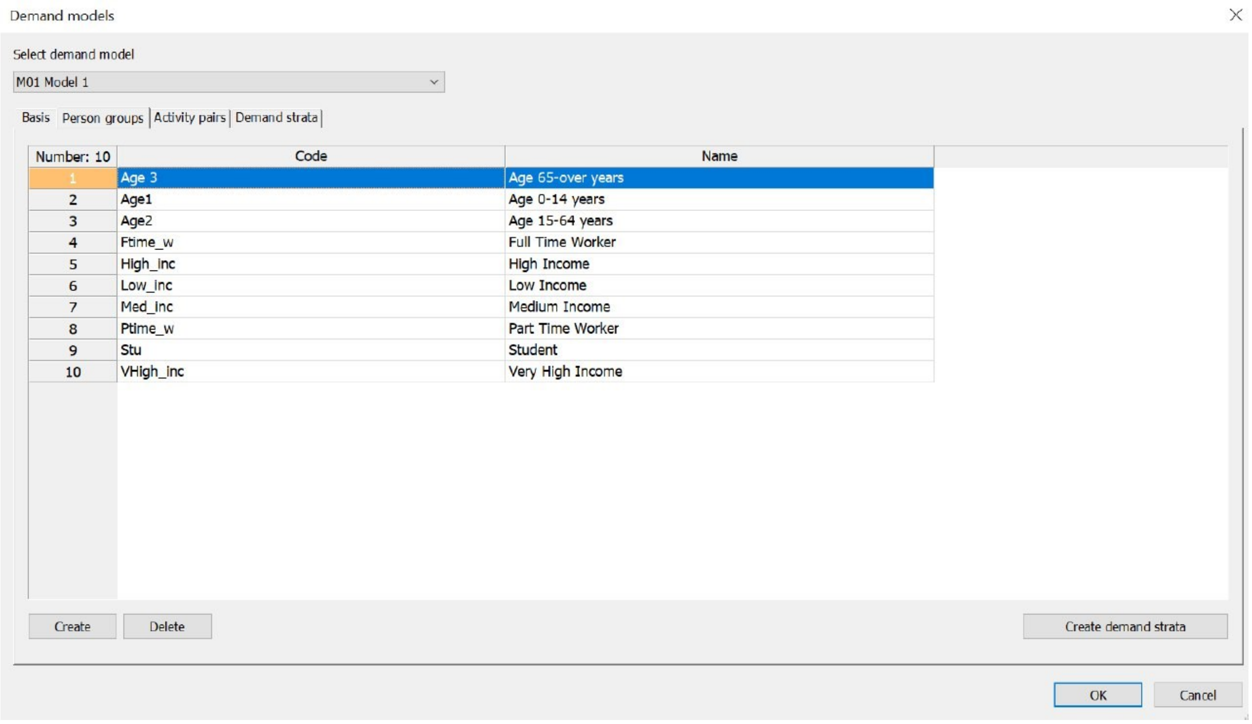
Many four-step models use so-called matrix correction (or matrix update) techniques. Matrix correction methods are used in VISUM are meant to adjust a demand matrix, to adjust a given OD matrix results for a supply match the real supply observed from traffic counts. Matrix correction can be useful in several situations: The results from the trip distribution matrix are not only will be based on the productions, attractions, and connection quality between zones but also a combination of factor and traffic counts. A demand matrix based on survey data is outdated and It can be updated without the need for a new O-D survey. The change will be based only on census data. (PTV VISUM manual, 2018).

3.3 VISUM model structure

The first step is to group population-based on similar characteristics in the study area. There is an assumption that needs to make here, which is the traffic behavior of the different groups should be different, but within the individual groups, it should be as homogenous as possible. In VISUM these groups called person-group. For this study, full-time worker, part-time worker, full-time student, Income level and car ownership has been chosen as person groups due to data availability. The second step is to define the trip purpose or activity pair. The demand model is based on the assumption that trip purposes or external activities cause mobility. The trip purposes used are home-based work, home-based school, and home-based other. A combination of person-groups and activity pairs will be demand stratums. It links an activity chain with one or several person groups. The third step gravity model, which is a mathematical model for trip distribution calculation, is used to distribute trips between zones for each demand stratum. In the fourth step, trips will be divided into two general modes, which are private such as car and public such as bus, metro, rail for each of the demand stratums. Finally, for each of the two modes, these demand strata are linked and separately assigned to the road network. The following sections will give detail information from each four-step models in VISUM.

3.3.1 Trip Generation (Production and Attraction) VISUM procedure

The selected approach in this step is to calculate trip rates based on the purpose of trips considering the person groups which represent the same mobility behavior. Indicating the critical variables to group mobility behavior is an easy task. Depending on the available O-D survey and the demographical data in the study area, these key variables, such as Income-level, employment, age groups, car ownership, etc., can be extracted. For this study, different age groups, different income levels, and employment status had been considered. Figure 3-2 shows the person groups in VISUM.

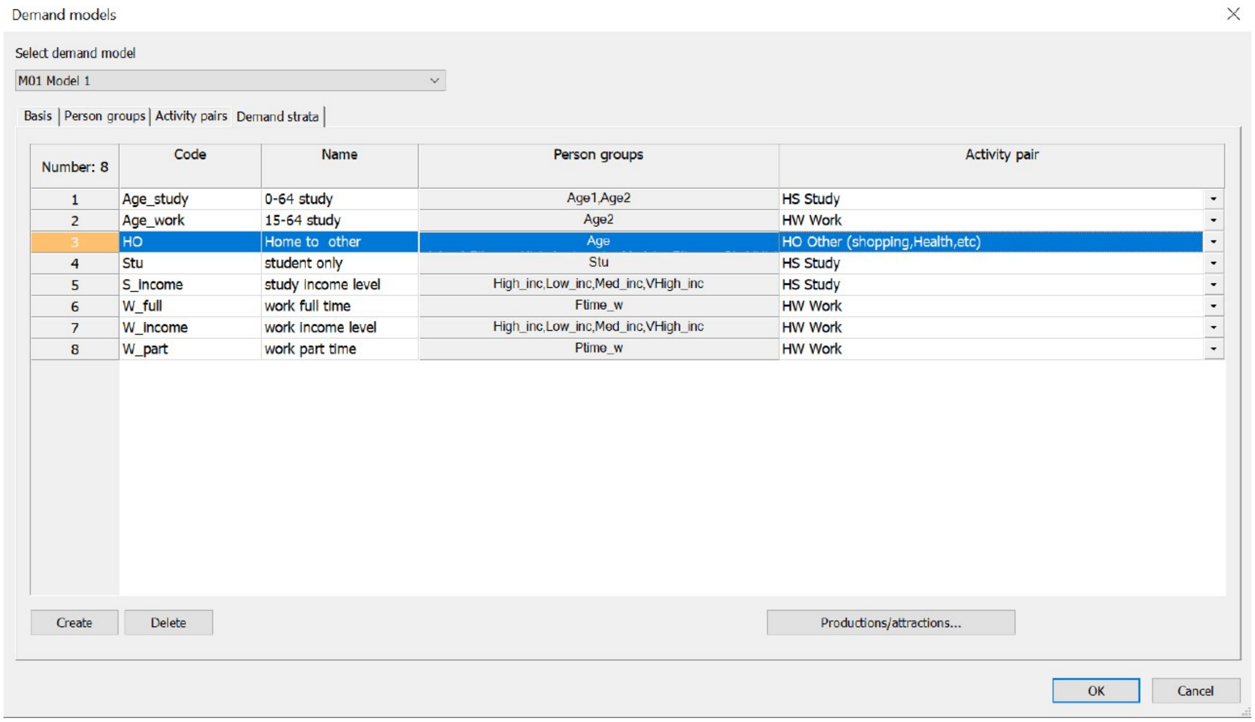


Select demand model: M01 Model 1

Number: 10	Code	Name
1	Age 3	Age 65-over years
2	Age1	Age 0-14 years
3	Age2	Age 15-64 years
4	Ftime_w	Full Time Worker
5	High_inc	High Income
6	Low_inc	Low Income
7	Med_inc	Medium Income
8	Ptime_w	Part Time Worker
9	Stu	Student
10	VHigh_inc	Very High Income

Figure 3-2 Person group characteristics

The next step in the trip generation model is to define the activities to describe the location of the population during the day. Activities used for this study are work, school, and others. The combination of the person groups and activity pairs will create the demand stratums (demand strata). Figure 3-3 shows the demand strata for the four-step model.



Number: 8	Code	Name	Person groups	Activity pair
1	Age_study	0-64 study	Age1,Age2	HS Study
2	Age_work	15-64 study	Age2	HW Work
3	HO	Home to other	Age	HO Other (shopping,Health,etc)
4	Stu	student only	Stu	HS Study
5	S_income	study income level	High_inc,Low_inc,Med_inc,VHigh_inc	HS Study
6	W_full	work full time	Ftime_w	HW Work
7	W_income	work income level	High_inc,Low_inc,Med_inc,VHigh_inc	HW Work
8	W_part	work part time	Ptime_w	HW Work

Figure 3-3 Demand strata four-step model

After defining the person groups, O-D survey is used for estimating trip rates to determine how many trips a person does per day, depending on the category of the person group. Two methods have been used. The first method is linear regression to evaluate the number of generated trips based on historical data. Linear regression equations evaluate the number of generated trips that attract to the study area (dependent variable) from independent variables (Zenina & Borisov, 2014). The following equation represents this relation between variables.

$$Y = a + b_1x_1 + b_2x_2 + \cdots + b_nx_n \qquad \textbf{[3.1]}$$

Where

Y: the dependent variable (trips/household)

x_1, x_2 ,…, x_n: independent variables (population, number of vehicles, gross floor area for different land-use)

b_1, b_2 ,…, b_n: regression coefficients (trip rates) that show to what extent Y changes

The second method for estimating trip rates that have been used for this study is called Cross-Classification or Category Analysis. This method is based on estimating the response; for example, the number of trip productions per household for a specific purpose. The method determines these rates empirically and typically requires large quantities of data. The number of households in each class is indeed a crucial element for this method (Ortúzar & Willumsen, 2011). The following equation 3.2 is used.

$$t^p(h) = \frac{T^p(h)}{H(h)} \qquad \textbf{[3.2]}$$

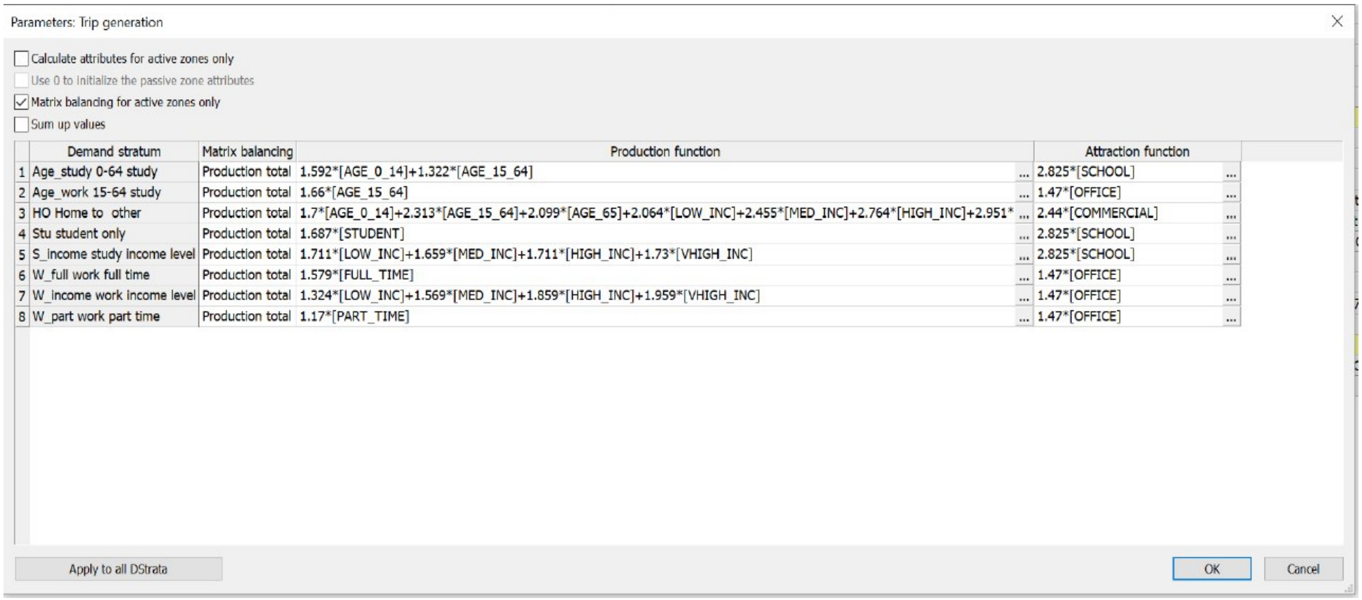
Where

$t^p(h)$: average number of trips with purpose p made by members of households of type h

$T^p(h)$: observed trips by purpose group

$H(h)$: number of households in the same category

After that, we need to find out where the population in the study area is going; therefore, there is a need for measurement of attraction per zone. The available data for this study was the floor area in square meters of different land-uses such as schools, offices, and others. For that matter, Arcmap software has been used to calculate the gross floor area of each category in each zone. Furthermore, the estimated measurement units need to be multiplied with a trip rate. For example, a school might generate one trip per 2 m^2 while a factory generates one trip per 13 m^2. Figure 3-4 shows the trip generation model in VISUM.



☐ Calculate attributes for active zones only
☐ Use 0 to initialize the passive zone attributes
☑ Matrix balancing for active zones only
☐ Sum up values

	Demand stratum	Matrix balancing	Production function	Attraction function
1	Age_study 0-64 study	Production total	1.592*[AGE_0_14]+1.322*[AGE_15_64]	2.825*[SCHOOL]
2	Age_work 15-64 study	Production total	1.66*[AGE_15_64]	1.47*[OFFICE]
3	HO Home to other	Production total	1.7*[AGE_0_14]+2.313*[AGE_15_64]+2.099*[AGE_65]+2.064*[LOW_INC]+2.455*[MED_INC]+2.764*[HIGH_INC]+2.951*	2.44*[COMMERCIAL]
4	Stu student only	Production total	1.687*[STUDENT]	2.825*[SCHOOL]
5	S_income study income level	Production total	1.711*[LOW_INC]+1.659*[MED_INC]+1.711*[HIGH_INC]+1.73*[VHIGH_INC]	2.825*[SCHOOL]
6	W_full work full time	Production total	1.579*[FULL_TIME]	1.47*[OFFICE]
7	W_income work income level	Production total	1.324*[LOW_INC]+1.569*[MED_INC]+1.859*[HIGH_INC]+1.959*[VHIGH_INC]	1.47*[OFFICE]
8	W_part work part time	Production total	1.17*[PART_TIME]	1.47*[OFFICE]

Figure 3-4 Trip generation model in VISUM

3.3.2 Trip Distribution (gravity model) VISUM procedure

The next step is to define the distribution model in VISUM. Production and attraction per zone for each person group estimated from the previous step now it is the time to distribute those population groups between each pair of the zone. VISUM uses a gravity model to calculate the trip distribution. The program estimates the free-flow travel time and trip length to create a skim matrix which is a matrix of all the travel times and distances between all the zones. Then skim matrix used as an indicator for the gravity model to distribute the trips. The general formula for the gravity model is showed as follows.

$$T_{ij} = P_i \left[\frac{A_j F_{ij}\ K_{ij}}{\sum_{k=1}^{zones} A_K F_{ik}\ K_{ik}}\right] \qquad \textbf{[3.3]}$$

Where:

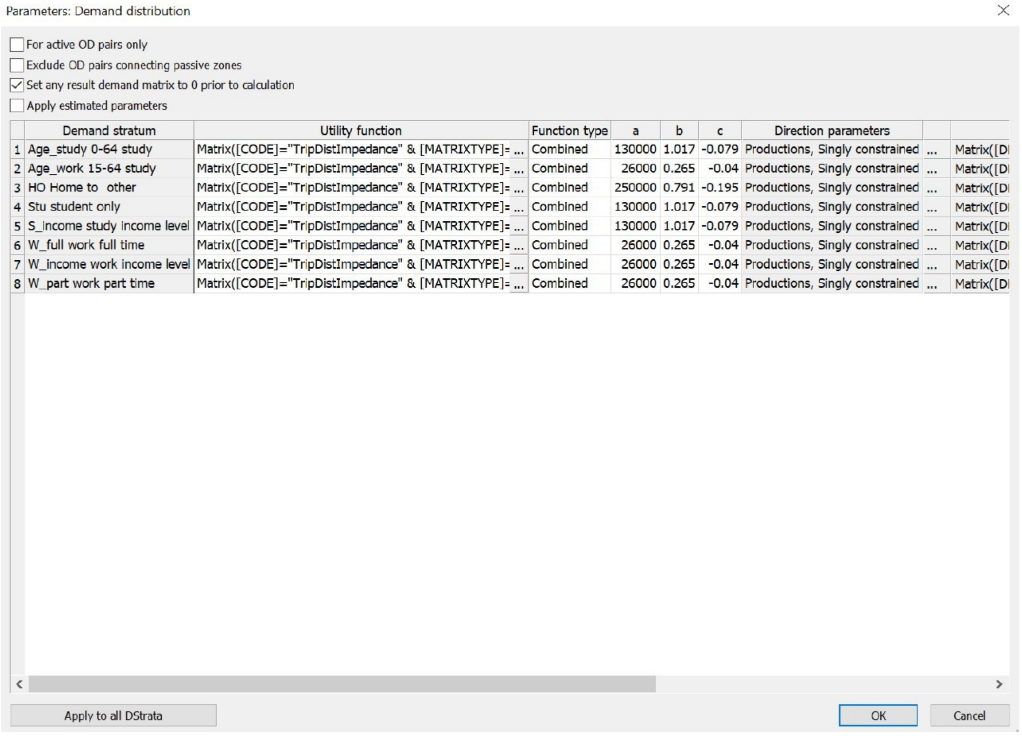
T_{ij} = number of trips from zone i to zone j,
P_i = number of trips productions in zone i,
A_j = number of trips attractions in zone j,
F_{ij} = friction factor relating the spatial separation between zone i and zone j, and
K_{ij} = optional trip distribution adjustment factor for interchanges between zones i and zone j

The gravity model has parameters to adjust the relationships between travel cost and travel time for each trip purpose. Such parameters influence every average trip length of each trip type. In this thesis, the "Combined" utility function controls the impact of the distance factor in the gravity model.

$$F\left(c_{ij}\right) = a * b^{c*ij} e^{-c*c_{ij}} \qquad \textbf{[3.4]}$$

Where:
a,b and c = friction coefficients

Figure 3-5 shows the trip distribution procedure, which has been implemented after trip generation in order to distribute trips between zones.



Parameters: Demand distribution

☐ For active OD pairs only
☐ Exclude OD pairs connecting passive zones
☑ Set any result demand matrix to 0 prior to calculation
☐ Apply estimated parameters

	Demand stratum	Utility function	Function type	a	b	c	Direction parameters		
1	Age_study 0-64 study	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	130000	1.017	-0.079	Productions, Singly constrained	...	Matrix([D
2	Age_work 15-64 study	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained	...	Matrix([D
3	HO Home to other	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	250000	0.791	-0.195	Productions, Singly constrained	...	Matrix([D
4	Stu student only	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	130000	1.017	-0.079	Productions, Singly constrained	...	Matrix([D
5	S_income study income level	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	130000	1.017	-0.079	Productions, Singly constrained	...	Matrix([D
6	W_full work full time	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained	...	Matrix([D
7	W_income work income level	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained	...	Matrix([D
8	W_part work part time	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained	...	Matrix([D

Figure 3-5 Trip distribution setup in VISUM

3.3.3 Mode choice (logit model) VISUM procedure

The third step of the four-step model is mode choice. In this step zone to zone person trips which is calculated from the previous step, is split into different modes using public transport and private transport. The private transport in this demand model is car and for public transport is the bus network. Trip matrices calculated in the previous step (one for each demand stratum) will be split into trip matrices for each mode of transportation. The trip matrices will be joined together for each mode to be an input for the trip assignment step. The generalized logit model is the most common approach in mode choice models. The model calculates the probability of choosing a particular mode for road users (NCHRP Report 365, 1998). The generalized logit model is given in equation 3.5.

$$\boldsymbol{P_i = \frac{e^{u^i}}{\sum_{i=1}^{k} e^{u^i}}} \qquad \textbf{[3.5]}$$

Where

Pi = the probability of a traveler choosing mode i,

Ui = a linear function of the attributes of mode i that describe its attractiveness, also known as the utility of mode i or impedance, and
$\sum_{i=1}^{k} e^{u^i}$ = the sum of the linear functions of the attributes of all the alternatives k, for which a choice is available.

The utility function of attributes or in VISUM term impedance u_i, is the linear function of the attributes, or impedance ui, is made up of:

$$u_i = a_i + b_i * IVTT_i + c_i * OVTT_i + d_i * Cost_i \qquad \textbf{[3.6]}$$

Where

$IVTT_i$ = in-vehicle travel times for mode i,

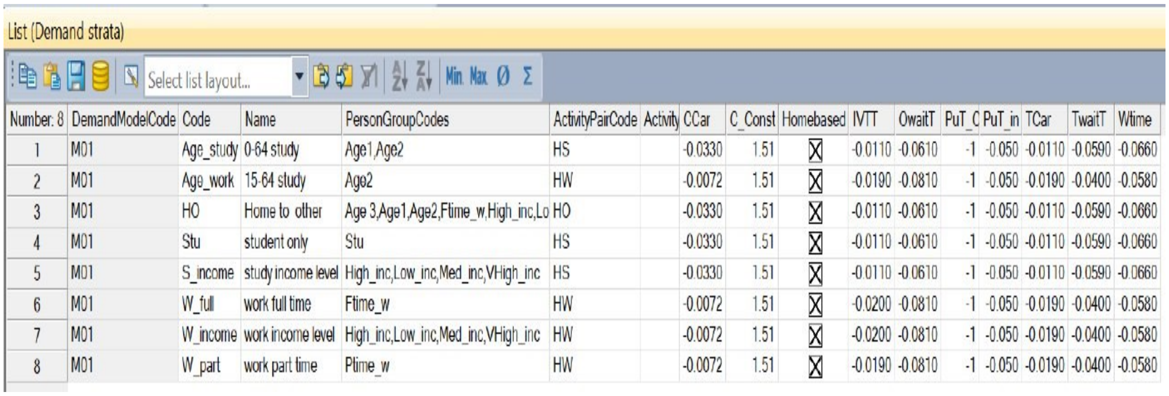
$OVTT_i$ = out of vehicle travel time for mode i,

$Cost_i$ = the cost of mode i,

a_i = mode specific constant to account for mode bias

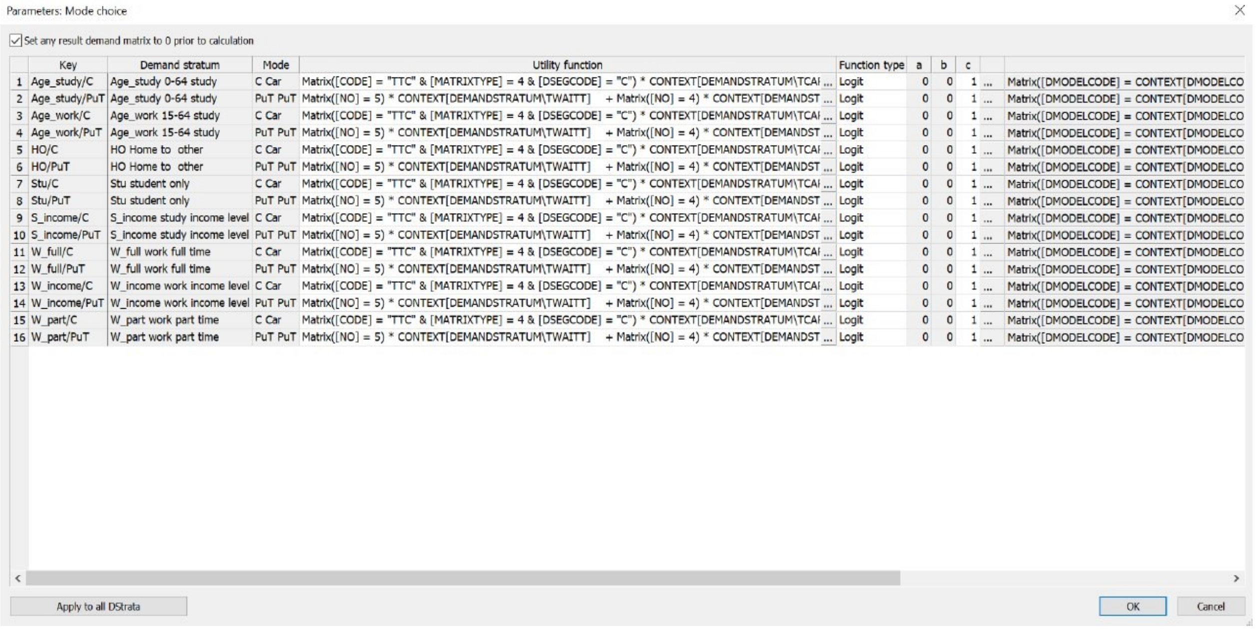
b_i , c_i , d_i = calibration coefficient for each specific mode

The logit model had been chosen for this study due to popularity and easy access to information. Because there are two modes have been defined in the model, there is a need for mode attractiveness of each mode for the model to be able to what mode road user will choose. The attractiveness or impedance is the function of travel time and travel cost equation 3.6. In-vehicle time, out of vehicle time and cost are the unit of attractiveness in this model. In VISUM skim matrix calculation tool will take care of this section to calculate this attractiveness. The in-vehicle travel time, representing the time of travel (in minutes) between each pair of zones for the specific mode. Out off vehicle is the time spent looking for a car park and walking to or from a car park for example, when traveling by car. In the case of public transport is time consists of several components of skim (walk times, wait times), which is computed from the public transport network model. The following figures show the utility function setup and the mode choice step in the VISUM environment.



Number: 8	DemandModelCode	Code	Name	PersonGroupCodes	ActivityPairCode	Activity	CCar	C_Const	Homebased	IVTT	OwaitT	PuT_C	PuT_in	TCar	TwaitT	Wtime
1	M01	Age_study	0-64 study	Age1,Age2	HS		-0.0330	1.51	☒	-0.0110	-0.0610	-1	-0.050	-0.0110	-0.0590	-0.0660
2	M01	Age_work	15-64 study	Age2	HW		-0.0072	1.51	☒	-0.0190	-0.0810	-1	-0.050	-0.0190	-0.0400	-0.0580
3	M01	HO	Home to other	Age 3,Age1,Age2,Ftime_w,High_inc,Lo	HO		-0.0330	1.51	☒	-0.0110	-0.0610	-1	-0.050	-0.0110	-0.0590	-0.0660
4	M01	Stu	student only	Stu	HS		-0.0330	1.51	☒	-0.0110	-0.0610	-1	-0.050	-0.0110	-0.0590	-0.0660
5	M01	S_income	study income level	High_inc,Low_inc,Med_inc,VHigh_inc	HS		-0.0330	1.51	☒	-0.0110	-0.0610	-1	-0.050	-0.0110	-0.0590	-0.0660
6	M01	W_full	work full time	Ftime_w	HW		-0.0072	1.51	☒	-0.0200	-0.0810	-1	-0.050	-0.0190	-0.0400	-0.0580
7	M01	W_income	work income level	High_inc,Low_inc,Med_inc,VHigh_inc	HW		-0.0072	1.51	☒	-0.0200	-0.0810	-1	-0.050	-0.0190	-0.0400	-0.0580
8	M01	W_part	work part time	Ptime_w	HW		-0.0072	1.51	☒	-0.0190	-0.0810	-1	-0.050	-0.0190	-0.0400	-0.0580

Figure 3-6 Sample screenshot of utility functions in VISUM



☑ Set any result demand matrix to 0 prior to calculation

	Key	Demand stratum	Mode	Utility function	Function type	a	b	c		
1	Age_study/C	Age_study 0-64 study	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
2	Age_study/PuT	Age_study 0-64 study	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
3	Age_work/C	Age_work 15-64 study	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
4	Age_work/PuT	Age_work 15-64 study	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
5	HO/C	HO Home to other	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
6	HO/PuT	HO Home to other	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
7	Stu/C	Stu student only	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
8	Stu/PuT	Stu student only	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
9	S_income/C	S_income study income level	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
10	S_income/PuT	S_income study income level	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
11	W_full/C	W_full work full time	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
12	W_full/PuT	W_full work full time	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
13	W_income/C	W_income work income level	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
14	W_income/PuT	W_income work income level	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
15	W_part/C	W_part work part time	C Car	Matrix([CODE] = "TTC" & [MATRIXTYPE] = 4 & [DSEGCODE] = "C") * CONTEXT[DEMANDSTRATUM\TCAI ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO
16	W_part/PuT	W_part work part time	PuT PuT	Matrix([NO] = 5) * CONTEXT[DEMANDSTRATUM\TWAITT] + Matrix([NO] = 4) * CONTEXT[DEMANDST ...	Logit	0	0	1	...	Matrix([DMODELCODE] = CONTEXT[DMODELCO

Figure 3-7 Sample screenshot of mode choice

3.3.4 Trip Assignment VISUM procedure

The last step in four-step modeling is the trip assignment. This includes both private car and public transportation of vehicle and person trips. The assignment results are the final output from the four-step model and are the foundation for validating the estimated values from the model with observed travel values. Before the assignment person trips matrices determined in the previous step for each mode are joined together for that specific mode, for this purpose, there is a function in VISUM called "combination of matrix and vector" which take care of this matrix aggregation. The person trips matrix for a car must then be converted into a vehicle trip matrix by dividing the matrix with the car occupancy factor. The car occupancy factor used to start with is 1,28. In the case of public transport, the matrix will be assigned as person trips (number of passengers). VISUM offers different assignment methods. For this thesis, equilibrium assignment had been chosen for car assignment, and for the public assignment, timetable-based assignment is used. The chosen methods for both assignments are believed to give the best results compared to the information used. In a case of timetable-based assignment, it is assumed that passengers have timetable information available and can find the shortest route to their destination. Once this information is available, it is assumed that all passengers take the shortest journey between each pair of zones in means of travel time. In case of car assignment, the Equilibrium assignment distributes the demand according to Wardrop's first principle. "Every road user selects his or her route in such a way, that the impedance on all alternative routes is the same, and that switching to a different route would increase personal travel time (user optimum)." (Ortúzar & Willumsen, 2011). This behavioral hypothesis underlies the unrealistic assumption that every road user is fully informed about the network state. In transport planning, this hypothesis is approved of given a fundamental methodical advantage of the equilibrium assignment - with quite general requirements, the existence and uniqueness of the assignment result (expressed in volumes of the network object) are guaranteed.

This method concentrates on capacity restrains as a generator of a spread of trips on a network. For a start, models of capacity constraints need to use functions related to cost flow or travel time on a link. This process can be explained in three simple steps. First, the traffic on the network is allocated based on the initial travel time determined by free-flow capacity. In the second step, the number of trips allocated to each link is compared with the link's ability to determine to what degree link travel time has been reduced. The new link travel time can be recalculated with the relationships between volume and speed (or travel time) (equation 3.7). A reassignment is finally made dependent on those new values. The process of iteration continues until a balance is achieved.

$$t = t_0 \left[1 + \alpha\left(\frac{V}{C}\right)^{\beta}\right] \qquad [3.7]$$

Where

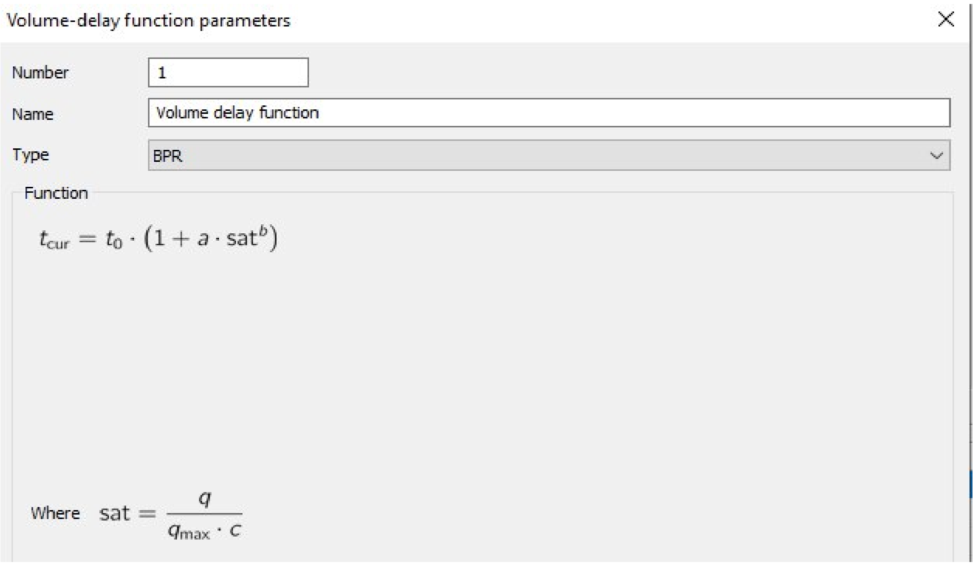
t = loaded link travel time,

t_0 = free - flow travel time,

V = volume on the link,

C = capacity of the link, and

α, β = volume/delay coefficients



Volume-delay function parameters

Number	1
Name	Volume delay function
Type	BPR

Function

$$t_{\mathrm{cur}} = t_0 \cdot \left(1 + a \cdot \mathrm{sat}^{b}\right)$$

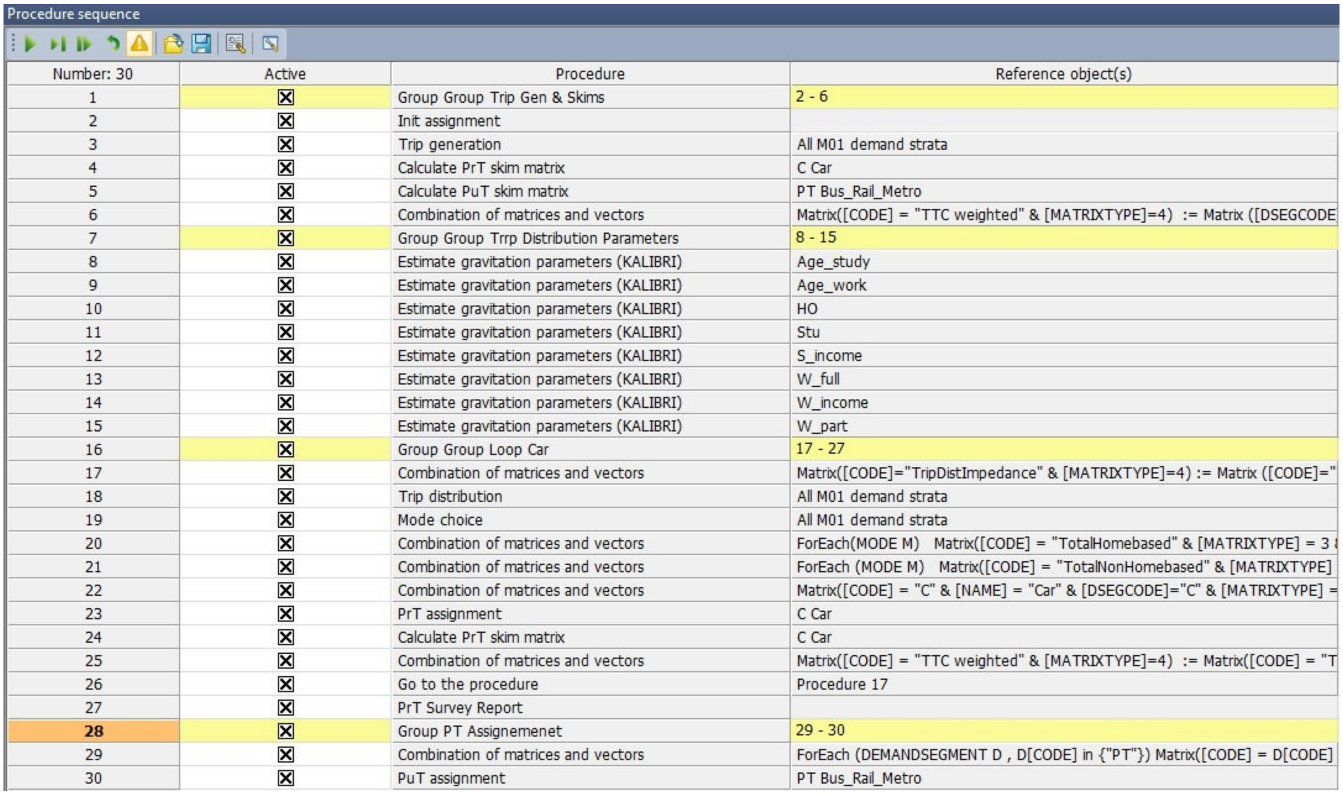
Where $\mathrm{sat} = \dfrac{q}{q_{\max} \cdot c}$

Figure 3-8 Example of Volume Delay Function for Links in VISUM

Defining the VDF’s function depends on the link type. Since in the road network, different link types defined, such as freeway, highway, arterial roads and local roads and each of them has specific characteristics in terms of number of lanes, speed and free flow capacity, VDF’s coefficients need to be specified for each link type. The VDF’s coefficients control how the traffic reacts to congested conditions (equation 3.7). The highway capacity manual provides guidelines for choosing the coefficients (HCM, 2000). In addition, the free flow capacities for each link type had been chosen from tables in HCM to reflect average conditions for various link types for the model. Because it is not feasible to calculate the capacities specific to the physical limitations in each link.

All the different steps in-demand model and calculation are done in VISUM using the procedure sequence. It is possible to execute several work steps successively. A procedure sequence includes several pre-defined procedures with a specific user-defined procedure setting. Additionally, it is possible to adjust the general procedure settings which apply to all procedures Figure . The procedure sequence created for the VISUM model included the following steps:

1. Initial assignment
2. Estimating trip generation model (production and attraction)
3. Calculation of PrT and PuT skim matrix
4. Estimation of the gravity model parameters with TTC input parameters
5. Trip distribution: The impedance function set to use the Logit model.
6. Mode choice: calculating the share of trips between different mode of transport
7. Combination of matrices and vectors: All trips were copied to PrT Car assignment matrix and an overall occupancy rate was applied
8. PrT assignment: Assignment of demand segment Car.
9. Go to procedure: Convergence check and feedback to step Trip Distribution if necessary
10. PuT assignment: Assignment of demand segment Bus.



Number: 30	Active	Procedure	Reference object(s)
1	☒	Group Group Trip Gen & Skims	2 - 6
2	☒	Init assignment	
3	☒	Trip generation	All M01 demand strata
4	☒	Calculate PrT skim matrix	C Car
5	☒	Calculate PuT skim matrix	PT Bus_Rail_Metro
6	☒	Combination of matrices and vectors	Matrix([CODE] = "TTC weighted" & [MATRIXTYPE]=4) := Matrix ([DSEGCODE
7	☒	Group Group Trrp Distribution Parameters	8 - 15
8	☒	Estimate gravitation parameters (KALIBRI)	Age_study
9	☒	Estimate gravitation parameters (KALIBRI)	Age_work
10	☒	Estimate gravitation parameters (KALIBRI)	HO
11	☒	Estimate gravitation parameters (KALIBRI)	Stu
12	☒	Estimate gravitation parameters (KALIBRI)	S_income
13	☒	Estimate gravitation parameters (KALIBRI)	W_full
14	☒	Estimate gravitation parameters (KALIBRI)	W_income
15	☒	Estimate gravitation parameters (KALIBRI)	W_part
16	☒	Group Group Loop Car	17 - 27
17	☒	Combination of matrices and vectors	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]=4) := Matrix ([CODE]="
18	☒	Trip distribution	All M01 demand strata
19	☒	Mode choice	All M01 demand strata
20	☒	Combination of matrices and vectors	ForEach(MODE M) Matrix([CODE] = "TotalHomebased" & [MATRIXTYPE] = 3
21	☒	Combination of matrices and vectors	ForEach (MODE M) Matrix([CODE] = "TotalNonHomebased" & [MATRIXTYPE]
22	☒	Combination of matrices and vectors	Matrix([CODE] = "C" & [NAME] = "Car" & [DSEGCODE]="C" & [MATRIXTYPE] =
23	☒	PrT assignment	C Car
24	☒	Calculate PrT skim matrix	C Car
25	☒	Combination of matrices and vectors	Matrix([CODE] = "TTC weighted" & [MATRIXTYPE]=4) := Matrix([CODE] = "T
26	☒	Go to the procedure	Procedure 17
27	☒	PrT Survey Report	
28	☒	Group PT Assignemenet	29 - 30
29	☒	Combination of matrices and vectors	ForEach (DEMANDSEGMENT D , D[CODE] in {"PT"}) Matrix([CODE] = D[CODE]
30	☒	PuT assignment	PT Bus_Rail_Metro

Figure 3-9 Sample screenshot of procedure sequence in VISUM

3.3.5 VISUM demand model calibration and validation

Calibrating the VISUM demand model require specific data such as transit agency surveys on passenger ridership along transit routes and alighting and boarding at transit stops, local household survey for trip production according to socio-economic characteristics and traffic count data of vehicles on local roads which is expensive to collect and process (Mitran, Ilie, & Nicolae, 2010) therefore, in developing a demand model a balance must be established between model accuracy and the available resources depending on the project priorities.

Accuracy requirements for model validation depend on the intended use of the model is validated. Models used for project design or complex regional policy and planning studies might require tight matches between modeled and observed travel data. In other cases, such as the evaluation of alternative transportation policies or simple traffic impact analyses, the correct sensitivity of the model might outweigh the need for a close match of observed data and validation could be relaxed.

How well the validation data represent, the reality is a primary validation question. This question can be illustrated by a review of the veracity of commonly used validation data from traffic counts. Counts are often collected from multiple sources using multiple counting techniques. They may be stored as raw counts or factored counts, such as average annual daily traffic (AADT). Traffic volume checks compare modeled to observed traffic volumes on a link-by-link basis.

Consequently, the amount of difference between the modeled and observed traffic for each link contributes directly to the overall measure of closeness. The calibration of a model often involves some trial and error approach in which the model parameters are adjusted on the trip distribution and mode choice steps to be able to predict the volume of vehicles to be in the same magnitude of observed volumes across the network. The traffic volume related checks in this thesis are the coefficient of determination (R2) and GEH statistic which is an empirical formula widely used in traffic modeling. As shown in Table 3-1, observed and model-predicted volumes are compared for each link, and a global measure of fitness GEH is used to estimate the overall fitness of the model.

Table 3-1 Sample comparison of volumes (observed versus predicted) and measures of fitness

Link			Model	Evaluation	
Number	**From node number**	**Count Station**	**Volume PrT [veh]**	**%Deviation**	**GEH**
20202	**16375**	**37946**	**32000**	**-33%**	**31.79**
21207	**91558**	**14360**	**13129**	**-9%**	**10.5**
21207	**91820**	**14360**	**14964**	**4%**	**5**
22323	**18422**	**37946**	**26218**	**-31%**	**65.5**
26234	**21653**	**9883**	**5283**	**-47%**	**52.8**
26234	**22133**	**9883**	**4642**	**-53%**	**61.5**
38617	**39182**	**12126**	**12451**	**3%**	**2.9**
38617	**39183**	**12126**	**12522**	**3%**	**3.6**
43505	**33816**	**15226**	**12432**	**-18%**	**23.8**
43505	**36205**	**15226**	**12895**	**-15%**	**19.7**
…	**…**	**…**	**…**	**…**	**…**

Evaluation aggregate	
GEH: Avg	**37.1**
GEH:<5.0	**13%**
Deviation: Avg	**23%**
Deviation: Avg weighted	**22%**
Deviation:<10	**32%**

The calculation of the GEH index is given by equation 3.8.

$$GEH = \sqrt{\frac{2\,(M-C)^2}{M+C}} \qquad \textbf{[3.8]}$$

M corresponds to the modeled values

C corresponds to the counted values

Further discussion for the selection of parameters and the concrete examples of calibration can be observed in the case studies presented in chapters 4 and 5 of this thesis.

3.4RMS model development

3.4.1 Allocation of M&R Activities

This section presents the procedure followed to link car travel demand to road management systems to accomplish long-term performance-based optimal coordinated M&R activities.

3.4.1.1 Decision Support for Road Management

Mathematical formulations for optimizing decisions of M&R activities in a road network with spatially distributed segments can be found elsewhere (Amin and Amador-Jiménez, 2015; Faghih-Imani and Amador-Jimenez, 2013; Li, Haas, and Huot, 1998). A typical optimization process tries to meet the goals while being restricted by constrains. Optimization strategies to maximize the overall condition at the network level are employed in road management systems (Equation 3.9) subject to a given annual budget (Bt) over a planning horizon of several years. Other traditional constraints include the limitation that each asset should receive no more than one maintenance or rehabilitation per year, and, in some circumstances, the preclusion of treating assets within a certain period after they have received a specialized intervention.

As seen in Equation 3.10, it should be noted that the binary decision variable x has three sub-indices representing time (t), asset (i), and treatment (j). Solutions for this optimization will enumerate chains of variables $x_{t,i,j}$ that represent sets of assets at different periods of time receiving M&R treatments that produce the most cost-effective solution in terms of the objectives and the constraints. Objectives are traditionally related to asset condition or expenditure levels.

$\sum_{i=1}^{N} L_i Q_{t,i}$ for all values of t **[3.9]**

Subject to

$\sum_{i=1}^{N} \sum_{j=1}^{K} C_{t,j} x_{t,i,j} L_i \leq B_t$ for all values of **[3.10]**

$x_{t,i,j} \in Binary\ Set[0,1]$

Where the following time links connect consecutive periods of times

$Q_{t,i,j} = x_{t,i,j}\ (Q_{(t-1),i,j} + E_{i,j}) + (1 - x_{t,i,,j})\ (Q_{(t-1),i,j} - D_{i,t})$

Z= total aggregated condition at the network-level;

$x_{t,i,j}$ = 1 if treatment j is applied on road segment i at year t, 0 otherwise;

$Q_{i,t}$ = the asset condition index for road segment i at year t;

$Q_{i,(t-1)}$ = the asset condition index for road segment i at year $(t-1)$;

$Q_{t,i,j}$ = the asset condition index of road segment i at year t for intervention j;

$Q_{(t-1),i,j}$ = the asset condition index of road segment i at year $(t-1)$ for intervention j;

$C_{t,j}$ = the cost of intervention j at year t;

L_i = the size of asset i;

$E_{i,j}$ = the improvement of asset i from intervention j;

$D_{i,t}$ = the deterioration of asset i at time t;

B_t = the budget at year t;

N = the total number of assets;

T = the total number of time periods; and

K = the total number of applicable treatments.

Alternative formulations based on goal programming can also be employed combining the objective and constrains with penalties. The objective is linked to the variables through “Goal Constraints.” In this approach, the objective is formulated to minimize the sum of deviations for the prescribed goal values defined for each constraint. The deviations are formulated to fit the pre-defined set of key performance indicators (KPI), as shown in equation 3.11. The negative deviations (d_k^-) would be the life-cycle costs, IRI condition, travel time, and demand/capacity ratio. However, the positive deviation (d_m^+) will be the deflection area basin condition. The model was built on REMSOFT, and MOSEK optimization engine was used such that; it features a branch, bound, and cut optimization algorithm to solve mixed-integer problems (Abu-Samra, S, and Amador, 2019).

$$Min\ (Z) = \sum_{i=1}^{n_s} \sum_{v=1}^{v} \sum_{t=1}^{T} [W_i * W_v * (d_k^- + d_m^+)] \qquad \textbf{[3.11]}$$

$$d_{k_t}^- = \sum_{i=1}^{n_s} \sum_{h=1}^{H} \frac{KPI_{h_{i_t}} - TH_{h_i}}{TH_{h_i}} \ ; for\ all\ k\ and\ t$$

$$d_{m_t}^+ = \sum_{i=1}^{n_s} \sum_{h=1}^{L} \frac{TH_{l_i} - KPI_{l_{i_t}}}{TH_{l_i}} \ ; for\ all\ m\ and\ t$$

$$Decision\ variables\ = \begin{bmatrix} I_{t_0} & \cdots & I_{T_0} \\ \vdots & \ddots & \vdots \\ I_{t_0} & \cdots & I_{T_0} \end{bmatrix}$$

For $I_{t_0} = 0, 1, \ldots 10$

$t = 1, 2, \ldots T$

$o = 1, 2, \ldots O$

where; Z is the summation of the deviational variables of ns system throughout the planning horizon T (%); W_v represents the deferential weights among the conflicting goals (%); v is the KPIs' counter (number); V is the total number of KPIs (number); d_k^- is the summation of all the negative deviational variables at the point of time (t) (%); and d_m^+ is the summation of all the positive deviational variables at the point of time (t) (%);$I_{t_0}$is the intervention at time (t) and for segment (o).

3.4.2 Data sources

The main data sources for RMS are the current condition of the road network in terms of its physical state; also, other measures of performance may be added, such as travel time per link, a number of collisions per link, and so on. In addition, the user must create performance models based on past historical trends and the information available about the future progression of key performance indicators. Finally, it is necessary to count on cost and effectiveness information for any congestion strategy, safety treatment, maintenance intervention, or in general any countermeasure or remedial work being considered by the model.

3.5RMS Software Logic

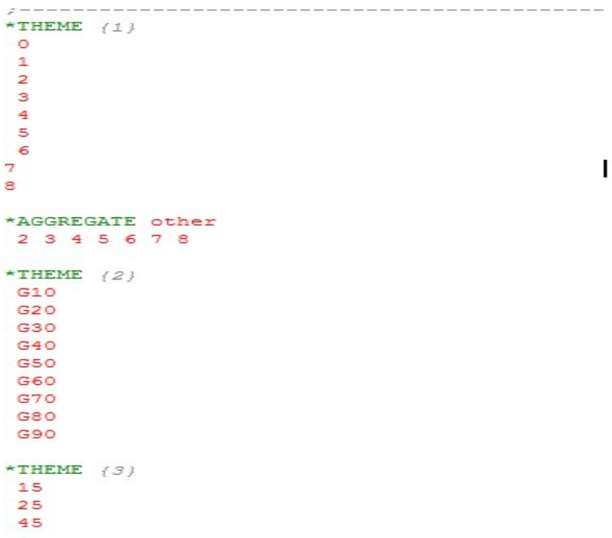
A decision support system is known as Woodstock (REMSOFT) which uses object-oriented computer programming, was used to code several interacting modules to define the decision-making model. The modules and their purpose are listed below and explained the following subsections:

- LANDSCAPE: This module is used to define the structure of the attribute data, including current and future (not yet existent) attribute characteristics

- AREAS: Inventory of Assets classified according to the LANDSCAPE
- ACTIONS: Rules to define when countermeasures are applicable
- TRANSITIONS: Rules to define the change experienced by an asset receiving a given ACTION
- YIELDS: definition of time-related rules and time progression of indicators such as cost, condition, and effectiveness of a given ACTION. YIELDS are activated by TRANSITIONS and their aggregated results are handled by OUTPUTS
- OUTPUTS. User-defined variables that aggregate any time-dependent indicator for each period of time. Typical OUTPUTS include total condition per year, the total length of a given ACTION, the total amount of assets within a given range, total expenditure per type of ACTION, the total amount of assets within a given range of quality or performance.
- OPTIMIZATION: Module used to control GOAL PROGRAMMING or WEIGHTED AVERAGE OPTIMIZATION utilizing the OUTPUTS to control the constraints and the objectives.
- SEQUENCE: is the module that captures back from the external optimization solver the results of the linear programming algorithm.

3.5.1 Landscape

The LANDSCAPE is used to define TEXT codes for the attributes and to group them (THEMES). The landscape can utilize loops to facilitate the incorporation of large amounts of numbers. The landscape can also create subgroups of various possible attributes together. Below a sample screenshot of the LANDSCAPE.



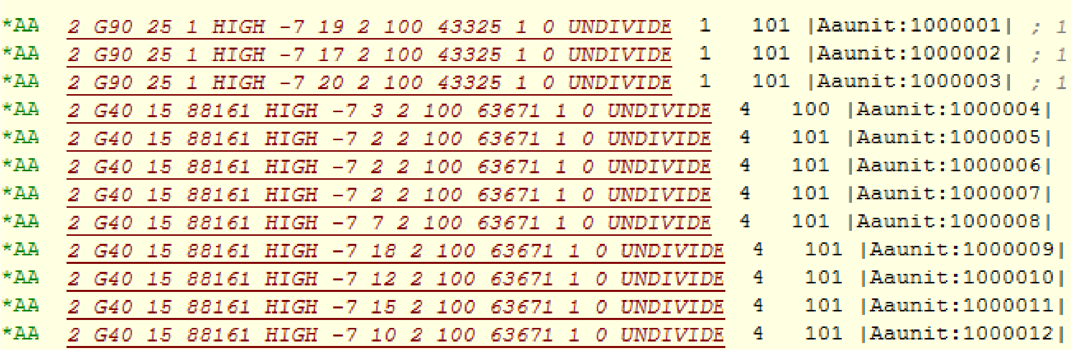
```
;--------------------------------------------
*THEME {1}
 0
 1
 2
 3
 4
 5
 6
7
8

*AGGREGATE other
 2 3 4 5 6 7 8

*THEME {2}
 G10
 G20
 G30
 G40
 G50
 G60
 G70
 G80
 G90

*THEME {3}
 15
 25
 45
```

Figure 3-10 Sample Screenshot of the LANDSCAPE section

3.5.2 Areas

The AREAS section should follow the same order defined in the attributes. Ideally, the data from VISUM and other software should be sorted in a way that captures the desirable THEMES of attributes, per instance: type of asset, type of sub-asset, type of material, intensity of loads received, number of lanes, presence of a given characteristic (for example a bus stop), initial level for a given characteristic, apparent age-related to level of performance of a given indicator. Each asset is contained in a row, which starts with the AA* declaration and could optionally end with an identifier number called AAUNIT to distinguish it from the other assets handled.

The area section should also capture the size or length for each segment and the age of one of the time-dependent performance indicators (often the condition, but in theory, any performance indicator that the optimization targets to improve and for which we count with performance curves that define the time dependency. An example of AREAS section is shown below.

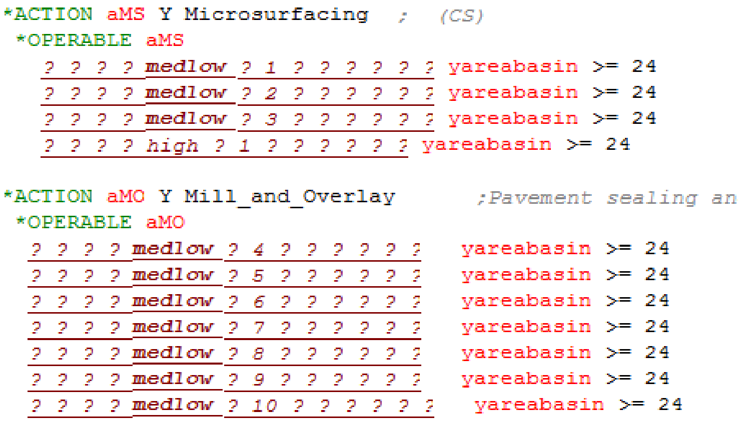


```
*AA  2 G90 25 1 HIGH -7 19 2 100 43325 1 0 UNDIVIDE  1   101 |Aaunit:1000001| ; 1
*AA  2 G90 25 1 HIGH -7 17 2 100 43325 1 0 UNDIVIDE  1   101 |Aaunit:1000002| ; 1
*AA  2 G90 25 1 HIGH -7 20 2 100 43325 1 0 UNDIVIDE  1   101 |Aaunit:1000003| ; 1
*AA  2 G40 15 88161 HIGH -7 3 2 100 63671 1 0 UNDIVIDE  4   100 |Aaunit:1000004|
*AA  2 G40 15 88161 HIGH -7 2 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000005|
*AA  2 G40 15 88161 HIGH -7 2 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000006|
*AA  2 G40 15 88161 HIGH -7 2 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000007|
*AA  2 G40 15 88161 HIGH -7 7 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000008|
*AA  2 G40 15 88161 HIGH -7 18 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000009|
*AA  2 G40 15 88161 HIGH -7 12 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000010|
*AA  2 G40 15 88161 HIGH -7 15 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000011|
*AA  2 G40 15 88161 HIGH -7 10 2 100 63671 1 0 UNDIVIDE  4   101 |Aaunit:1000012|
```

Figure 3-11 Sample Screenshot of the AREA section

3.5.3 Actions

The definition of countermeasures, remedial treatments, upgrades (i.e., gravel to the paved road), and expansion (creation of new assets) is defined in this module. Each action starts with a declaration of operability, which could be a YES or NO condition, followed by a particular combination of attributes following the predefined LANDSCAPE. The applicability criteria can also include levels of performance or age of the asset. A sample of the actions is shown below

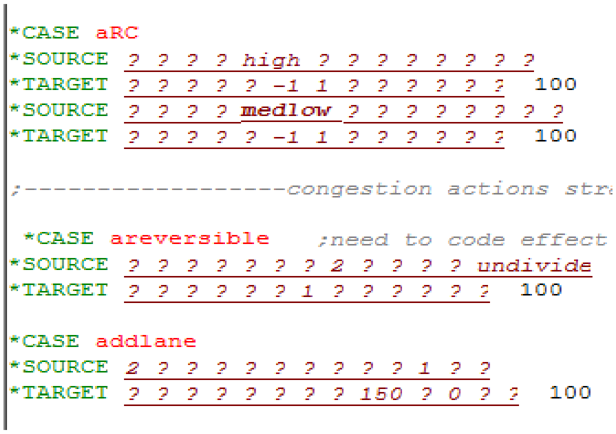


```
*ACTION aMS Y Microsurfacing  ;  (CS)
 *OPERABLE aMS
   ? ? ? ? medlow ? 1 ? ? ? ? ? ? yareabasin >= 24
   ? ? ? ? medlow ? 2 ? ? ? ? ? ? yareabasin >= 24
   ? ? ? ? medlow ? 3 ? ? ? ? ? ? yareabasin >= 24
   ? ? ? ? high ? 1 ? ? ? ? ? ? yareabasin >= 24

*ACTION aMO Y Mill_and_Overlay      ;Pavement sealing an
 *OPERABLE aMO
  ? ? ? ? medlow ? 4 ? ? ? ? ? ?   yareabasin >= 24
  ? ? ? ? medlow ? 5 ? ? ? ? ? ?   yareabasin >= 24
  ? ? ? ? medlow ? 6 ? ? ? ? ? ?   yareabasin >= 24
  ? ? ? ? medlow ? 7 ? ? ? ? ? ?   yareabasin >= 24
  ? ? ? ? medlow ? 8 ? ? ? ? ? ?   yareabasin >= 24
  ? ? ? ? medlow ? 9 ? ? ? ? ? ?   yareabasin >= 24
  ? ? ? ? medlow ? 10 ? ? ? ? ? ?   yareabasin >= 24
```

Figure 3-12 Sample Screenshot of the ACTION section

3.5.4 Transition

This module follows from the ACTIONS and defines for each action the corresponding initial conditions (SOURCE) and the target conditions (TARGET), which could alter the nature of any of the asset characteristics as captured by the LANDSCAPE definitions. A final TRANSITION called DEATH is used to capture all assets that arrive at the last stage of the various performance curves in order to hold the asset within the inventory with the terminal value of performance defined (prevent the asset from disappearing).

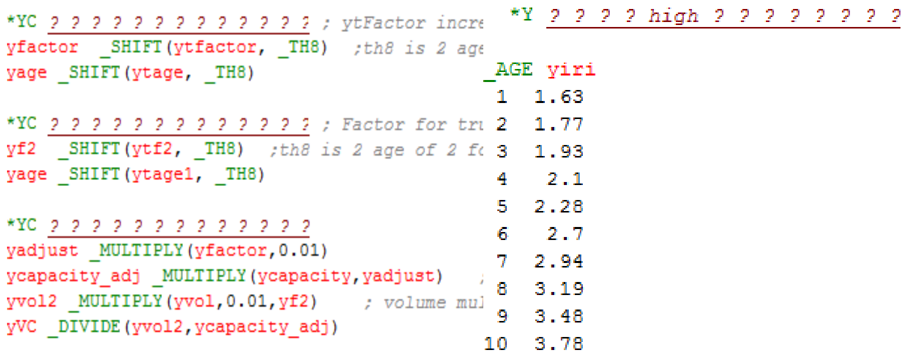


```
*CASE aRC
*SOURCE ? ? ? ? high ? ? ? ? ? ? ? ?
*TARGET ? ? ? ? ? -1 1 ? ? ? ? ? ?  100
*SOURCE ? ? ? ? medlow ? ? ? ? ? ? ? ?
*TARGET ? ? ? ? ? -1 1 ? ? ? ? ? ?  100

;-------------------congestion actions str

 *CASE areversible    ;need to code effect
*SOURCE ? ? ? ? ? ? ? 2 ? ? ? ? undivide
*TARGET ? ? ? ? ? ? 1 ? ? ? ? ? ?  100

*CASE addlane
*SOURCE 2 ? ? ? ? ? ? ? ? ? 1 ? ?
*TARGET ? ? ? ? ? ? ? ? 150 ? 0 ? ?  100
```

Figure 3-13 Sample Screenshot of the TRANSITION section

3.5.5 Yields

This module plays the most significant role in dynamic programming as it captures the time dependencies for all types of indicators such, but not limited to, cost, condition, safety, congestion, and in many cases is used to define additional performance indicators through the _SHIFT function and by utilizing apparent ages that are explicitly tied to a given theme whose initial value is shifted every year. The YIELD section can also be used to define complex structures that read values from the AREAS and use them along with yields to define secondary amounts (for example, Vehicle Operating Cost). A sample chunk of code from the YIELD section is shown in Figure 3-14



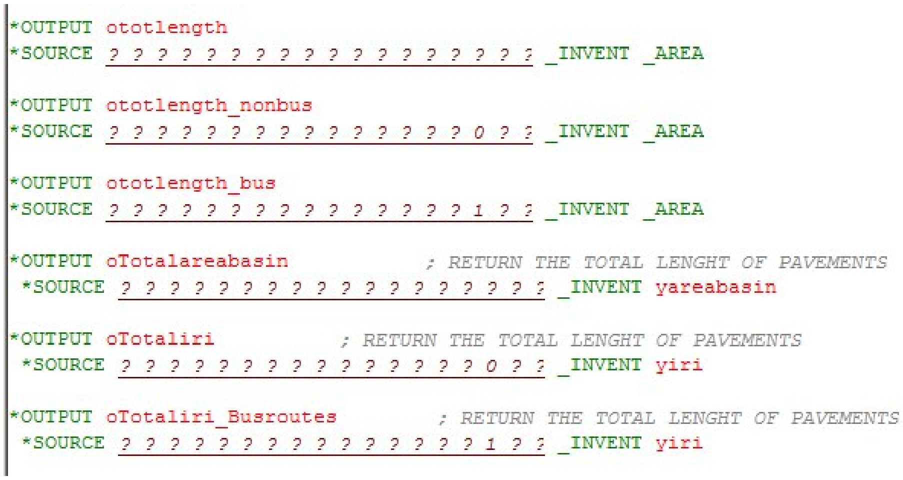
```
*YC ? ? ? ? ? ? ? ? ? ? ? ? ? ; ytFactor incre
yfactor  _SHIFT(ytfactor, _TH8)  ;th8 is 2 age
yage _SHIFT(ytage, _TH8)

*YC ? ? ? ? ? ? ? ? ? ? ? ? ? ; Factor for tru
yf2  _SHIFT(ytf2, _TH8)  ;th8 is 2 age of 2 fc
yage _SHIFT(ytage1, _TH8)

*YC ? ? ? ? ? ? ? ? ? ? ? ? ?
yadjust _MULTIPLY(yfactor,0.01)
ycapacity_adj _MULTIPLY(ycapacity,yadjust)   ;
yvol2 _MULTIPLY(yvol,0.01,yf2)    ; volume mul
yVC _DIVIDE(yvol2,ycapacity_adj)
```

```
*Y ? ? ? ? high ? ? ? ? ? ? ? ?

_AGE yiri
 1   1.63
 2   1.77
 3   1.93
 4    2.1
 5   2.28
 6    2.7
 7   2.94
 8   3.19
 9   3.48
10   3.78
```

Figure 3-14 Sample Screenshots of the YIELD Section

3.5.6 Outputs

The outputs module is used to aggregate amounts across assets of a given group or across the entire Inventory of assets. Amounts such as total condition, total safety, total congestion, total gas emission, the total cost can be obtained in this module. The outputs require a source definition where the combination of attributes to create an aggregation is specified; specific commands are used to obtain a summation (_INVENT) or to obtain the total amount (_AREA).

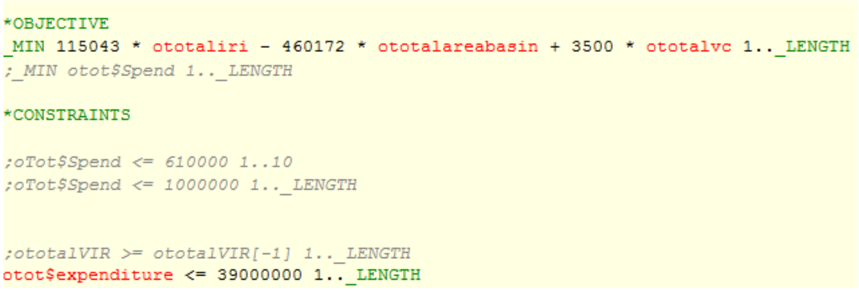


```
*OUTPUT ototlength
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT _AREA

*OUTPUT ototlength_nonbus
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 0 ? ? _INVENT _AREA

*OUTPUT ototlength_bus
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 1 ? ? _INVENT _AREA

*OUTPUT oTotalareabasin           ; RETURN THE TOTAL LENGHT OF PAVEMENTS
 *SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yareabasin

*OUTPUT oTotaliri          ; RETURN THE TOTAL LENGHT OF PAVEMENTS
 *SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 0 ? ? _INVENT yiri

*OUTPUT oTotaliri_Busroutes        ; RETURN THE TOTAL LENGHT OF PAVEMENTS
 *SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 1 ? ? _INVENT yiri
```

Figure 3-15 Sample Screenshots of the YIELD Section

3.5.7 Optimization

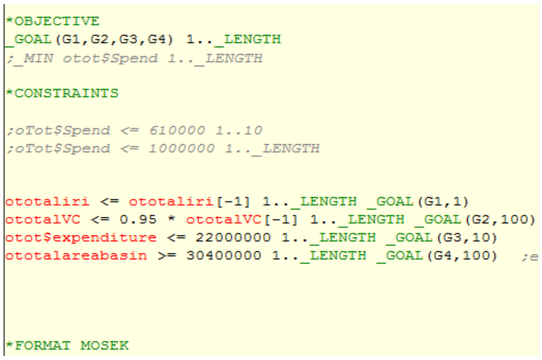
This module defined the optimization with two subcomponents the *OBJECTIVE and the *CONSTRAINTS which are used to control the Minimization or maximization and the budget or any desired threshold of sequence of values between two points on time: per-instance the requirement that the total performance improves over the previous year by a 1%, or the requirement that the total level of a given performance indicator exceeds a given constant value, or to define the need to do not expend more than a given budget per year. The following Figure 3-16 illustrates a weighted average traditional optimization.



```
*OBJECTIVE
_MIN 115043 * ototaliri - 460172 * ototalareabasin + 3500 * ototalvc 1.._LENGTH
;_MIN otot$Spend 1.._LENGTH

*CONSTRAINTS

;oTot$Spend <= 610000 1..10
;oTot$Spend <= 1000000 1.._LENGTH


;ototalVIR >= ototalVIR[-1] 1.._LENGTH
otot$expenditure <= 39000000 1.._LENGTH
```

Figure 3-16 weighted average traditional optimization

The second type of OPTIMIZATION is through a GOAL PROGRAMMING, where penalties for under and overperformance can be added to each constraint, including those related to performance and cost. Figure 3-17 shows Goal programming.



```
*OBJECTIVE
_GOAL(G1,G2,G3,G4) 1.._LENGTH
;_MIN otot$Spend 1.._LENGTH

*CONSTRAINTS

;oTot$Spend <= 610000 1..10
;oTot$Spend <= 1000000 1.._LENGTH


ototaliri <= ototaliri[-1] 1.._LENGTH _GOAL(G1,1)
ototalVC <= 0.95 * ototalVC[-1] 1.._LENGTH _GOAL(G2,100)
otot$expenditure <= 22000000 1.._LENGTH _GOAL(G3,10)
ototalareabasin >= 30400000 1.._LENGTH _GOAL(G4,100)   ;e



*FORMAT MOSEK
```

Figure 3-17 goal programming optimization

Chapter 4: Investment planning to handle roads congestion while waiting to implement public transit: a case study of costa Rica

Abstract

Good public transportation is widely accepted as the solution to handle common congestion problems in road networks by shifting trips between modes of transportation instead of incrementing the capacity of the road. However, measures to deal with road congestion are required while public transportation systems get approved and implemented. This paper looks into the case study of Costa Rica's central valley road network and the extensive nature of its daily congestion. This paper uses an extension of the classical mathematical formulation used in Road Management Systems to incorporate actions and strategies related to congestion management and illustrates them on a case study of the Costa Rica network. Countermeasures such as reversible lanes, truck restrictions, and the addition of lanes on certain roads are used to reduce congestion during the commute to work. A commercial optimization tool has been coded to allocate budget to improve the condition of roads and to implement as much as possible congestion countermeasures while the nation waits for its train systems to be developed.

It was found that it is possible to improve the condition of the surface and the structure of the pavement and to reduce the overall level of congestion by either increasing the network capacity or in most cases by implementing daily-based strategies which do not reflect on long term performance trends of maximum capacity or total demand but that do have an effect on the daily movement of the vehicular fleet.

4.1 Introduction

In the last few decades, traffic congestion has increased significantly (Figure), and this pattern tends to continue across most low-income and developing nations, with only some developing nations having sufficient capacity in their metro-transit and regional trains systems to counter-effect against road congestion, especially during peak hour times. (Evren, 2005).

There is a growing movement since the 2000's that attempts to convince decision-makers about the need to walk away from automobiles. In the USA this movement has sought to convince the public to abandon single passenger vehicles encouraging an increase in vehicle occupancy by sharing the ride to work. In Europe and Asia, significant investments have been done in public transit through larger vehicles connecting villages and towns with the city center (Spain 2010's, Switzerland since the 1990s, Singapore since the 1990s, etc).

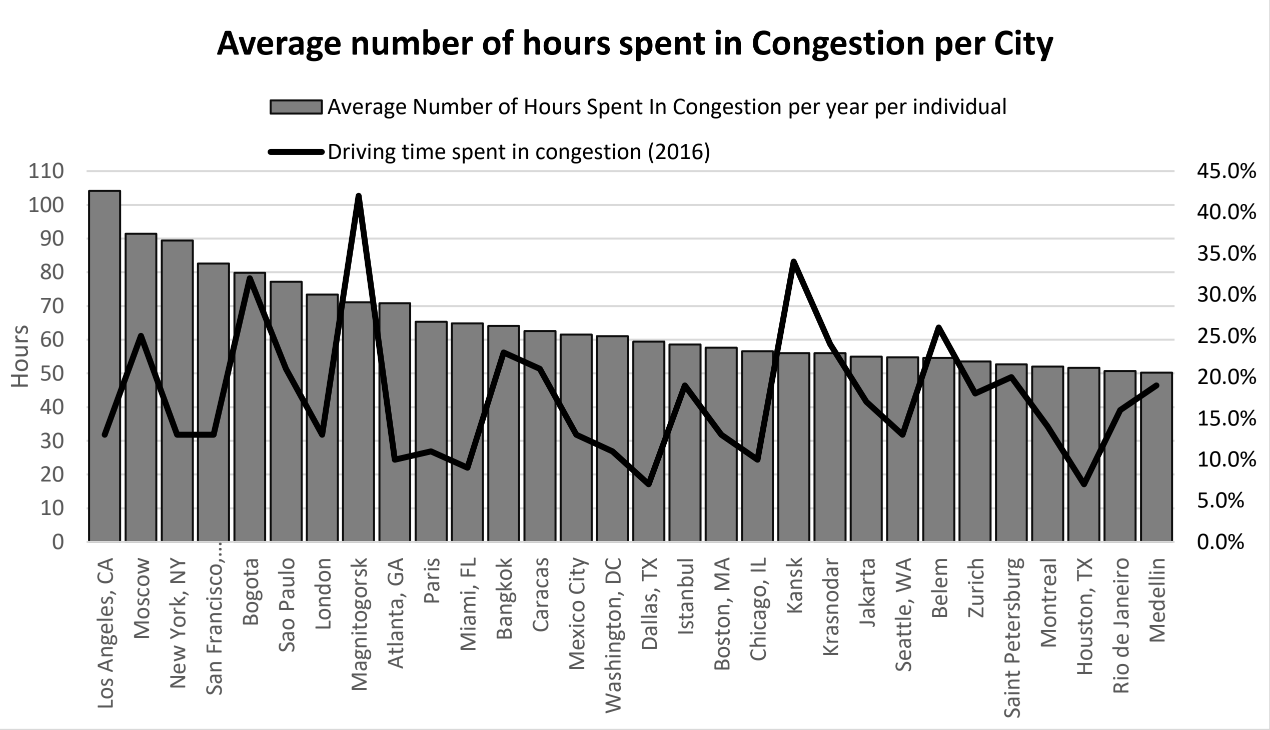


Figure 4-1 Traffic Congestion (INRIX 2016 Global Traffic)

Global support for public transit and active transport is growing (Replogle & Fulton, 2014; The California State University, 2019). Recently in 2016, the United Nations identified the need to develop strong Public Transportation Systems. Many cities around the globe have initialized the long-overdue enhancement of their public transportation systems after decades of the wrongful misconception that continual expansion of streets and roads was the solution for traffic congestion: per-instance Panama City just recently opened its second Mass rapid transit (MRT) line, Doha just recently opened their MRT system, Montreal recently started construction of new LRT and Ottawa just recently opened its second LRT line. However, in general, the implementation of public transit systems is often done through stages (Mishra, Welch, & Jha, 2012) and takes a significant amount of time, for instance, recent implementation in Panama City of the MRT system has been staged over 15 years. The traffic congestion needs to be dealt with while PT systems arrive.

Even after the full implementation of PT systems in the city, suburbs and rural locations still require the management of roads to preserve them in proper levels of condition and to enable access to local facilities and services adequately, and to the closest PT terminal through park and ride and other similar facilities. For this reason, a Road Management System is needed to accomplish adequate management of the road network. However, to date, no RMS handles road congestion.

4.2 Literature Review

Attempts to consider road's operational characteristics within road management systems have opened the door for broader management frameworks such as those proposed by the Highway Economic Requirements System (HERS/ST) (Federal Highway Administration, 2018) or the Highway design manual (HDM) of the World Bank, however, lacking dynamic optimization techniques. A well-developed RMS must generate a systematic and consistent framework for selecting Maintenance, Repair, and Rehabilitation (M, R&R) countermeasures and determining the priorities and optimal timing for their implementation (Chin, Babashamsi, & Yusoff, 2019; France-Mensah & O'Brien, 2019; Han & Kobayashi, 2013).

At the core of any RMS, one can find a decision-making system which commonly seeks the accomplishment of maximum levels of performance, in the form of surface or structure indicators. In some cases, they look into goals related to safety and travel time (Amin, & Amador-Jiménez, 2015; Tighe, Li, Falls, & Haas, 2000). In the late 2000s, (Louis and Magpili) proposed the use of an asset management system (AMS) considering capacity. Also, (Bernhardt et al. 2008) studied Agent-Based Modeling as a paradigm in order to develop asset optimization. In 2011, Dynamic Programming Models were taken by Faddoul in the field of bridges management to optimize (inspection, maintenance, and rehabilitation) groups of structures.

A paper from Amador 2011 suggested the possible benefits of integrating land use and transport modeling with Transportation Asset Management (L. E. Amador-Jiménez, 2011). Later a paper by Amin and Amador 2014 provided proof of concept that an integrated truck traffic travel demand could be beneficial to more accurately represent flows of trucks and their impact through ESALs on the deterioration forecasting of highways (Amador-Jiménez, L. and Reza Amin, M., 2014). Another paper by Amin and Amador developed a 4-step model of New Brunswick's Regional Highways, where only truck traffic movements were forecasted and feedback into the pavement management model (L. Amador-Jiménez & Amin, 2013). Research from Duncan 2012 examined how the management of different assets can be combined with travel demand forecasting under different scenarios to show the national economic consequences of lack of funding for transportation and the consequential performance gaps (Duncan, Landau, Cutler, Alstadt, & Petraglia, 2012). The Institute of Labor and Industrial Relations (Webb et al., 2008) analyzed the economic relationship between road-bridge rehabilitation and repair (R&R) and increased capacity of new roads (IC / NR). Booz (2011) review and document cases in which State's DOTs had incorporated travel demand within transportation asset management (Booz Allen Hamilton, 2011).

Despite all these efforts, no model to date has supported explicit linkage between TDM and RMS systems to enable allocation of strategies to counteract congestion at the same time as those intended to handle road deterioration.

Therefore, the addition of travel demand modeling is key to assist decision-makers in making informed decisions to allocate resources and counteract traffic congestion through road management strategies to reduce private car traffic usage, encourage non-motorized trips and public transportation, which altogether can lead to shorter travel time. Travel time is the result of interactions between demand and capacity and is impacted by weather conditions, accidents, temporary road works, and traffic composition (Charlotte, Helene, & Sandra, 2017; J. Javid & Jahanbakhsh Javid, 2018; MEHRAN & NAKAMURA, 2009).

To date, no solution has integrated both demand modeling and decision making for investment planning to handle road congestion (in the interim time while PT arrives) in addition to pavements condition.

4.3 Objective

The objective of this paper is to propose an Investment Planning tool to allocate funds for handling road congestion and deploying remedial works to upkeep pavement conditions at acceptable levels.

4.4 Methodology

The methodology of this paper is divided into three main sections:

- First, the maximum capacity of road links is estimated, and the demand is forecasted from historical trends (future research will make such estimation endogenous).
- Second, deterioration trends are produced for surface conditions and pavement-structure strength.
- Third, an optimization algorithm is run to optimally allocate actions and interventions to achieve and sustain improved road conditions and capacity in the network. Figure 4-2 summarizes the proposed approach, and the results for a case study of regional roads arriving at the Great metropolitan area of central Costa Rica in the next section are presented.

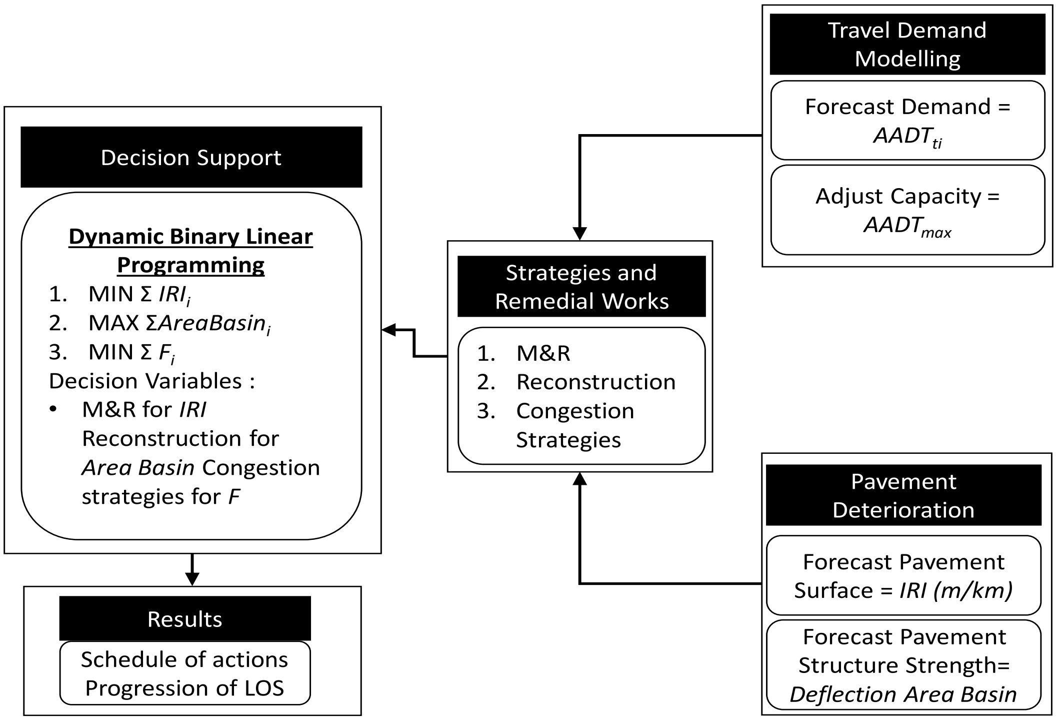


Figure 4-2 High-level overview of the Methodology

4.4.1 Travel Demand Model Development

A travel demand model was developed using VISUM 18 from the PTV group (Chaverri et al. 2020). ArcGIS was used as a database manager for compiling all required data types. The VISUM model was built to reflect the great central valley of Costa Rica, where most of the population lives, and the majority of the job opportunities are located. The model developed in VISUM required the creation of a procedure sequence that comprises several libraries where the data and parameters for the model were populated. Each step involved the preprocessing of the data. Two main data types were used: the network data and the socio-economic and land use data. These two data types were preprocessed using ArcGIS. The preprocessing involved gathering all road networks and census block data into two geodatabases. Attributes such as posted speed limits, number of lanes, functional class, and whether the road section was one-way or two-way were assigned to each road segment in the road network database. For the socio-economic data, transportation analysis zones (TAZs) were delineated from census block shapefiles. Data from census blocks within each TAZ were aggregated to the TAZ level. The steps followed in developing the two datasets are presented in Figure 4-3.

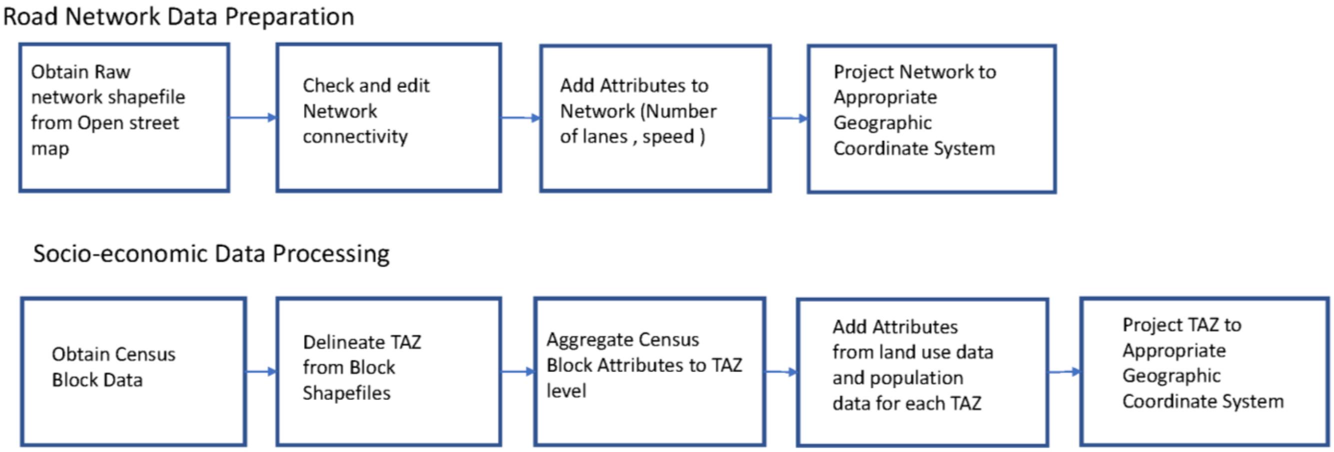


Figure 4-3 Data Preprocessing Steps

The travel demand model development used a modified four-step travel demand modeling process. The modification involved excluding all other travel modes with the exception of private passenger cars in the mode choice step, whereas the other steps remain unchanged. For the purpose of this research, all socio-economic and network data were from the year 2011. The traffic volume outputs of the model were validated against available ADT data collected in the study location from the Ministry of Transports and Public Works (2017).

4.4.1.1 Highway Skim

In this component, the model produces a matrix that shows the costs associated with traveling from one zone to another. The costs are presented in terms of travel distance in miles and the associated travel time. The costs are calculated using link distances and the associated link speed. The link distance and speed information are obtained from the network file, which is used as an input into software as "highway skim."

4.4.1.2 Trip Generation

In the first step of the four-step modeling process, trips generated (attraction and production trips) were computed for each of the analysis zones. The TAZ database contained attribute data on population, employment by type, households, and housing units. A total of 340 zones were created for the study area (MIVAH, 2007). The network was connected to the TAZ in the VISUM environment using two tools, namely the “Automatic Add Centroid” and the “Automatic Add Centroid Connectors.”

The “Automatic Add Centroid” feature automatically generates centroids at the center of each zone, and the “Automatic Add Centroid Connectors” creates links from the nearest network segments to the centroid of the zone. The centroid connectors are imaginary access roads that connect traffic generated in a zone to the network. In this model, centroids were allowed to connect to all road types except Interstate Highways. This is because highways are not typically connected to driveways (centroid connectors). All the centroid connectors were assigned the program’s default travel time of 0.5 minutes which represents an approximate time it would take for a car to traverse a driveway and leave a block. Figure 4-4 shows the study area with TAZ demarcations and connectors.

4.4.1.3 Trip Rates

Trip Generation rates were estimated from the OD survey for each household in Costa Rica (Chaverri et al. 2020). The obtained numbers were compared with other benchmark trip rates from Singapore, the United Kingdom, and Abu Dhabi. Attraction rates were based on the Institute of Transportation Engineers (ITE) and the estimated Gross Floor Area in each zone.

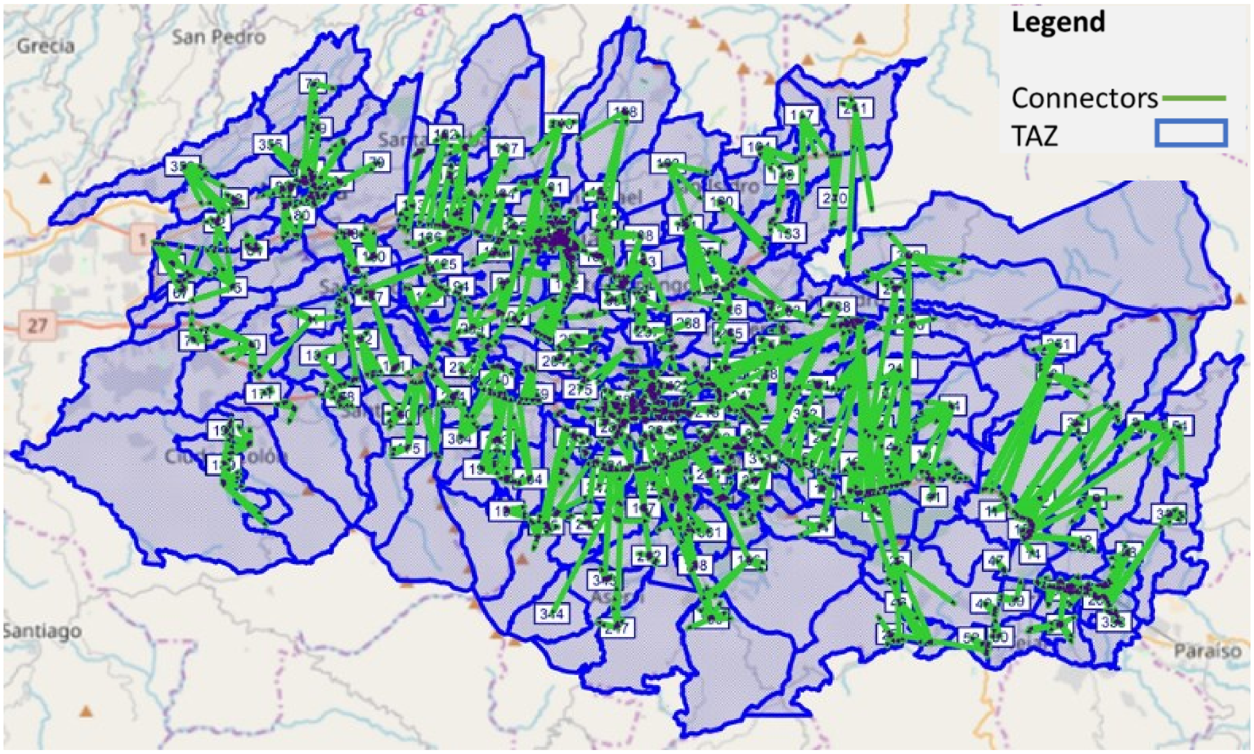


Figure 4-4 Central Valley of Costa Rica Traffic Analysis Zones (Chaverri et al. 2020; MIVAH, 2007)

4.4.2 Balancing Productions and Attractions

Production and attraction trips calculated at the stage of trip generation for the study area are usually not equal. However, the four-step process considers trips to be two-way, with every trip production having an attraction, and therefore the total trip production and attraction for the study area must be balanced for each trip. The trip productions and attractions were balanced by making the productions constant and scaling the attractions equal to the total productions for each trip purpose. Trip production is often used as a framework for balance, as the household information used in the measurement of production is typically more precise than the land-use data used to measure travel attractions. The balancing process is built into VISUM and so the productions and attractions were automatically balanced out during the trip generation step.

4.4.3 Trip Distribution

During this step, the productions and attractions estimated from the trip generation stage were matched based on the relative attractiveness of traveling between two zones compared to others. The willingness of an individual to travel between zones is measured by the impedance to travel and is typically represented by travel time or distance between pair of zones. VIUSM uses the gravity model approach to calculate trip distribution with several choices of utility functions. Gravity models determined the relative number of trips made between two TAZs directly proportional to the number of productions and attractions in each TAZ and inversely proportional to a function of the spatial separation or travel time between the two zones and friction factor. The model is defined by the Equation 4.1. Utility function works with friction coefficients, with values within the utility function, which map the reaction of road users to travel cost or time. Several choices of utility functions are defined in VISUM. In this study, the combined function is used by Equation 4.2.

$$T_{ij} = P_i \left[\frac{A_j F_{ij} \; K_{ij}}{\sum_{k=1}^{zones} A_K F_{ik} \; K_{ik}} \right] \qquad \textbf{[4.1]}$$

Where:
T_{ij} = number of trips from zone i to zone j ,
P_i = number of trips productions in zone i ,

A_j = number of trips attractions in zone j ,

F_{ij} = friction factor relating the spatial separation between zone i and zone j , and

K_{ij} = optional trip distribution adjustment factor for interchanges between zones i and zone j

$$F(c_{ij}) = a * b^{c*ij} e^{-c*c_{ij}} \quad \textbf{[4.2]}$$

Where:
c_{ij} = travel costs from zone i to zone j
a,b and c = friction coefficients

Trip distribution calculates the proportion of the total traffic between each pair of zones based on how good a connection there is between the zones. The connection quality is often measured in travel time and referred to in technical terms as skim matrices.

4.4.4 Mode Choice

Personal vehicle travel is the only mode considered in this study as there was no significant representation in the study area of other travel alternatives such as transit. The mode choice step has been modified to serve as step-in, in which occupancy have been applied to the model. This led to the transformation of expected individual trips (production-attraction trips) into vehicle trips (origin-destination trips) by category between zones.

Trips by purpose and occupancy rates of the vehicle typically vary all day long. For example, a more significant portion of morning and evening trips are home-based work (HBW) trips with the lowest occupancy rates of morning trips. Most trips have relatively higher occupancy during off-peak hours and are usually intended for shopping and social trips.

Automobile occupancy and diurnal factors by the purpose of the trip and direction taken from the NCHRP report 365 (TRB 1998) were applicable to the person trip output from the trip distribution step to obtain estimates of total daily trips in the hourly origin-destination format. This is done by dividing total person trips by auto occupancy rates to obtain vehicle trips for each trip purpose type. Diurnal factors enabled the total vehicle trips to be spread over 24 hours time period. Time of day (diurnal) factoring enabled the estimation of trip tables indicating peak and off-peak activities.

Each of home-based trip is divided into trips from productions to attractions and from attractions to productions. Productions represent the location of the trip's home end, and attractions show the trip's work, school, or shop end. The final conversion to origin-destination format was performed using equation 4.3 (Converting Production-Attraction Trips to Origin-Destination Trips) to account for the split of each trip into two. The next step in the modeling was to allocate trips between the zones.

$$Daily\ Vehicle\ Trips(O-D) = 0.5 * (HBW_{PA} + HBW_{AP} + HBO_{PA} + HBO_{AP}) + NHB \quad \textbf{[4.3]}$$

Where

PA is production attraction and AP is attraction production

HBW_{AP} and HBO_{AP} are the transpose of HBW_{PA} and HBO_{PA} respectively.

The NHB trips are not factored because they are already balanced in the origin-destination format.

4.4.5 Trip Assignment

The origin-destination trips developed in the modified mode choice step for all pairs of zones are distributed among the network connecting zones in this final step. In this study, the traffic assignment step used the User Equilibrium method to assign the network traffic. Equilibrium assignment distributes the demand, according to Wardrop's first principle. "Every road user selects his route in such a way, that the impedance on all alternative routes is the same, and that switching to a different route would increase personal travel time (user optimum)." The network assignment method of user equilibrium is based on the principle that, as congestion delays occur, road users seek alternative routes until all vehicles traveling between two zones use the shortest available routes.

This method increases the travel time on a link when traffic volumes approach or exceed the link capacity and divert traffic to other routes — resulting in a higher degree of saturation. Travel time associated with the highway is calculated by applying the volume-day relationship formula in equation 4.4. Volume-delay functions (VDF) describe the relationship between travel time or average traffic flow rate and the number of vehicles in the traffic stream. In VISUM, multiple VFDs have been defined in this study CONICAL VDF is used.

$$\boldsymbol{t_{cur}} = \boldsymbol{t_0} * (\sqrt{\boldsymbol{2 + a^2 * (1 - sat)^2 + b^2}} - \boldsymbol{a * (1 - sat) - b}) \qquad \textbf{[4.4]}$$

$$b = \frac{2a - 1}{2a - 2}$$

Where $Sat = \frac{q}{q_{max}}$

t_{cur}: Current travel time on a network object in a loaded network [s]

t_0: Travel time on a network object with free-flow time [s]

a, b: volume delay function parameters

q: Current volume

sum of volumes of all private transport systems (PrT) including preloaded volume [car units/time interval]

q_{max}: Capacity [car units/time interval]

The output from the traffic assignment step includes a road network shapefile with the assigned ADT for each link. Then, when validating the model, these estimated ADT values could be compared with observed ADT values.

4.4.5.1 Model Validation and Calibration

The calibration of the VISUM model was based on the observed volumes of traffic on the links obtained from the ministry of transportation 2017 providing historical road traffic data. The actual traffic volumes were assigned to a number of links, and a comparison was made between the actual traffic volumes observed and the modeled traffic volumes. A maximum of 86 links with the traffic volumes observed is assigned to perform a comparative analysis. An additional attribute called Count was defined to assign observed traffic volumes into the network. For example, if count on a link is 2,500vpd, it means the discussed link carries 2,500vpd in real life.

The results of the model traffic volumes are plotted against the actual traffic volumes on links in order to assess the reliability of the traffic volume calibration. Figure 4-5 displays the VISUM scatter plot containing the result of the model calibration assessment.

The linear trend line shows the accuracy of the traffic-volume comparisons between those modeled and the actual traffic. A portion of the dot points follows a linear trend, as shown in Figure 4-5 (Chaverri et al. 2020).

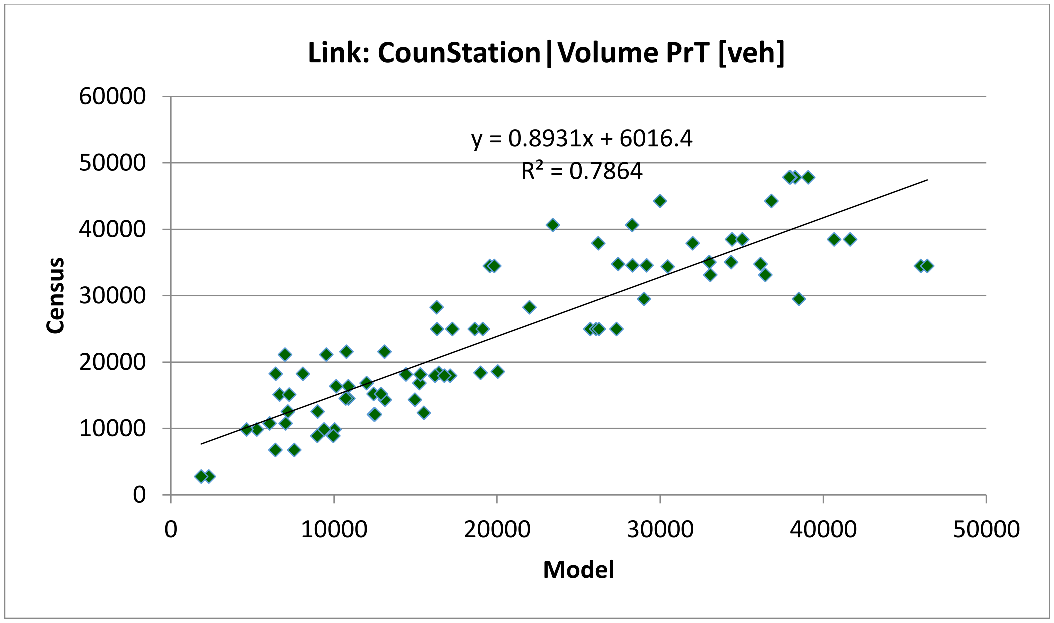


Figure 4-5 Link scatter plot for comparing traffic volumes (Chaverri et al. 2020)

As a result of the analysis, the R^2 of the scatter plot (according to VISUM) was established at 0.786, which shows the accuracy of the traffic-volume calibration. It is noted that calibrating the traffic volumes in such a large modeling area is a challenging task and the outcome of 0.786 for R^2 is considered a reasonable outcome.

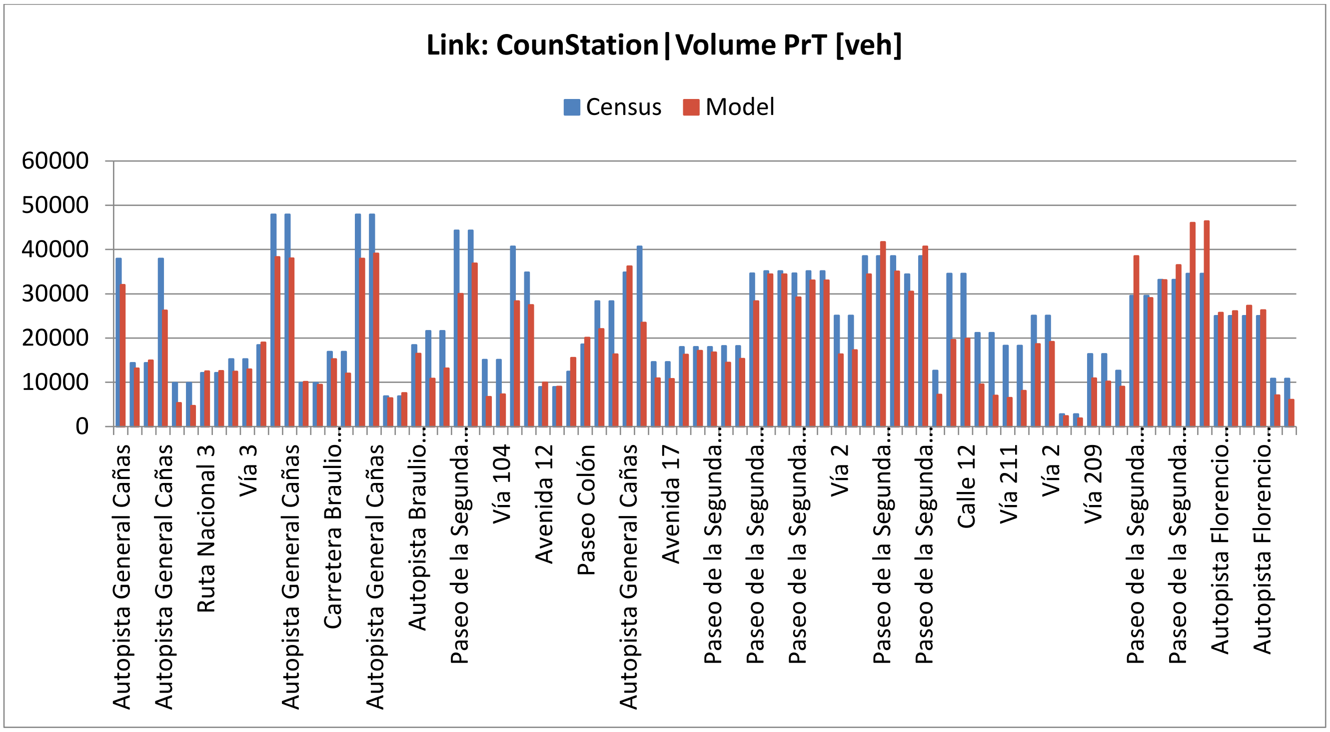


Figure 4-6 Comparing traffic count values with estimated volumes (Chaverri et al. 2020)

Next, Volume-to-Capacity Ratio (F) was estimated, dividing the forecasted volume for a given year over the observed capacity V/C ratio. Volume means the number of vehicles that pass through a point along a street, on a path or on a road.

$$\frac{\boldsymbol{V}}{\boldsymbol{C}}\,\boldsymbol{ratio} = \frac{\boldsymbol{Demand\ flow\ rate\ (Volume)}}{\boldsymbol{Capacity}} \qquad \textbf{[4.5]}$$

Where:

Demand flow rate = volume of vehicles on a transportation facility (vehicles per hour per lane, or veh/h/ln) for a given segment length (VISUM output)

Capacity = the maximum number of vehicles a transportation facility can handle (veh/h/ln)) for a given segment length

V / C ratio is an indicator of the quality of a segment's traffic operations. It also shows how close a road is to its capacity. V/C ratios are used for capacity and analysis of Level of Service (LOS). Table 4-1 shows typical ranges for V/C and the definition of LOS categories.

Table 4-1 Volume Capacity ratio ranges (Transportation Research Board, 2000)

Level of Service	**Description**	**Volume to Capacity Ratio (F)**
A	Highest driver comfort; free-flowing	<0.60
B	High degree of driver comfort; little delay	0.60-0.70
C	Acceptable level of driver comfort; some delay	0.70-0.80
D	Some driver frustration; moderate delay	0.80-0.90
E	High level if driver frustration; high level of delay	0.90-1.00
F	Highest level of driver frustration, excessive delays	>1.00

In this study, three congestion strategies have been considered in order to improve network capacity the first two are temporary and can handle congestion up to the certain level of V/C the last one is permanent and take into account when the network is fully congested, and there is enough space to expand the network. Table 4-2 presents the strategies and expected effect on the modeling and their cost associated with them.

Table 4-2 congestion strategies

Strategy	**Effectiveness**	**Applicable to**	**Rule Set for applicability (F)**	**Cost**
Reversible Lanes	N = +1 (Temporary)	3 lanes roads	F >= 0.8	1 officer @ 5km, $50,000/5 = $10000/km or 10$/m per year
Truck Restrictions	P = 5% (temporary)	All	F > 0.6	1 officer @ 5km , $50,000/5 = $10,000/km or $10/m per year
Add lane (existent ROW)	N + 1 (permanent)	2 lanes and more	F > 2 and available space on the ROW	400,000/km = 400$/m

4.5Pavement Deterioration and countermeasures

The available information for Costa Rica in this case study for pavement consisted of linearly referenced international roughness index (IRI) data and referenced falling weight deflectometer (FWD) measurements of coordinates (point data). All data sets are obtained by the National Materials and Structural Models Laboratory (LANAMME) of the University of Costa Rica.

4.5.1 International roughness index (IRI)

Pavement deterioration for roads in Costa Rica was previously estimated by Amador (L. Amador-Jiménez & Mrawira, 2011b), and their results are used in this research: Figure 4-7 contains IRI deterioration trends for three groups of traffic intensity, although the medium and low groups could be merged into one group.

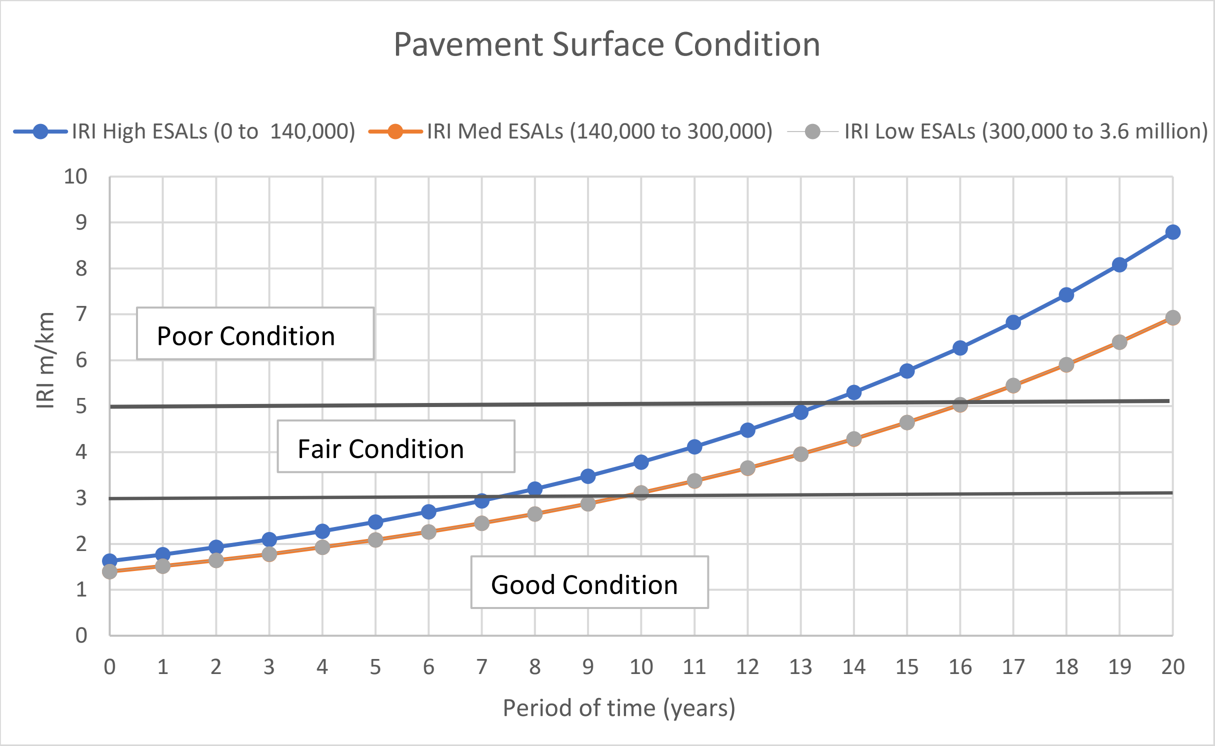


Figure 4-7 Pavement Surface Deterioration

4.5.2 Deflection area basin

Previously proposed by Xu, Ranjithan, and Kim (2002), the Deflection Basin Parameters (*AreaBasin*) is used as a surrogate for pavement strength in this paper. This normalized indicator is positively correlated to the strength of the pavement structure without accounting for the subgrade. Equation 4.6 shows the calculation of AreaBasin, where D_0, D_1, D_2, and D_3 are FWD deflection readings at zero offset, first offset, second offset, and third offset geophones, respectively.

$$AreaBasin = 6\left[1 + 2\left(\frac{D_1}{D_0}\right) + 2\left(\frac{D_2}{D_0}\right) + \left(\frac{D_3}{D_0}\right)\right] \qquad \textbf{[4.6]}$$

It is essential to take note that the theoretical maximum value of the Area DBP is 36 inches; this occurs when the pavement structure is extremely stiff – in this case, $D_0=D_1=D_2=D_3$ (refer to Equation 4.6. The theoretical minimum value of the Area DBP is 11.1 inches; this occurs when all pavement layers have the same elastic modulus, meaning the pavement structure does not contribute any additional stiffness to the underlying subgrade – in this case, $D_1/D_0 = 0.26$; $D_2/D_0 = 0.125$; $D_3/D_0 = 0.083$. Expected deterioration of the Deflection *AreaBasin* indicator for Costa Rica using the approach proposed by Amador and Mrawira (2011) is illustrated in Figure 4-8. Rapid decay in pavement condition can be explained by the tropical weather circumstances with an average precipitation of about 3,500 mm of rain per year.

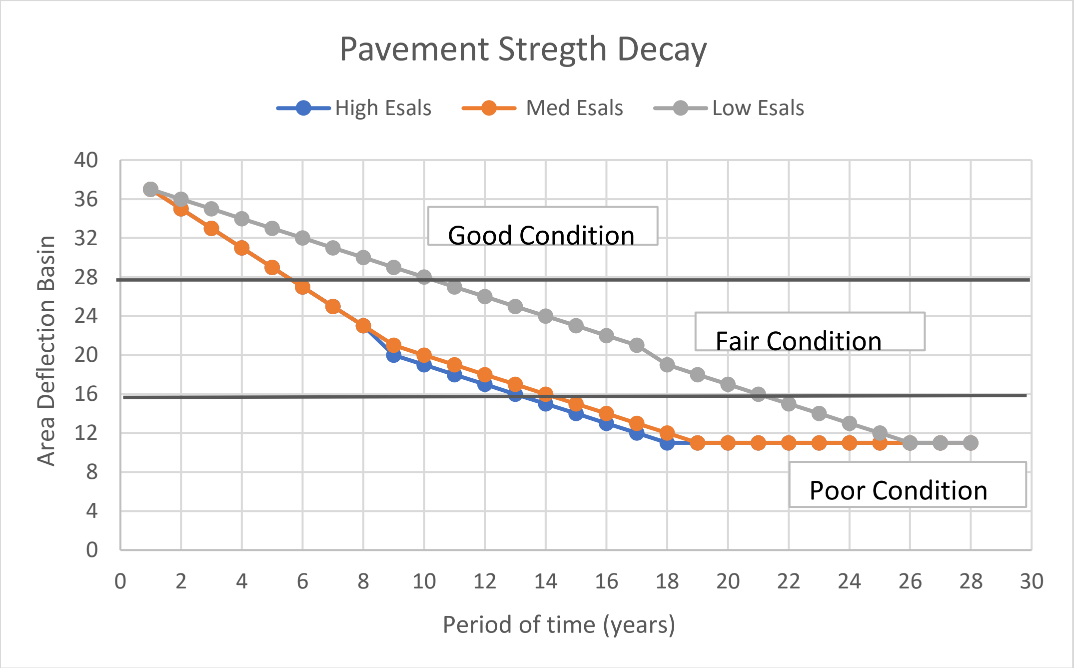


Figure 4-8 Predicted Deterioration of AreaBasin for this case study

Table 4-3 summarizes maintenance and rehabilitation interventions for the surface and the structure of the pavement, their cost, range of applicability, and expected effectiveness.

Table 4-3 Treatments and Operational Windows Used in Network-level Trade-off Analysis

Treatment	**Operational Window**	**Unit Cost ($)**	**Effectiveness**
Micro-surfacing	IRI < 2 m/km and AreaBasin >= 24	80,000 /lane-km	IRI = 1.4 m/km
Minor Rehab (mill and overlay)	Arterial: 2 <= IRI < 4 m/km and AreaBasin >= 24	175,000 /lane-km	IRI = 1.4 m/km
Major Rehabilitation (partial reconstruction)	IRI >= 4 m/km and 18 <= AreaBasin < 24	400,000 /lane-km	IRI = 1.4 m/km , AreaBasin = 30
Reconstruction	IRI >= 4 m/km and AreaBasin < 18	600,000 /lane-km	IRI = 1.4 m/km, AreaBasin = 30

Notes: * This treatment are an oversimplification of those existent in practice. The effect of sealing the cracks after a micro-surfacing which reduces the rate of decay of the structure has been ignore.

4.6 Decision Support System

A decision support system is known as Woodstock (REMSOFT), which uses object-oriented computer programming, is known was used to code several interacting modules to define the decision-making model. The modules and their purpose are listed below and explained the following subsections:

- LANDSCAPE: This module is used to define the structure of the attribute data, including current and future (not yet existent) attribute characteristics
- AREAS: Inventory of Assets classified according to the LANDSCAPE
- ACTIONS: Rules to define when countermeasures are applicable

- TRANSITIONS: Rules to define the change experienced by an asset receiving a given ACTION
- YIELDS: definition of time-related rules and time progression of indicators such as cost, condition, and effectiveness of a given ACTION. YIELDS are activated by TRANSITIONS and their aggregated results are handled by OUTPUTS
- OUTPUTS. User-defined variables that aggregate any time-dependent indicator for each period of time. Typical OUTPUTS include total condition per year, the total length of a given ACTION, the total amount of assets within a given range, total expenditure per type of ACTION, the total amount of assets within a given range of quality or performance.
- OPTIMIZATION: Module used to control GOAL PROGRAMMING or WEIGHTED AVERAGE OPTIMIZATION utilizing the OUTPUTS to control the constraints and the objectives.
- SEQUENCE: is the module that captures back from the external optimization solver the results of the linear programming algorithm

4.6.1 Model Definition

The coding of the model followed a structure of modules in WOODSTOCK software from REMSOFT ANALYTICS. The LANDSCAPE section included the THEMES shown in Table 4.4.

Table 4-4 Decision Support System LANDSCAPE Definitions

Characteristics	Description
Theme1	Number of lanes
Theme2	Truck percentage
Theme3	Terrain Type
Theme4	AADT
Theme5	ESALS
Theme6	Deflection Area Basin age
Theme7	IRI age
Theme8	Constant factor
Theme9	Constant factor
Theme10	Capacity
Theme11	Binary variable (Add new lane)
Theme12	Binary variable (Candidate for HOV)
Theme13	Binary variable (divided or undivided road)

The actions included in this model cover the pavement treatment and congestion strategies which are presented in Table 4-5.

Table 4-5 Actions defined in the model

Condition intervention for surface and structure	Congestion Strategies
Micro-surfacing	
Mill and Overlay	Reversible lane
Major Rehabilitation	Truck Restriction
Reconstruction	Add new lane

The transitions included in the model included one dynamic link for each action previously defined. For annually triggered actions (such as reversible lanes and truck restrictions) the transitions were handled through a fixed benefit as follows:

- For reversible lanes it increased the capacity of the road in one direction and on a temporary basis, that is with an effect that disappears after a one period of time
- For truck restrictions, the transition reduced the flow of vehicles through the percentage of trucks estimated over traffic volume and vehicle classification
- For the pavement condition actions, the transitions produced a jump from the current performance curve to a new (after treatment) performance curve, which was shifted to reflect the extension in the lifespan of the pavement.

The add lane transition was simply the permanent alteration of the attribute structure for the road corridor benefiting from an additional lane, plus the corresponding increase in capacity experienced.

4.6.2 Optimization Algorithms

The decision-making support system had, at its core, an optimization algorithm that identifies the optimal scheduling of strategies and remedial works that accomplish the optimal value of the objective, including deviation (d) for the prescribed goal values (Equations 4.7 to 4.11). Negative deviations for IRI, v/c and travel time were encouraged, as well as a positive deviation for the Deflection Basin Area (Equation 4.7)

$$MIN\ \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}[W_{IRI}IRI - W_{DBA}DBA + W_{VC}VC] \qquad \textbf{[4.7]}$$

The following goals (G) where defined for the key performance indicators of interest (Equations 4.8 to 4.11).

$$G_1 = \sum_{t=1}^{T}\sum_{i=1}^{N} IRI_{ti} \leq \sum_{t=1}^{T}\sum_{i=1}^{N} IRI_{(t-1)i} \qquad \textbf{[4.8]}$$

$$G_2 = \sum_{t=1}^{T}\sum_{i=1}^{N} VC_{ti} \leq 0.89 * \sum_{t=1}^{T}\sum_{i=1}^{N} VC_{(t-1)i} \qquad \textbf{[4.9]}$$

$$G_3 = \sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j=1}^{K} C_{t,j}x_{tij}\, L_i \leq B_t \qquad \textbf{[4.10]}$$

$$G_4 = \sum_{t=1}^{T}\sum_{i=1}^{N} DBA_{ti} \geq 1.01 * \sum_{t=1}^{T}\sum_{i=1}^{N} DBA_{(t-1)i} \qquad \textbf{[4.11]}$$

The Mathematical formulation herein presented is an expansion of that previously used formulation for optimizing M&A activities in a network of spatially distributed assets (Amin & Amador-Jiménez, 2015; Faghih-Imani & Amador-Jimenez, 2013; Li, Haas, & Huot, 1998). Such a previous optimization process attempted to achieve the objective while subject to constraints.

This formulation relied on the forward dynamic links of Equation 4.12, which support a decision tree containing all possible paths of pavement condition across time, after hypothetically receiving available strategies or remedial measures (Amador-Jiménez and Afghari, 2013; Amin and Amador-Jiménez, 2015; Faghih-Imani and Amador-Jimenez, 2013). This tree is based upon a transfer function used to estimate the updated value of a given key performance indicator (i.e., pavement condition IRI_{ti} or DBA) as a combination based on the decision variable (x_{tij}) and the effectiveness (E_{ij}) or deterioration (D_{it}) of the specific road segment on-time t (Equation 4.12 and 4.13).

$IRI_{tij} = x_{tij}\ (IRI_{(t\text{-}1)ij} - E_{ij}) + (1\text{-}x_{tij})\ (IRI_{(t\text{-}1)ij} + D_{it})$ **[4.12]**

$DBA_{itj} = x_{tij}\ (DBA_{t\text{-}1)ij} + E_{ij}) + (1\text{-}x_{tij})\ (DBA_{(t\text{-}1)ij} - D_{it})$ **[4.13]**

Travel demand was adjusted for those segments where truck restrictions were imposed (Equation 4.14). The capacity of a link was also affected whenever a reversible lane strategy was implemented (Equation 4.15) or add a lane was added (Equation 4.16); otherwise, capacity was kept intact (Equation 4.17).

$V_{tij} = x_{t,i,j=truckrestriction} * V_{t0,i,j} * F1 * (1+g)$ where F1=1-truck% if x=1,
F1=1 otherwise and $V_{tij} = x_{t,i,j\neq truckrestriction} * V_{t0,i,j} * (1+g)$ **[4.14]**

$C_{tij} = x_{t,i,j=reversiblelanes} * F2 * C_{t0} * N$ **[4.15]**

where $F2 = \left(\frac{N+1}{N}\right)\ for\ time = t\ only,$ when x=1, F2=1 otherwise
$C_{tij} = x_{t,i,j=addlane} * C_{t0} * (N+1)$ where N = number of lanes in one direction **[4.16]**

$C_{tji} = C_{t0}$*N where Ct0 = capacity per lane on base year **[4.17]**

4.7 Analysis and Results

Allocation of expenses concentrated on adding lanes during the first six years. Both congestion strategies (truck restrictions and reversible lanes) were used across all periods. Reconstructions started in year seven and remained until year 14.

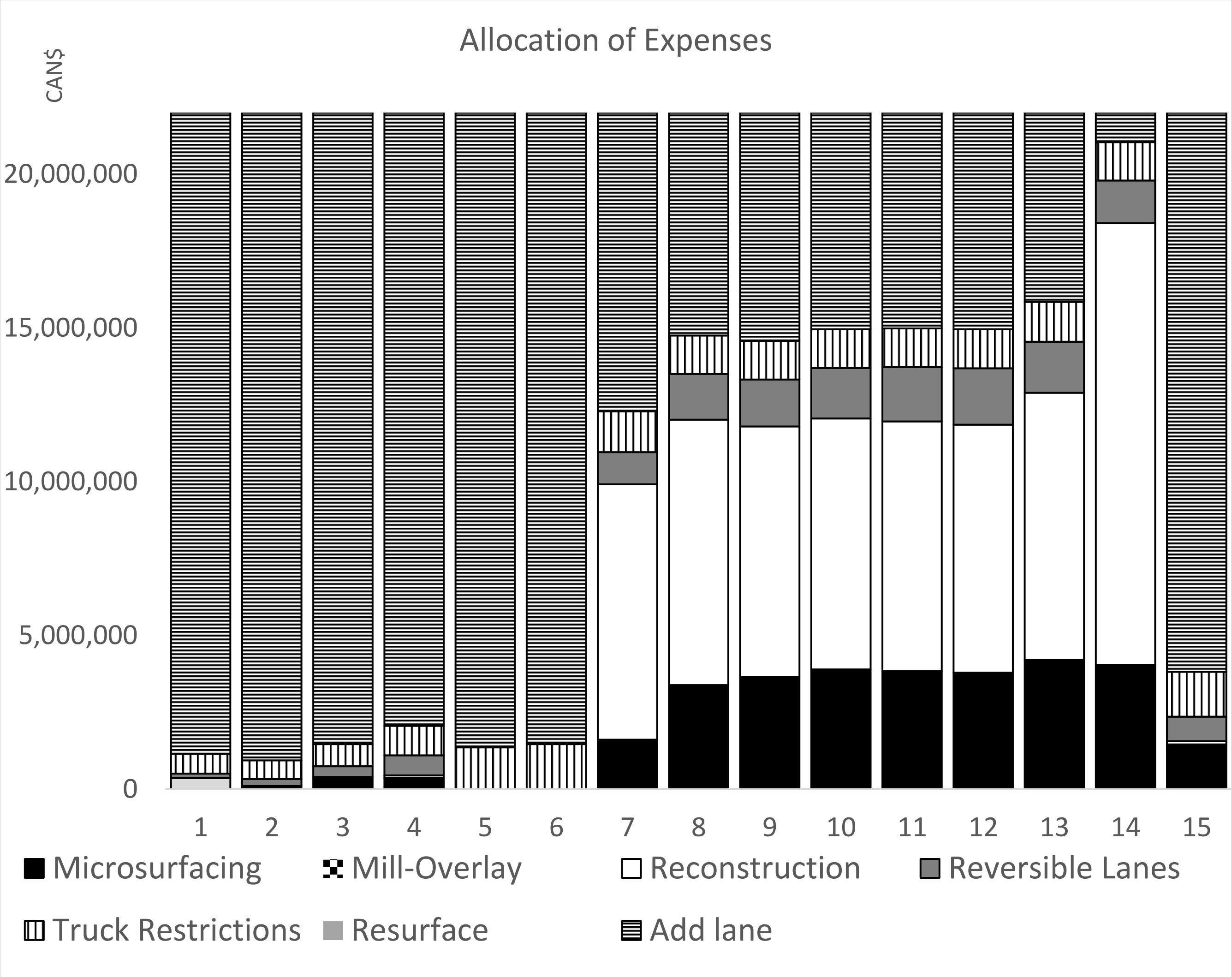


Figure 4-9 Expenditure on Road Congestion Strategies

In terms of pavement condition the surface and structural condition improved consistently during the 15 year period of investments, the expenses allocated (Figure 4-10) resulted in the most pavement strength in the category of fair and good, and all surface condition categorized as good the decision support system was able to deliver improved road condition.

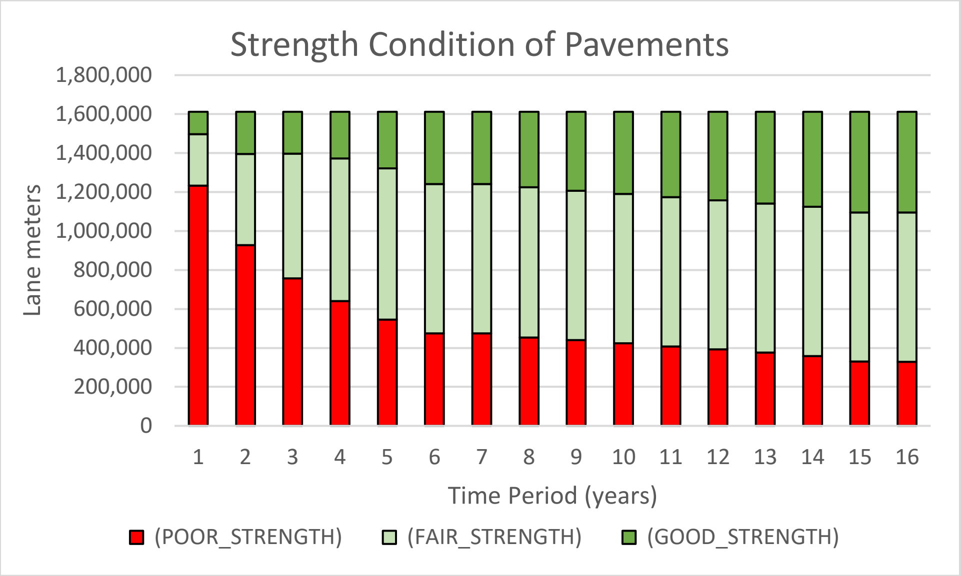


Figure 4-10 Pavement strength condition

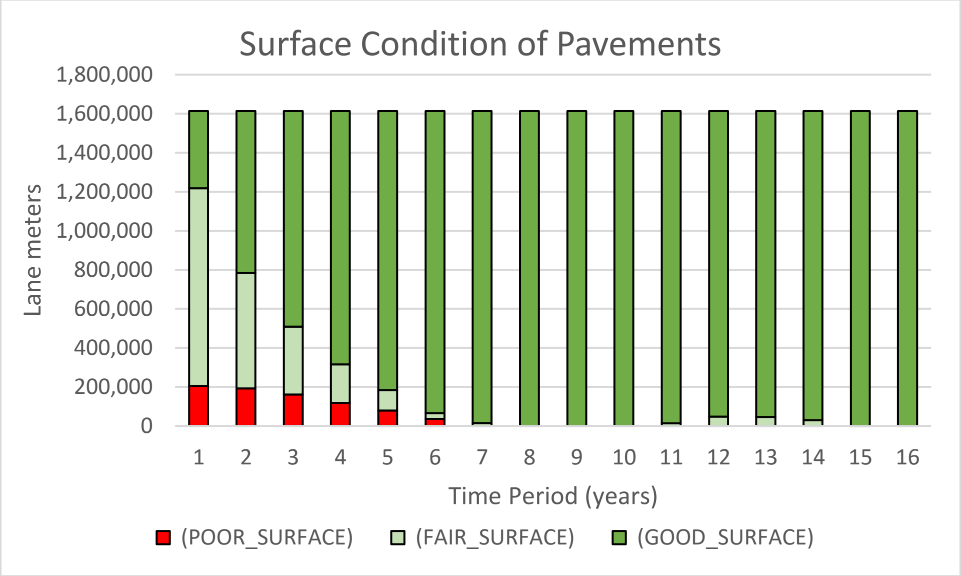


Figure 4-11 Pavement Condition Progression

Spatial allocation of interventions can be observed in the maps of Figures 4-12 to 4-15. Truck restrictions were employed all across the network every year. Reversible lanes were restricted to locations where three or more lanes were available.

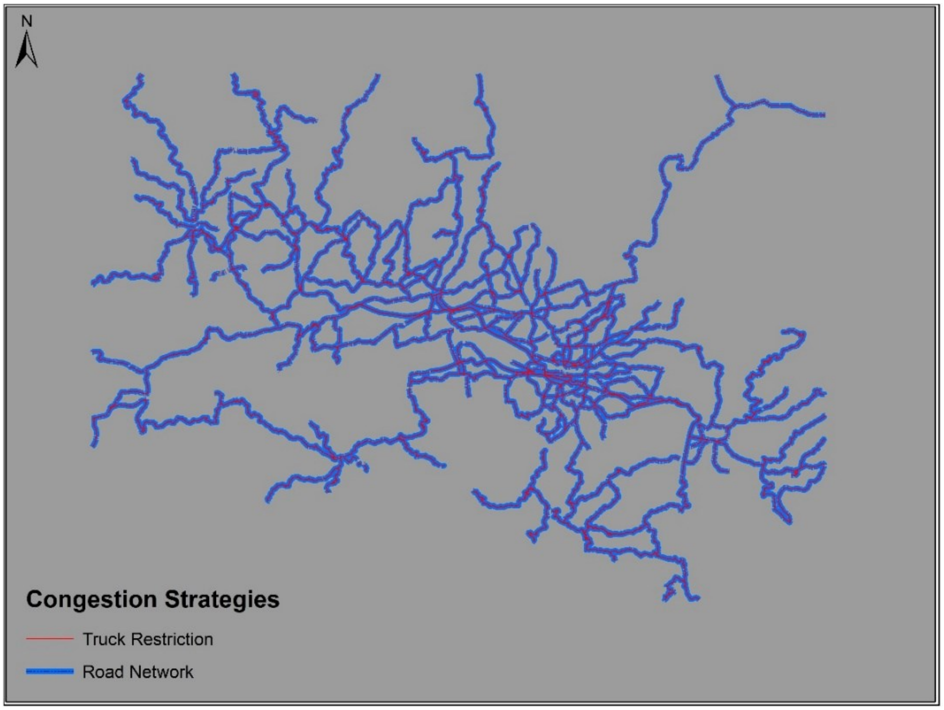


Figure 4-12 Spatial allocations of the truck restriction strategy over 15 year

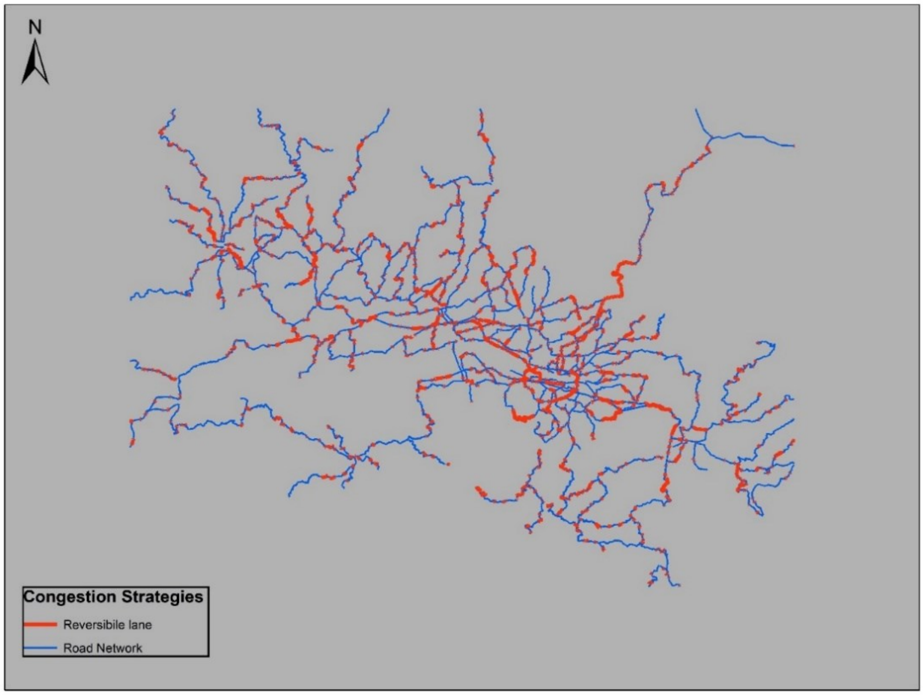


Figure 4-13 Spatial allocations of the reversible lane strategy over 15 years

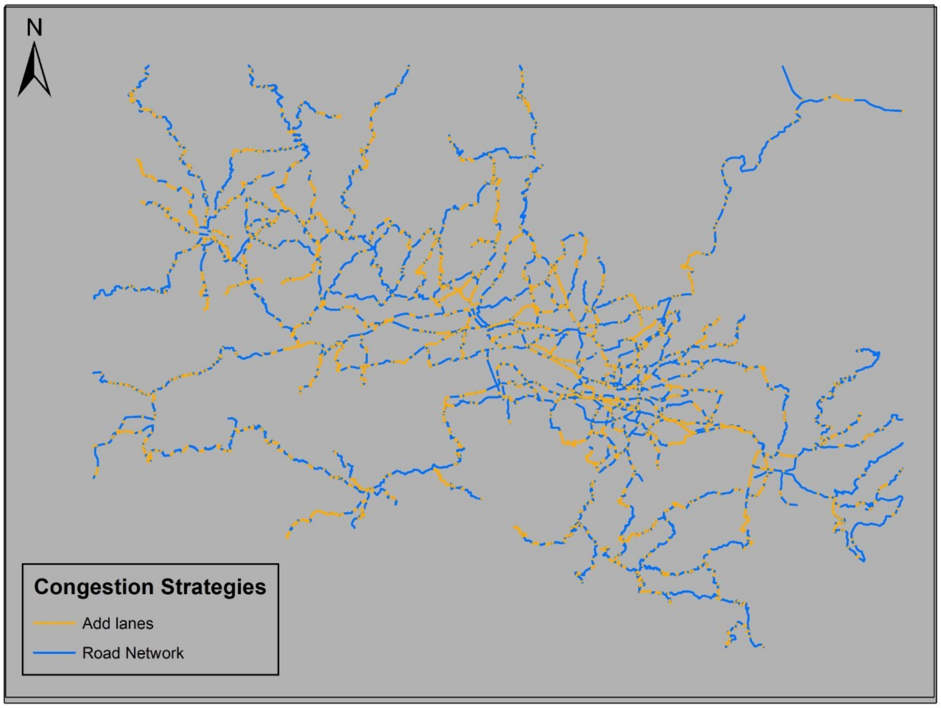


Figure 4-14 Spatial allocations of the add lanes strategy over 15 years

In terms of pavement maintenance and rehabilitation, reconstructions were predominant in addition to micro-surfacing.

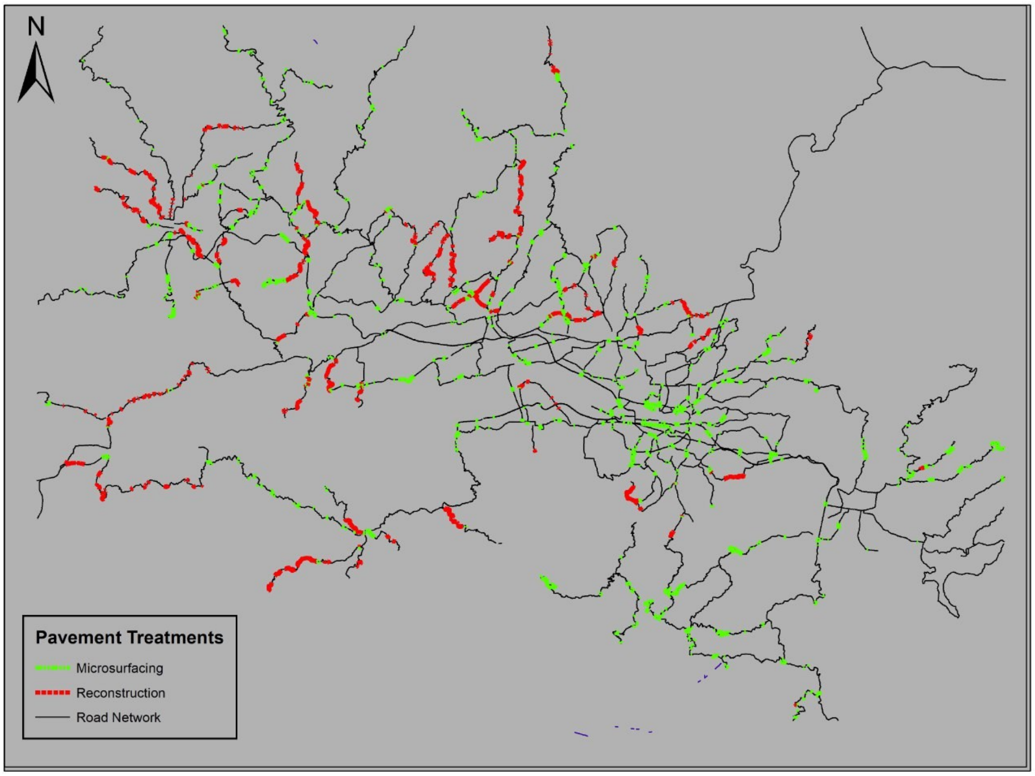


Figure 4-15 Pavement Maintenance and Rehabilitation

4.8 Chapter Conclusions

Pavement management systems can be expanded to consider interventions to increase the network capacity and strategies to handle daily congestion issues. The first requires larger capital investments, which will likely weaken the government's ability to upkeep the pavements in good condition. Hence as shown on the results of this case study, strategies are preferred to handle congestion as they are much cheaper and effective. The increasing improvement of surface and structural conditions for the network of pavements was also observed. Goal programming strategy resulted in cheaper and better results in general. Future studies must analyze similar case studies for transit road networks such that priority is given to such roads not only in terms of condition but also in terms of congestion for public transportation. The results presented are specific to the case study and may vary depending on the particular circumstances such as the level of budget, the extensiveness of the network, level of demand, and degree of deterioration of the roads.

Future research should develop a coordination mechanism that reorganizes the allocation of actions and strategies along corridors or large segments that accomplish their deployment, avoiding gaps.

Chapter 5: Adapting road management systems to support traditional bus transit: a case study of Montreal

Abstract

Traditional Bus transit is among the cheapest and most utilized modes of public transportation in the world. However, it is often associated with more inconvenient travel because it often shares the same road as automobiles suffering from common traffic congestion. Improvements such as the use of bus-exclusive lanes, truck restrictions, and reversible lanes during peak times can be used to reduce travel time. Pavement surface improvements can also be deployed to enhance the rider's comfort. However, road management systems rather concentrate on keeping all roads in good condition without prioritizing limited annual resources to improve the convenience of buses. This paper extends road management systems and enables cost-effective decisions on the bus network to improve travel time and surface conditions of the roads used by bus-routes. A case study of the island of Montreal is used to illustrate the approach. It is found that all temporary strategies were continuously selected year after year. Both reversible lanes and the addition of lanes were schedule steadily for the entire period and resulted in significant reductions in travel time for buses of 89.5% on average across the network. IRI was also reduced from 6.49 to 1.48 meters per kilometer. Future research could study how this improvement may affect mode split and attract more riders.

5.1 Introduction

As most municipalities, the city of Montreal faces numerous transportation challenges. The latest household travel survey data indicates that rates of car use in the greater metropolitan region continue to grow Hori, K., & Sakajiri, A. (n.d.). *Household Travel Survey report*. From 2010 to 2015, Greater Montréal's population increased by 1.1% on average per year, with 1.75 million inhabitants (Montreal Transport authority: *Sociéte de transport de Montréal*, 2010). Ridership on the overall Montreal island transit system amounts to 500 million trips per year in 2013, of which 60% are shared between buses and metro, and 15% are exclusively made by bus as the primary mode.

Car ownership and travel demand have increased despite an aging road infrastructure, mostly constructed in the 1950s, which is today at an advanced state of deterioration and need of major rehabilitation, upgrading, or even reconstruction. Average congestion levels experienced on the island have been (Canadian Automobile Association, 2017) and indicate that on average trips made by car require 40 minutes.

The city of Montreal, in partnership with the provincial and federal governments, is currently investing in new public transit routes, including a new LRT system spanning from the south shore into the city and covering the southwest sectors of Kirkland. The extension of the MRT blue line has also been announced. Traditional buses, however, rely on roads, and existent road infrastructure is not able to persevere with increased travel demand from those who utilize their automobiles. The government has understood that building more roads and infrastructure is not the solution to adequately accommodate travel demand because it will merely attract more car traffic *(Communaute Metropolitaine de Montreal, 2016*). Traffic congestion on bus routes arrives from car trips utilizing the same roads as buses and exceeding the capacity of such roads. In general, more traffic is often associated with detriments in road safety and pavement deterioration when there is a significant percentage of trucks on the vehicle mix.

In general, municipalities use a mix of strategies to tackle congestion, one of the commonly used strategies is to shift the demand from single-occupancy automobiles into car-pooling or transit options such as the MRT, BRT, LRT systems *(Ville de Montréal, 2018*), but traditional buses are often relegated to feed the other systems and function as first mile / last mile systems. While in reality, many commuters still rely heavily on traditional buses as the primary mode of transportation on their daily travel.

Significant investments are currently being poured into the expansion of the MRT and LRT systems in Montreal, but these efforts fail to support traditional buses properly. In addition to this, the cities infrastructure management system concentrates on upkeeping the condition of pavements and pipes. Recent replacement of bridges and interchanges made it clear that road expansion is not pursued as this only encourages car trips, but exception needed to be done for roads used by bus routes.

This paper proposes a modified road management system that introduces congestion strategies (temporary and permanent) in order to reduce travel time on bus routes (by reducing congestion) and to upkeep bus-route pavements in good condition. A decision-making framework is used to prioritize investments using the most cost-effective strategies and remedial measures while observing annual budget constraints.

5.2 Literature Review

The Federal Administration of Highways (FHWA) reports that congestion can be expressed in ideal conditions as a result of delay compared with the amount of time it takes to travel. The best measure of congestion is based on the travel time faced by road users. Congestion happens when more cars than space are available on the road or if traffic demand comes near or exceeds the ability of the road system available. Congestion is also the product of abnormal circumstances such as inclement weather, presence of animals, or fallen objects on the road and road collisions.

It is necessary to model congestion in order to optimally make decisions to improve travel time. Transportation Assets Management is a natural extension of travel demand models because it uses the forecasted impacts of alternative strategies and remedies to identify the most cost-effective sequence of actions that will accomplish effective reduction of travel time and improvement of road condition.

As detailed in the next section, urban transportation planning has clearly postulated the need to identify public policies and strategies that support non-motorized travel and public transportation.

5.2.1 Urban transportation planning

In recent decades, urban transportation planning has shifted in focus from increasing infrastructure capacity for automobile traffic to broader policies with environmental and social dimensions (Carmona & Sieh, 2008; Lucas, Marsden, Brooks, & Kimble, 2007). Therefore Planner's goals are moving towards sustainable development, including air quality improvements, automobile dependency reduction, and promotion of active modes of transportation, including public transit (Advani & Tiwari, 2006).

Bus transport is one of the most enticing and sustainable systems from a societal perspective**.** A well-planned bus system can encourage users to ride public transit, especially during peak hours, and also provide a high level of mobility to a large section of the population with the least cost. However, a poorly planned system causes inconvenience to the users, loses ridership, encourages the use of private vehicles, and imposes a well-planned financial burden on the operator.

5.2.2 Public policies to support public transit

In Quebec, many public policies have been adopted to support public transit (Sociéte de transport de Montréal, 2010). About one-quarter of the population of Québec lives on the Island of Montréal, producing high population density in a relatively small territory with a boom to public transit and active transportation. Indeed, it is within the island of Montréal that the proportional use of these transportation modes is the greatest in the overall Metropolitan region.

Table 5-1 Proportion of Public Transportation in Montreal Region

	Morning Rush Hour		Complete Day	
	Public Transit	ActiveTransportation	Public Transit	ActiveTransportation
Montreal	26.0%	14.5%	24.0%	18%
Longueil	20.6%	7.3%	13.9%	8%
Laval	18.8%	5.2%	12.9%	5%
South shore	7.5%	6.9%	4.8%	7%
North shore	6.6%	5.9%	4.3%	6%

Source : SECRETARIAT A L'ENQUETE ORIGINE. Destination. Mobilité des personnes dans fa région de Montréal. ENQUETE ORIGINE. Destination 2013 (Online, version 13.2a. [tic caiM edl Dela1.1 Lipcifis ection arenitrete .041-2 31-irri _..nhilite Terser --. rovon. iriontr le,d1 pd1] (Convoked September 21, 20t 5)

The latest studies from the *Ministère des Transports du Québec* estimated the cost of traffic congestion in Greater Montreal to be $1.9 billion (in 2008). Moreover, cars take up much more space than public transit vehicles. For example, to move the same number of people, cars take up roughly six times more space than a bus. Besides, public transit contributes to economic activity by facilitating passenger transportation and helps reduce traffic.

The 2019 Urban Mobility Report in the USA (Schrank, Tim Lomax, & Bill Eisele, 2019) mentions that public transportation is playing an essential role considering congestion. Since congestion is affected by local, regional, and state funding, project selections, and operational strategies. It indicates that without public transportation services, the national congestion cost will grow from $166 billion in 2017 to $200 billion in 2025 (in 2017 dollars), and the average commuter will waste 62 hours (almost eight vacation days) and 23 gallons of fuel in 2025.

According to the American Public Transportation Association (APTA), expanding public transportation is vital to reduce traffic congestion. APTA states that even if someone does not ride public transportation, it is still in his/her best interest to support investments in public transit. Because better public transportation means less congestion on the roads, however, certain forms of transit systems, especially rails, can only cover limited regions where the density of population (expected demand) is sufficiently high to deem public transportation financially feasible. Other forms of transit systems are more feasible and cheaper according to STM (2010). As seen in Table 5-2, buses are the cheapest mode of public transportation, their stops can be placed more often than those of other alternative modes of public transportation, but they are limited in capacity.

Table 5-2 Comparison of bus public transportation options in Montreal (Sociéte de transport de Montréal 2010)

System Characteristic	**Minibus**	**Bus**	**Articulated Bus**	**Trolleybus**	**BRT**	**Tramway**	**Metro**
Site (Length)	8 to 11 meters	12 meters	18 meters	18 meters	18 meters	(1 unit = 1 car) 30 to 40 meters	(1 train of 9 cars) 152 meters
Seating Capacity	20	30	54	54	47	75	306
Maximum Capacity	35	75	105	105	105	200	1200
Passenger/Hour/Peak Direction	500 to 750	1000 to 1500	1500 to 2000	1500 to 2000	2000 to 3000	2000 to 4000	20,000 to 30,000
Distance between Stops	250 to 500 meters	250 to 500 meters	250 to 500 meters	250 to 500 meters	400 to 500 meters	400 to 500 meters between stops	950 meters between stops
Journey Speed	10 to 25 Km/h	10 to 25 Km/h	10 to 25 Km/h	10 to 25 Km/h	17 to 25 km/h	17 to 25 km/h	35 to 38 km/h
Service Life	12 to 16 years	16 years	16 years	20 to 25 years	16 years	25 years	40 years
Base Unit Cost Per Vehicle	$550,000 to $670,000 (hybrid propulsion)	$470,000 (diesel propulsion) $900,000 (hybrid propulsion)	$700,000 (diesel propulsion) $900,000 (hybrid propulsion)	1,000,000	$2,000,000 (diesel propulsion) $3,000,000 (hybrid propulsion)	approx. $2,000,000	$2,000,000 to $3,000,000
HG Emissions (gCO2e/Km)	approx,900 (hybrid propulsion)	1,453(diesel propulsion) 1,023(hybrid propulsion)	2,099(diesel propulsion) 1,561(hybrid propulsion)	none	2,099(diesel propulsion) 1,561(hybrid propulsion)	none	none

Traditional buses that operate in mixed traffic lanes are usually subject to delays caused by traffic congestion, which reduces the appeal of bus transit. One of the possible solutions is using articulated buses and enabling dedicated (separated) lanes with elevated stops. Such a system called Bus Rapid Transit (BRT) has been proposed as a possible remedy for increasing the transit system's effectiveness since the 1970s with experiences such as those in Curitiba (Brazilian National Association of Urban & Transport, 2013) While BRT systems are less expensive than Rail alternatives, they are still cost-prohibitive for many transit agencies and inappropriate for many bus routes. Transit agencies need a low-cost alternative to BRT that can provide effective and efficient surface transit. Hence, various measures can be implemented to enhance bus as a transit choice, among others: (a) Improving travel time (waiting and on-vehicle time), (b) reducing the number of turning movements which affects lateral acceleration, (c) enhancing the smoothness of the ride, (d) controlling air quality and temperature while waiting and riding. All these are of paramount importance to encourage transit ridership (Mohammadi, Amador-Jimenez, & Nasiri, 2019).

Making decisions to prioritize the before mentioned actions is not straight forward. For this reason, every municipality or county government has some planning that precedes budgeting (Government of Canada, 2019). The quality of the planning and budgeting process has a significant impact on the condition of the pavement network and on the life-cycle cost of maintaining it. However, planning often misses the ability to identify a schedule for the most cost-effective solutions. This can be solved by employing asset management techniques because they give tools to find the optimal by taking into consideration the most cost-effective solution. The current state of the practice has ignored such a connection between planning and asset management. Budget is scarce at most local governments requiring a rational allocation process that can help them maintain all transportation networks at acceptable levels of condition.

5.2.3 Travel Demand Modelling

According to the NCHRP Report 365 “Travel Estimation Techniques for Urban Planning”, travel demand modeling is roughly 55 years old (MARTIN et al., 1998) and the objective is to predict changes in travel behavior and transportation conditions, as a result of proposed transportation projects, policies, and future changes in socioeconomic characteristics of the users and land-use patterns.

Four-Step Modelling (FSM) approach has been used for many years by the vast majority of the researchers and the most common tool used for travel demand modeling (McNally, 2007). FSM is a multi-stage process in which several different techniques can be utilized at each stage, includes trip generation, trip distribution, modal split, and traffic assignment (Ortúzar & Willumsen, 2011). The trip Generation step tries to calculate the number of trips produced and attracted in each zone for a particular trip purpose based on information from each land use within the zone. The trip distribution stage of the four-stage tends to make interactions between the produced and attracted trips to form an origin-destination trip pattern. The model essentially produces a trip table know as Origin-Destination (O-D Matrix), which provides a comprehensive illustration of the number of trips between each zone in the study area. The mode choice attempts to predict how the trips will be divided among the available modes of travel. The final step of the four-step modeling process involves assigning the vehicle trips developed in the mode choice step to the road network. Such as highways, freeways, and roads within the locality of the area intended for modeling.

Further details and application of each step can be found in a trip generation (Abane, 2011; Javanmardi, Langerudi, Shabanpour, & Mohammadian, 2015; Moeckel, Fussell, & Donnelly, 2015; Paulssen, Temme, Vij, & Walker, 2014; Rich, Holmblad, & Hansen, 2009).trip distribution (Abdel-Aal, 2014; Celik, 2010; de Grange, Fernández, & de Cea, 2010; Karoonsoontawong & Lin, 2015).Mode choice (Abane, 2011; Javanmardi et al., 2015; Moeckel et al., 2015; Paulssen et al., 2014; Rich et al., 2009; van den Berg, Arentze, & Timmermans, 2011). The route choice or assignment stage, all the distributed traffic between the generation and distribution zones is assigned to the road network, Belimer developed a new traffic assignment considering dynamic behavior into macroscopic modeling. In this study, a detailed review of dynamic assignment on four case studies two in the Netherlands and two in Australia was conducted. (Bliemer, Raadsen, & De, 2013). Rasouli investigated the use of the neural network for traffic distribution and showed the accuracy of using Neural Network for trip distribution practices (Rasouli, 2018). Saleh, Tofigh, and Zahra proposed a mechanism that includes two phases to investigate the optimal route choice, which is considered challenging for Intelligent Transportation Systems (Yousefi, Abbasi, & Anvari, 2014).

Travel demand models are very data-intensive and require a significant amount of data regarding the information on individual travelers and their travel habits to acquire a precise picture of travel demand. Route choice studies used either stated preference surveys (Hess, Rose, & Polak, 2010; Lindhjem & Navrud, 2011) or revealed preference surveys (Origin-Destination survey). In this survey, people have been asked about what actions they have already taken. For example, What mode of transport did they use to go to work yesterday?". Additional information on factors affecting respondents' decisions may require in the RP surveys (Ramaekers, Reumers, Wets, &

Cools, 2013). Geographic Positioning Systems (GPS) technology is another form of revealed preference and is sometimes used to augment travel surveys (Stopher, FitzGerald, & Xu, 2007). The latest is often focused on GPS-collected data, and there is a growing interest in using GPS in Montreal as it can provide very detailed information on the routes used by drivers, so it is a good source of data for travel demand models specifically route choice (Papinski, Scott, & Doherty, 2009; TRB, 2018; Usyukov, 2017). Travel demand modeling in this paper is used to forecast the number of passengers for traditional buses on the island of Montreal.

5.2.4 Transportation Asset Management

Transportation Asset Management is a strategic and systematic process for the effective operation, maintenance, upgrade, and expansion of physical assets. While demand and resources are on the rise, different ways to allocate budgets across assets are being developed. TAM helps decision-makers define appropriate strategies for a particular serviceable condition over a given period. (Haas, Hudson, & Falls, 2015). Public and private agencies around the world, faced with the problem of keeping the network and existing infrastructure at an acceptable level of services to their people because of budgetary limitations. Therefore, it has been a shift in investments towards Maintenance and Rehabilitation (M&R) programs by governments rather than new construction (Federal Highway Administration, 2019).

Recently the Asset Management Plan 2012 – 2015 for Public Transport Network of Auckland provided a useful review of the main features desirable on an Asset Management Framework and among others identified the need to provide a productive, resilient and good quality transport network that is easy to use and reliable in terms of capacity and quality. In the capacity section AMS plan should cover the following criteria: reduce road peak congestion, public transport capacity to match demand, reduce or maintain journey time for public transport and finally reduce or maintain road journey time. In the quality, section assets should be in good condition.

The concept of transportation asset management is not new and has evolved from pavement management systems. In the mid-1960s, an effort was made throughout the entire world to develop a systematic approach in managing pavement infrastructures. Engineers have been managing pavements using management concepts for about two decades. It has never been a smooth ride in going through the process of implementing a pavement management system (PMS) within an organization. PMS is a planning process and a framework for decision-making to define cost-effective strategies to sustain a pavement network. PMS is an effective way of addressing the growing concern of managing high expectations of road users while taking into account budgetary constraints. Government agencies and municipalities use PMS to be able to understand the productivity of road infrastructure before developing the optimization and design studies for pavement investment strategies. The three main crucial components of PMS are database, pavement prediction models, and optimization tools and methods in order to establish cost-effective strategies for the evaluation and maintenance of roadway pavement.

The appropriate and effective pavement performance prediction (PPP) models need an updated database for the long-term analysis of PMS. The goal of the PPP models is to predict future conditions of pavement under real traffic and environmental conditions (Kulkarni & Miller, 2003). To define low-cost rehabilitation strategies that maintain desired pavement performance levels, accurate PPP models are required. Therefore, the type of PMS data depends on the municipality's objectives and the tool used. Many agencies incorporated GIS into PMS to store location-referenced spatial data for multiple data items connected to specific roadway links or nodes and reported information necessary for decision-making related to the pavement (Zhou & Wang, 2012).

An economic optimization model can identify different maintenance scenarios by identified optimal actions and schedules with budgetary constraints. The aim of such models is to maximize the benefits of budgetary and other relevant policy controls or to reduce the total costs according to predefined performance levels and agency goals. In the 1980s, few project-level decision optimization models were created. (Kulkarni & Miller, 2003b). Several optimization methods have been used in PMS, such as linear optimization (L. E. Amador-Jiménez & Mrawira, 2009), dynamic optimization (Fwa & Farhan, 2012), and genetic algorithm (Moreira, Fwa, Oliveira, & Costa, 2017).

5.2.5 Gaps in the literature

There is a vast amount of research to date that concentrates on developing travel demand models (TDM) to forecast the number of passengers of public transportation. Such prediction can play a significant role for planning the budget allocation of different transportation management strategies (TMS) headed towards reducing travel time since travel time one the most important factor for travelers and keeping pavements in the bus network as smooth as possible to encourage commuters to use more public transport rather than private transportation. However, research in TDM does not get used in TMS to support decisions towards the sustainable movement of people. This research fill-up this gap by developing a road management system that utilizes the results from a travel demand model.

5.3Overall objective

This paper extends Road Management Systems to consider the traditional bus system in order to enable a strategic allocation of resources to improve travel time and surface conditions on bus routes in order to have an effective Bus System which encourages users to shift from private to public transport.

5.4 Methodology

This study introduces a novel approach in which a travel demand model is connected to a road management system RMS to facilitate scheduling strategies and remedial works for the bus system in order to accomplish reduced travel times and improved surface for the bus routes.

The approach comprises four steps Figure 5-1 with the objectives of improving travel time and improving the bus network condition using a road management system:

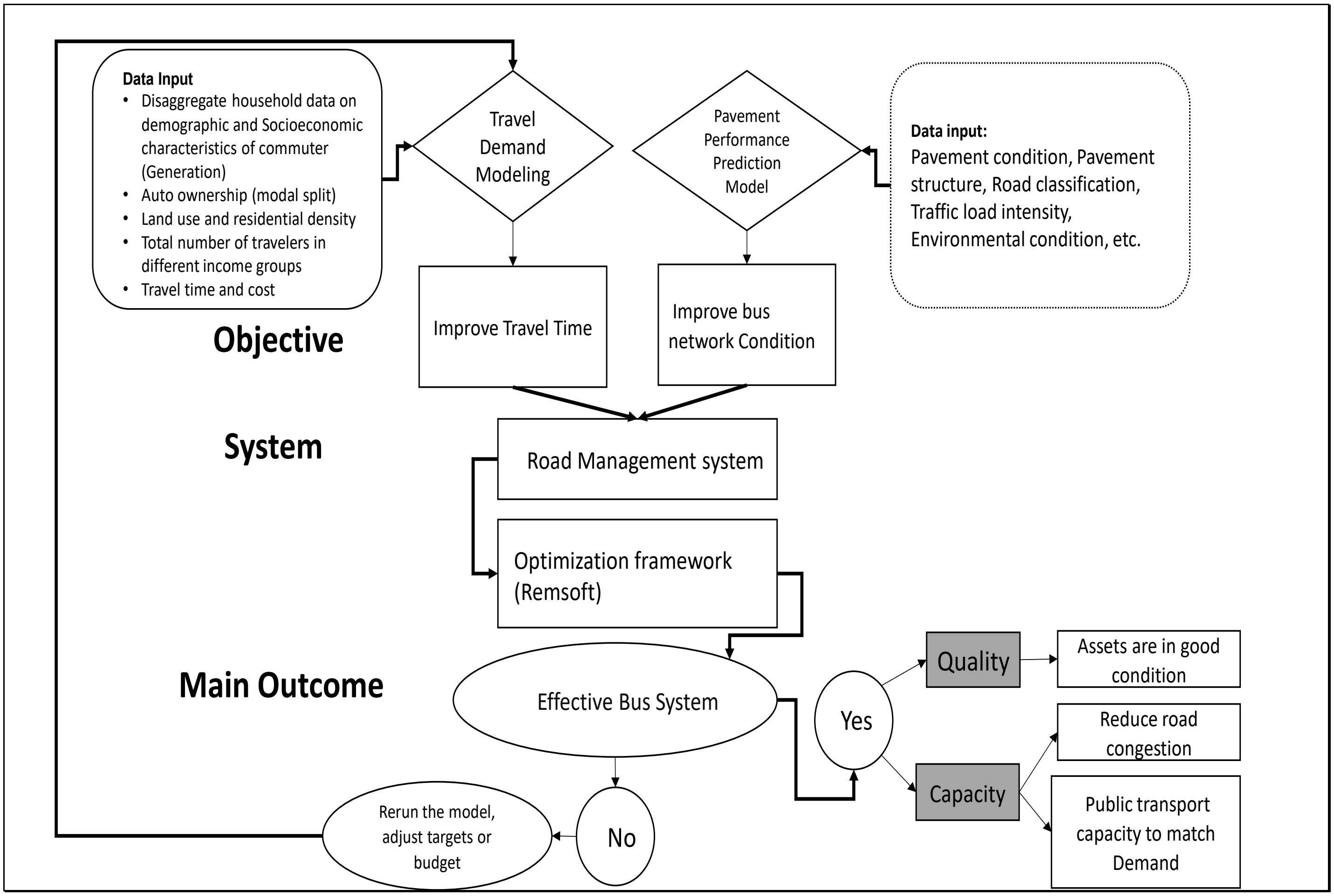


Figure 5-1 Methodology of linking travel demand with road management

1. The first step estimates travel demand (private cars and passengers on traditional buses). It uses data input from the sources given in Figure 5-1. Private cars are used to calibrate the network, given the absence of passenger counts data for Montreal. Travel demand in a number of passengers is then obtained and associated with road links used by buses. At the same time, passenger car units (PCU) volume is calibrated for the network. Overall travel time, speed and volume for the given level of congestion where estimated for each road link

2. The second step is the performance prediction model to simulate the deterioration decay on pavements. One model takes care of surface condition (IRI model) and the other of the pavement structure (Deflection Area Basin)
3. Within the road management system, it is required to identify countermeasures to enhance the convenience of riding in buses while upkeeping on a second level of priority the roads used by passenger cars exclusively.
4. The fourth step is the establishment of an optimization framework to handle decision-making. This is based on dynamic linear programming optimization, and that identifies the optimal sequencing of strategies and remedial works to be scheduled.

The main outcome of this process final step is an effective bus system where quality and capacity arrive at desired thresholds and provide the schedule of actions and progression of LOS. The inability to satisfy such thresholds should trigger adjustments on the VISUM model; however, this is left for future research. Further details of the travel demand and road management models are presented in the next section.

5.4.1 Travel Demand Model

Travel demand on the network was estimated on VISUM. The PTV group develops VISUM for travel demand modeling, traffic analysis, plan public transport services, and GIS data management. The software includes many functions related to network modeling, demand modeling (four-stage model), private and public transport assignment procedures. In this study, a network model of Montreal is used with a four-stage model implemented. The demand modeling estimated passengers on buses and passenger car units. The calculation of the model is a multi-stage process in which at each stage, several different techniques can be used. The function of each step in the model is shown below.

1. Trip generation (step one) serves to estimate the frequency of the origins or destinations for a specific trip purpose as a function of land use, demographics, and other socio-economic factors in each geographic zone.
2. Trip distribution (step two) provides a table with the number of trips between each pair of the geographic zones, based on how good a link between the zones is in terms of travel time.
3. Mode choice (step three) serves to estimate the percentage of trips between each zone using a specific mode of transport.
4. Trip assignment (step four) serves to identify how the traffic will distribute on the road network for each transportation system.

The following sections will present the travel demand model development for the case study in detail.

5.4.1.1 Data Input

The study area was divided into zones, which enable information about activities, travel, and households to be linked to the physical locations in the study area. In total 250 transportation analysis zones (TAZ) were created from Aggregate dissemination areas for the Greater Montreal Area from the 2016 Census (Statistics Canada) Shapefile containing TAZ boundaries were downloaded from the Statistic Canada imported into ArcGIS (ESRI 2016), and clipped to include the only Island of Montreal. The travel behavior data used in this study are obtained from the

Origin-Destination survey 2013 *Agence Métropolitaine de Transport* (*AMT)*, which contains detail information on the spatial and temporal distribution of travel behavior in the Montreal region considering people's characteristics, household attributes and time of trips. The data set contains 410741 active trips in total. Land use data 2016 *Communauté métropolitaine de Montréal* is also used, and Montreal territory has been divided into 11 main classes in this study, only three classes are considered Office, institutional, and commercial.

5.4.1.2 Trip Generation approaches in VISUM

Trip generation in VISUM is based on the different purposes of trips-person group combinations which depend on trip rates both for production and attraction. In this study, trip rates were calculated by the cross-classification method from O-D survey data to estimate the number of trip productions per household as a function of household attributes. Road users with similar mobility behaviors are grouped into person groups. Mobility behavior between age groups and income levels is very different, and these essential variables can be easily extracted from the available travel survey and demographic data. Based on the available data, the mobility groups; full time employed, part-time employed, students, different level of income Canadian dollars, and age. Activities are used in the day to explain the location of the population. Work, school, home, and other activities are going to be used. Activities are then combined to describe the purpose of the trip. Trip purposes used are Home-based work, Home-based school, and Home-based other.

Table 5-3 Trip rates for the different trip purpose from O-D survey

Person Group	Home-based work	Home-based Study	Home-based Other
Low Income ($30,000 or less)	1.324	1.711	2.064
Medium Income ($30,000 - $89,999)	1.569	1.659	2.455
High Income ($90,000 - $149,999)	1.859	1.711	2.764
Very High Income ($150,000 or more)	1.959	1.73	2.951
Full-Time employment	1.579	1.039	2.038
Part-Time employment	1.17	1.036	1.921
Student	1.085	1.687	1.724
0-14 years	1.05	1.592	1.7
15-64 years	1.66	1.322	2.313
65 over	1.228	1.079	2.099

A calculation of attraction per zone is needed to find out where the population in the study area is going. The Gross Floor Area (GFA) for different land-use groups measured in square meters and three categories have been considered regarding different trip purposes, institutional, commercial, and industrial and office area is available for this measurement in Montreal. Furthermore, to calculate the number of attractions, this basic measurement unit (floor area) needs to be multiplied with a trip rate. ITE trip rate has been implemented into the VISUM model for the attraction (*Trip Generation Manual, 10th Edition 2017*). The following Figure 5-2 shows the Montreal land use distribution.

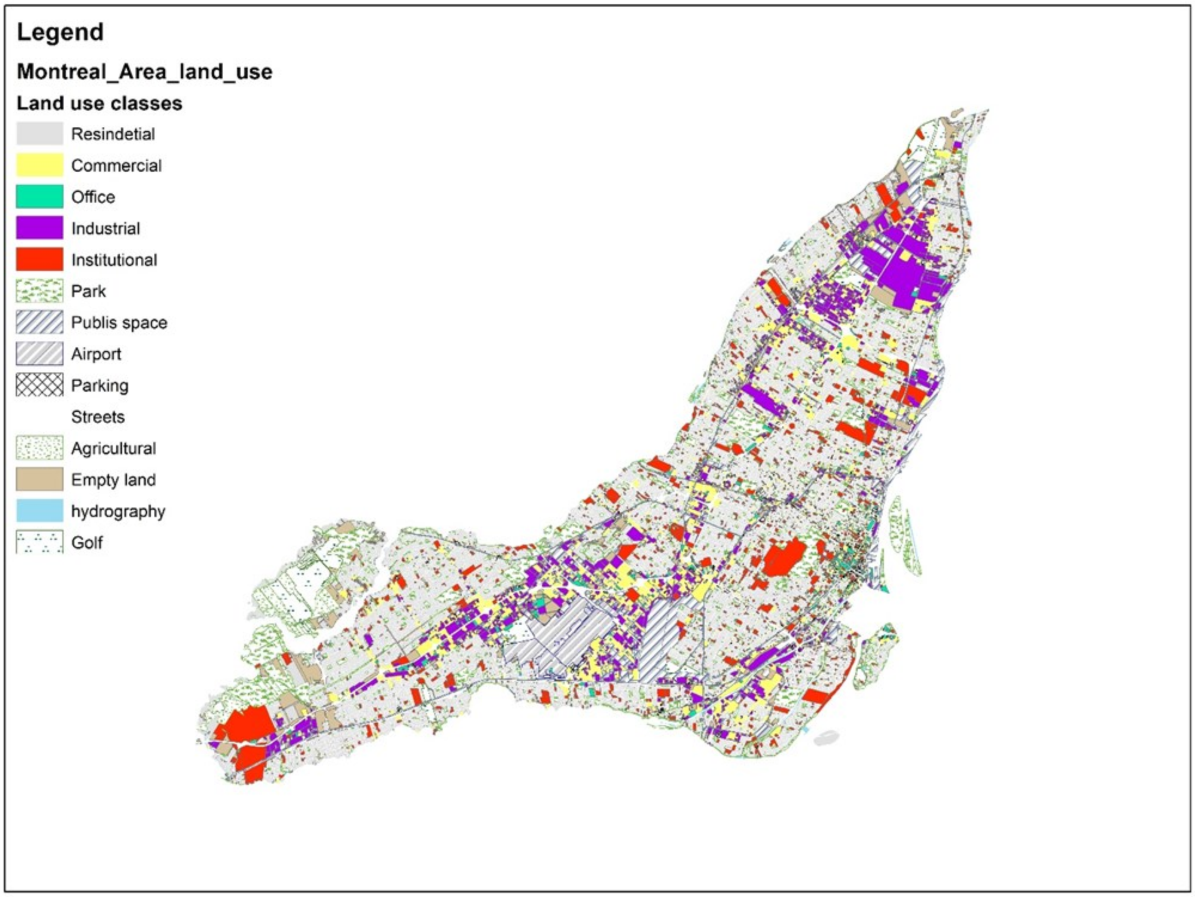


Figure 5-2 Montréal land-use area 2016 (*Communauté métropolitaine de Montréal*)

5.4.1.3 Trip Distribution approaches in VISUM

The production and attractions estimate from the trip generation stage were used to build a production and attraction matrix and were used to allocate trips between the TAZs. Trips are distributed between TAZs using the "gravity" model, which is implemented into the VISUM software. This gravity model is based on Newton's mass principle. The essence of the gravity model is that the relative attractiveness of trips between two pairs of TAZ's is directly proportional to the cross product of a measure of the propensity to create trips and inversely proportional to an impedance function.

The number of trips in a TAZ is used in the travel demand model to represent the mass size, and the travel time of the route is used to measure the friction factor (F) in the gravity model. The friction factor represents the willingness of travelers to choose a path when travel time increases; Travelers are gradually less likely to go on such long trips. The gravity model is calibrated by changing the friction factor parameters. In this study, the following Equation 5-1, called Gamma function is used for utility function, and friction parameters are different by trip purpose Table 5-4 and are based on guidance in NCHRP 716 Travel Demand Forecasting Parameters and Techniques (TRB, 2012). The more detail parameters per person group can be seen in Appendix.

$$\boldsymbol{F(U) = a * \left(U^{b}\right) * e^{cU}} \qquad \textbf{[5.1]}$$

Where:

U = travel time between zones

a,b and c = friction coefficients

Table 5-4 Gamma function parameters (NCHRP report 716)

Parameter	**Home-based work**	**Home-based non-work**	**Non-home-based**
a	26000	13000	260000
b	-0.265	-1.017	-0.791
c	-0.04	-0.079	-0.195

Trip distribution assigns productions (origins) to attractions (destinations) that generate matrices for the origin-destination. Such matrices of origin-destination are used in the steps of mode choice.

5.4.1.4 Mode choice approaches in VISUM

Mode choice analysis is the third major step of the travel demand modeling process. It is the step where step zone to zone person trips calculated in the previous step is split into trips using transit. In this study, private transport is a car, and public transport is the public bus system. A utility function calculates the degree of satisfaction that commuters obtain from their choices, and the generic cost associated with each choice is a disutility function. The most common approach in mode choice models is the generalized logit model. The model estimates the probability of choosing a particular mode for road users (MARTIN et al., 1998). For this study, the logit model was chosen. The primary basis of the decision was its popularity and easy access to information. Trips will be split into two modes: private and public transport. The generalized logit model is given in Equation 5.2 (NCHRP report 365, 1998).

$$\boldsymbol{P_i = \frac{e^{u^i}}{\sum_{i=1}^{k} e^{u^i}}} \qquad \textbf{[5.2]}$$

Where

Pi = the probability of a traveler choosing mode i,

Ui = a linear function of the attributes of mode i that describe its attractiveness, also known as the utility of mode i or impedance, and

$\sum_{i=1}^{k} e^{u^i}$ = the sum of the linear functions of the attributes of all the alternatives k, for which a choice is available.

The linear function of the attributes, or utility function $U_{i,}$ in order to calculate what mode road user will choose, a comparable unit of mode attractiveness is needed. Skim matrices will measure the unit of attractiveness or impedance. The program calculates this impedance between all the zones for each mode, in this case, is bus and car. The following tables show the utility functions that have been implemented in the model. The parameters are selected from Travel Demand Forecasting: Parameters and Techniques (NCHRP report 716) to multiply by skim matrices.

Table 5-5 Utility functions for Car (NCHRP report 716)

Trip Purpose	**Utility Function Car**
Study	$U_{car} = -0.0110*TT-0.0330*TC+1.51$
Work	$U_{car} = -0.0072*TT-0.0190*TC+1.51$
Other	$U_{car} = -0.0110*TT-0.0330*TC+1.51$

zones TT = Travel Time Skim matrix from one Zone to other

TC = Travel Cost Skim matrix from one Zone to other zones

Table 5-6 Utility functions for Bus (NCHRP report 716)

Trip Purpose	**Utility Function Car**
Study	$U_{bus}= -0.050*IVT-0.061*OWT-0.059*TWT-0.066*WKT-0.066*ACT-0.066*EGT -1$
Work	$U_{bus} = -0.050*IVT-0.081*OWT-0.040*TWT-0.058*WKT-0.058*ACT-0.058*EGT -1$
Other	$U_{bus} = -0.050*IVT-0.061*OWT-0.059*TWT-0.066*WKT-0.066*ACT-0.066*EGT -1$

IVT = In-vehicle time Skim matrix, OWT = Origin waiting time skim matrix, TWT = Transfer wait time skim matrix, WKT = walk time skim matrix, ACT = Access time skim matrix, EGT = Egress time skim matrix

Finally, the trip matrices for the modal share for the two vehicles are found. This is the final mode choice stage output. At this point, we get how many trips are made by different vehicle types between one zone and another.

5.4.1.5 Trip assignment approaches in VISUM

The assignment step is the fourth and last major step of the traditional four-step process, including both private car and public transportation of vehicle and passenger trips. The final output for this stage will be the amount of travel to be expected with a given transport system on each link in the network. VISUM contains six assignment method types. The equilibrium assignment approach is used in this analysis primarily because this method relies on capacity constraints as a generator of a network trip distribution.

Equilibrium assignment process can be divided into four steps: First, the line geographic file representing Montreal-area streets must be prepared; therefore, for this purpose, open street map data was used. Second, the network must contain the appropriate attributes of capacity, number of lanes, free-flow speed, and alpha and beta parameters according to the link type according to Table 5-7. Third, the traffic is assigned to the road network based on the initial travel time calculated according to free-flow speed. Forth, the number of trips assigned to each link is compared with the capacity of the link to determine the link that travel time was reduced.

Table 5-7 Road attributes by functional class

Road class	Functional class	Free-flow speed	Functional capacity per lane	Alpha	Beta
1	Freeway	100	1900	0.83	5.5
2	Primary highway	80	1500	0.71	2.1
3	Secondary highway	60	1200	0.71	2.1
4	Arterial Roads	50	900	0.6	2
5	Local Roads	40	400	0.6	2
6	Arterial provincial highways	50	900	0.6	2
7	Ramps	50	1400	0.83	5.5

The relationship between volume and travel time is defined by volume delay function. In this study, the standard BPR function is used in equation 5.3 to recalculate the new link travel time. Finally, the algorithm uses an iterative approach to reassign the volume to the network based on the new values. The iteration process continues until an equilibrium balance is achieved.

$$\boldsymbol{t = t_0 \left[1 + \alpha(\frac{V}{C})^{\beta}\right]} \qquad \textbf{[5.3]}$$

Where
t = loaded link travel time,
t_0 = free - flow travel time,
V = volume on the link,
C = capacity of the link, and
α, β = volume/delay coefficients

Finally, Equilibrium assignment is applied to simulate the average daily traffic on each road segment of Montreal City. Figure 5-3 shows the traffic assignment model output from VISUM.

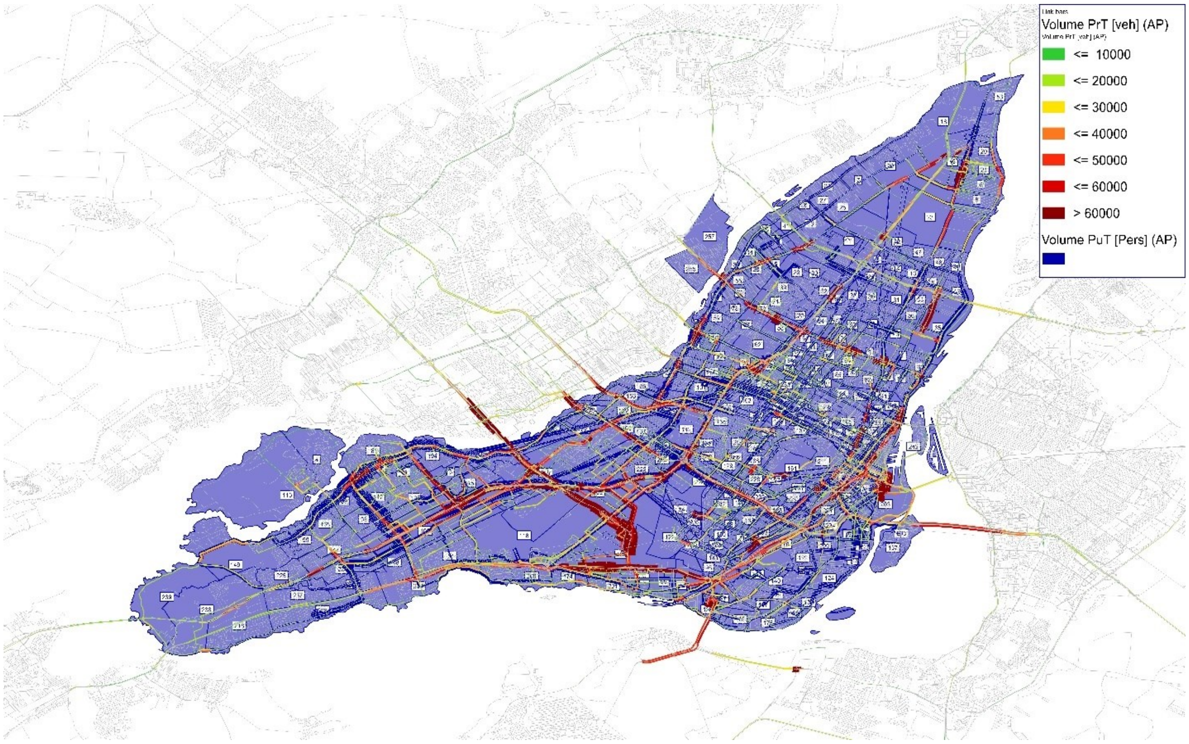


Figure 5-3 Traffic assignment output model from VISUM

5.4.2 Pavement deterioration models development

In the development of pavement deterioration, several factors could affect, for example, traffic loading, pavement structure such as number and thickness of layers, material types, soil strength, or environmental exposure conditions. In this study, for simplicity, traffic loading was used as the primary factor in the performance model. Traffic loading can be expressed in terms of equivalent single axle loads (ESALs). ESALs are generally accepted as a way to represent the damage to the pavement from its traffic loading. The International Roughness Index (IRI) was used as the indicator of pavement surface condition. Pavement surface condition data from road segments in Montreal for 2010 and 2015 were extracted from the city of Montreal open data portal and joined with the Montreal road network in ArcGIS software to develop the performance model. The performance model was developed according to a procedure proposed by Amador-Jiménez & Mrawira (2009, 2011). In this procedure pavement sections with similar characteristics such as pavement structure, environmental conditions, and traffic loading will be divided into sperate homogeneous groups. This helps improve the reliability of the performance model developed for long-term planning. Since the road absolute age data was not available, the IRI in 2010 was used to create homogeneous groups for pavement sections. Three-level of the condition were considered good, fair, and poor; also, traffic load intensity was divided into three levels: high, medium, and low. The following Table 5-8 is showing nine groups of pavements, corresponding to each pair of traffic-apparent age level.

The majority of roads in Montreal are in poor condition according to the criteria in Table 5-8, pavement surface condition is shown in Figure 5-4 in 2015. Since there are three levels of traffic load intensity, high, medium, and low, three Pavement Performance Prediction were developed corresponding to each level. Figure 5-5 shows the pavement deterioration for traffic loading and apparent age.

Table 5-8 Overview of Pavement group condition data, 2010-2015

Group	IRI 2010 rang (m/km)	Condition class	ESAL/year (10^4)	Mean 2010 IRI (m/km)	Mean 2015 IRI (m/km)
1	≤ 3	Good	>953	2.13	3.13
2	3-5	Fair	>953	3.30	4.31
3	> 5	Poor	>953	5.62	6.54
4	≤ 3	Good	389-953	2.12	3.24
5	3-5	Fair	389-953	3.24	4.28
6	> 5	Poor	389-953	5.60	6.60
7	≤ 3	Good	<389	2.12	3.21
8	3-5	Fair	<389	3.26	4.31
9	> 5	Poor	<389	5.57	6.60

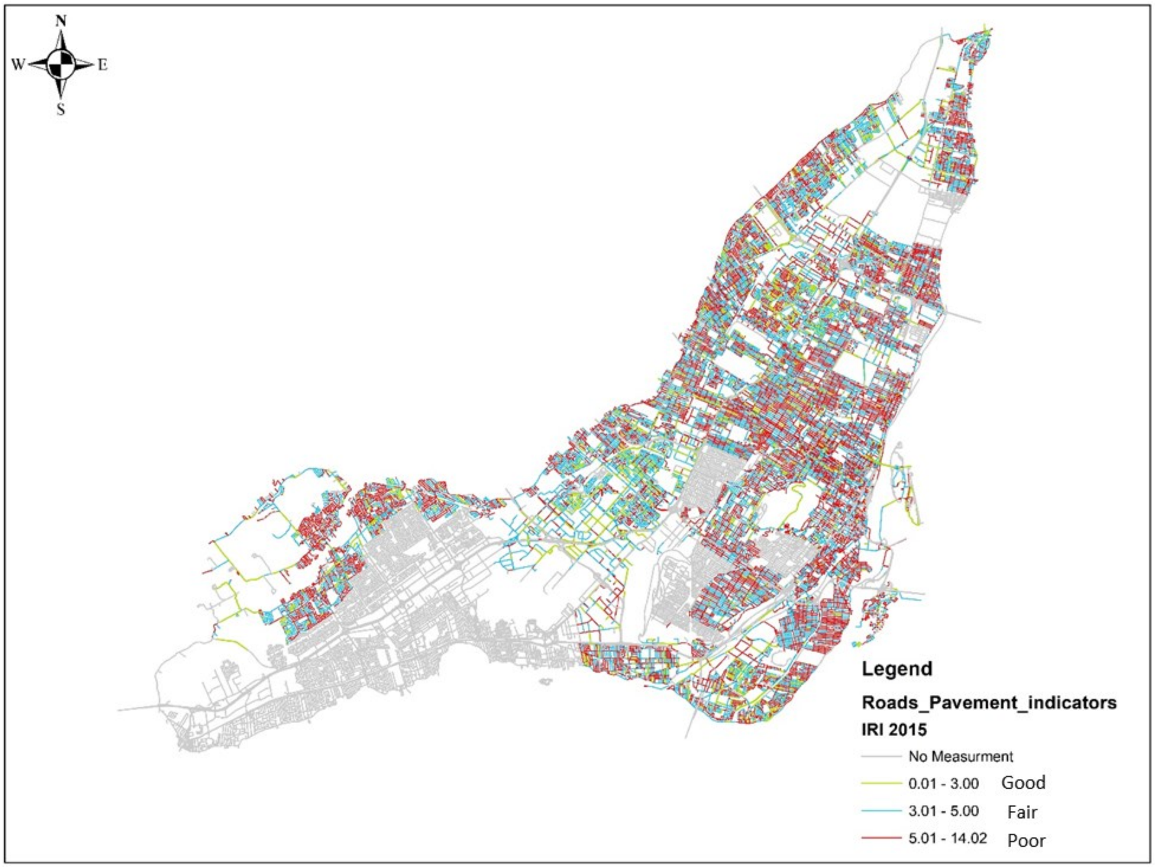


Figure 5-4 Pavement International roughness index 2015 – Montreal

5.4.3 Pavement Management System

Pavement management system (PMS) is an approach that includes an economic assessment of trade-offs between competing for alternatives to establish a decision-making system that includes an estimate of progressions of surface damage on roads on an accumulated number of ESALs based on current traffic levels. PMS mainly relies on mathematical programming and linear-optimization methods (Torres-Machí et al., 2014). Maintenance and rehabilitation actions to achieve an acceptable level of service at the network-level has been addressed (Md Shohel Reza Amin & Amador-Jiménez, 2015). In this study, goal programming, which is a branch of multi-objective optimization based on integer linear programming (ILP), is proposed to achieve a cost-effective allocation of the available budget.

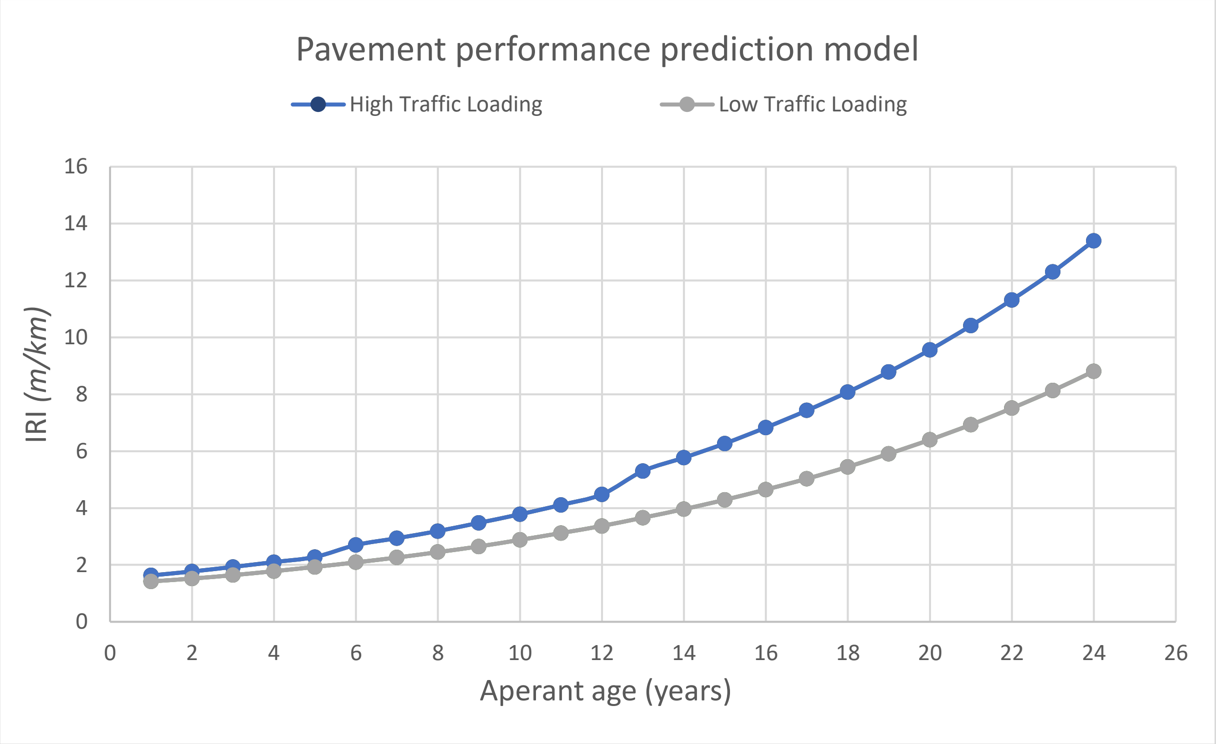


Figure 5-5 Pavement Performance Models

5.4.4 Decision-making system optimization algorithm and strategies

The decision-making system contained a definition of countermeasures to improve the condition of the surface of the pavement or its structure (when needed) as seen in Table 5-9.

Table 5-9 Treatments and Operational Windows Used in Network-level Trade-off Analysis

Treatment	**Operational Window**	**Cost (CAD$/lane-km)**	**Improvement in pavement condition**
Micro-surfacing (MS)	IRI < 2 m/km and AreaBasin >= 24	80,000	IRI = 1.4 m/km
Mill and overlay (MO)	Arterial: 2 <= IRI < 4 m/km and AreaBasin >= 24	175,000	IRI = 1.4 m/km
Resurfacing (RS)	IRI >= 4 m/km and 18 <= AreaBasin < 24	400,000	IRI = 1.4 m/km , AreaBasin = 30
Reconstruction (RC)	IRI >= 4 m/km and AreaBasin < 18	600,000	IRI = 1.4 m/km, AreaBasin = 30

Table 5-10 shows that congestion strategies have been defined into the optimization algorithm, and they applied whenever is needed based on the volume capacity ratio in a way to decreased travel time and congestion.

Table 5-10 Travel Demand Management (TDM)

Strategy	**Effectiveness**	**Applicable to**	**Cost**
Reversible Lanes	**Temporary** increase number of lanes (Lanes = N+1) and capacity (Capacity = (N+1)/N	Undivided carriageways	1 enforcement officer @ 5km, $50,000/5 = $10,000/km or 10$/m per year
Add lane (for all vehicles or exclusive for buses)	**Permanent increase** on number of lanes (Lanes = N+1) and corresponding increase in capacity (Capacity = (N+1)/N	2 lanes and more* (for academic purpose) Field investigation required	CAD$ 15,000 / km = $15/m
Truck Restrictions	truck percentage added back to new capacity	all	1 enforcement officer @ 5km , $50,000/5 = $10,000/km or $10/m per year

Note: *An identification of right of way available is necessary to narrow down the set of candidates for adding lanes.

Equation 5.4 was used to estimate Volume-capacity ratios (V/C). The travel demand model in the previous section estimated traffic volume, and road capacity has been defined in Table 5-7.

$$\text{Volume of Traffic / Segment Capacity} = V/C \text{ or VCratio} \qquad \textbf{[5.4]}$$

The formulation shown in Equation 5.5 was used to estimate current speed (Vcur) on any link.

$$S_{Current} = S_0 \left[1 + \alpha(\frac{V}{C})^{\beta}\right] \qquad \textbf{[5.5]}$$

Where

$S_{Current}$ = loaded link speed,

S = free - flow Speed,

V = volume on the link,

C = capacity of the link, and

α, β = are calibration constants obtained by an iterative process

A system of filters was used to classify the characteristics of relevance that would be used to prioritize focused attention of bus routes for better surface conditions, faster travel time, and serving most of the passengers. Table 5-11 shows the 18 filters used.

Table 5-11 Model optimization characteristics

Theme NO	**FILTER**	**Sample Elements**	**Brief Description**
Theme1	Number of lanes	1,2, 3,…,6	Effectiveness of adding lanes
Theme2	Truck percentage	10 = 10%, 11 = 11%, etc.	Effect on Truck restriction
Theme3	Terrain type	15, 25, 40	Effect on Truck restriction
Theme4	AADT	1000 - 300000	Congestion Level

Theme NO	**FILTER**	**Sample Elements**	**Brief Description**
Theme5	ESALS	Low Medium High	Pavement Deterioration
Theme6	Apparent Age (Deflection Area Basin)	Age 1 – 30	Pavement performance model
Theme7	Apparent age IRI	Age 1 – 30	Pavement performance model
Theme8	Starting Point	2 for everybody	Represent non-effectiveness
Theme9	Starting point	100 for everybody	
Theme10	Capacity	Volume of cars	Congestion Level
Theme11	Binary Variable	1 = candidate 0 = No candidate	Candidate for adding lane
Theme12	Binary Variable	1 = candidate 0 = No candidate	Candidate for HOV
Theme13	Binary variable division	1 = Divided, 0 = undivided	Divided or Undivided
Theme14	Speed (m/s)	-	Used to estimate travel time
Theme15	Passengers	Number of passengers in each link	Used to estimate travel time
Theme16	Bus route Identification	1 = Bus Route, 0 = Other	Priorizatior
Theme17	Length	-	Road segment length in meters
Theme18	Road Class	Local, Collector, arterial, freeway	Type of road

The decision-making support system had, at its core, an optimization algorithm that identifies the optimal scheduling of strategies and remedial works that accomplish the optimal value of the objective, including deviation (d) for the prescribed goal values (Equations 5.6 to 5.13). Negative deviations for IRI, v/c and travel time were encouraged, as well as a positive deviation for the Deflection Basin Area (Equation 5.6)

$$MIN\ \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}[W_{IRI}IRI - W_{DBA}DBA + W_{VC}VCratio + W_{TT}TT][d_{IRI}^{-} - d_{dba}^{+} + d_{vc}^{-} + d_{tt}^{-}]_i \qquad \textbf{[5.6]}$$

The following goals (G) where defined for the key performance indicators of interest (Equations 5.7 to 5.13).

$$G_1 = \sum_{t=1}^{T}\sum_{i=1}^{N} IRI_{ti} \leq \sum_{t=1}^{T}\sum_{i=1}^{N} IRI_{(t-1)i} \qquad \textbf{[5.7]}$$

$$G_2 = \sum_{t=1}^{T}\sum_{i=1}^{N} IRI\_bus_{ti} \leq \sum_{t=1}^{T}\sum_{i=1}^{N} IRI\_bus_{(t-1)i} \qquad \textbf{[5.8]}$$

$$G_3 = \sum_{t=1}^{T} \sum_{i=1}^{N} VCratio_{ti} \leq \sum_{t=1}^{T} \sum_{i=1}^{N} VCratio_{(t-1)i} \quad \textbf{[5.9]}$$
$$G_4 = \sum_{t=1}^{T} \sum_{i=1}^{N} VCratio\_bus_{ti} \leq 0.89 * \sum_{t=1}^{T} \sum_{i=1}^{N} VCratio\_bus_{(t-1)i} \quad \textbf{[5.10]}$$
$$G_5 = \sum_{t=1}^{T} \sum_{i=1}^{N} TravelTime_{ti} * passengers \leq 0.89 * \sum_{t=1}^{T} \sum_{i=1}^{N} TravelTime_{(t-1)i} * passengers \quad \textbf{[5.11]}$$
$$G_6 = \sum_{t=1}^{T} \sum_{i=1}^{N} \sum_{j=1}^{K} M_{t,j} x_{tij} \, L_i \leq B_t \quad \textbf{[5.12]}$$
$$G_7 = \sum_{t=1}^{T} \sum_{i=1}^{N} DBA_{ti} \geq 1.01 * \sum_{t=1}^{T} \sum_{i=1}^{N} DBA_{(t-1)i} \quad \textbf{[5.13]}$$

The Mathematical formulation herein presented is an expansion of that previously used formulation for optimizing M&A activities in a network of spatially distributed assets (Amin & Amador-Jiménez, 2015; Faghih-Imani & Amador-Jimenez, 2013; Li, Haas, & Huot, 1998). Such a previous optimization process attempted to achieve the objective while subject to constraints.

This formulation relied on the forward dynamic links of Equation 5.14, which support a decision tree containing all possible paths of pavement condition across time, after hypothetically receiving available strategies or remedial measures (Amador-Jiménez and Afghari, 2013; Amin and Amador-Jiménez, 2015; Faghih-Imani and Amador-Jimenez, 2013). This tree is based upon a transfer function used to estimate the updated value of a given key performance indicator (i.e., pavement condition IRI_{ti} or DBA) as a combination based on the decision variable (x_{tij}) and the effectiveness (E_{ij}) or deterioration (D_{it}) of the specific road segment on-time t (Equation 5.14 and 5.15).

$$IRI_{tij} = x_{tij} \left(IRI_{(t-1)ij} - E_{ij}\right) + (1 - x_{tij}) \left(IRI_{(t-1)ij} + D_{it}\right) \quad \textbf{[5.14]}$$

$$DBA_{itj} = x_{tij} \left(DBA_{t-1)ij} + E_{ij}\right) + (1 - x_{tij}) \left(DBA_{(t-1)ij} - D_{it}\right) \quad \textbf{[5.15]}$$

Travel demand was adjusted for those segments where truck restrictions were imposed (Equation 5.16). The capacity of a link was also affected whenever a reversible lane strategy was implemented (Equation 5.17) or adding a lane was added (Equation 5.18), otherwise capacity was kept intact (Equation 5.19).

$V_{tij} = x_{tij=truckrestriction} * V_{t0,i,j} * F1$ where F1=1-truck% if x=1, F1=1 otherwise and $V_{tij} = x_{tij\neq truckrestriction} * V_{t0,i,j}$ **[5.16]**

$C_{tij} = x_{tij=reversiblelanes} * F2 * C_{t0} * N$ **[5.17]**

where $F2 = \left(\frac{N+1}{N}\right)$ $for\ time = t\ only,$ when x=1, F2=1 otherwise

$C_{tij} = x_{tij=addlane} * C_{t0} * (N + 1)$ where N = number of lanes in one direction **[5.18]**

$C_{tji} = C_{t0}$*N where C_{t0} = capacity per lane on base year **[5.19]**

where
x_{tij} = 1 if treatment *j* is applied on road segment *i* at year *t*, 0 otherwise;
IRI_{it} = the pavement condition index for road segment *i* at year *t*;
$IRI_{i(t-1)}$ = the pavement condition index for road segment *i* at year (*t*-1);
IRI_{tij} = the pavement condition index of road segment *i* at year *t* for intervention *j;*
$IRI_{(t-1)ij}$ = the pavement condition index of road segment *i* at year (*t*-1) for intervention *j*;
M_{tj} = the cost (CAD$) of intervention *j* at year *t*;
L_i = the length (km) of road segment *i*;
E_{ij} = the improvement in terms of corresponding intervention units on road segment *i* from intervention *j*;
D_{it} = the deterioration on road segment *i* at time *t*;
B_t = the budget at year *t*;
I = the total number of road segments;
T = the total number of time periods; and
K = the total number of applicable treatments.

Current speeds were estimated based on the level of congestion for each link directly inside the decision-making software (REMSOFT) in order to capture the effect of temporary and permanent countermeasures and in the iteration process, the current speed will be affected by the updated value of V and C from the previous equations and used to estimate Equation 5.20 below from which travel time is estimated by dividing the road segment length over the current speed.

$$\textit{Travel time} = \textit{Travel time free flow}\ [1 + a * V/C^{\,b}]$$ **[5.20]**

5.5 Analysis and Results

A travel demand model was used to estimate the capacity and demand over each link. Links were classified as bus routes or not. Posted speed was adjusted, and link length used to estimate travel time. The product of the base year demand and capacity was feed into a decision support system called Woodstock from REMSOFT Inc., where the optimization model defined on Equations 5.7 through 5.20 was coded. The constants are shown on Equations 5.10 and 5.11 (0.89) and Equation 5.13 (1.01) force a minimum level of improvement from one year to the next one, and were found through an iterative process that reduced their values up until the algorithm hit the infeasible space.

Penalties for under accomplishment of VCratio, TT, IRI of Bus Routes were set to prioritize the attention of links used by buses over roads used by passenger cars. The results obtained from the goal programming showed a faster improvement of bus routes surface condition (IRI) as compared to the rest of the network.

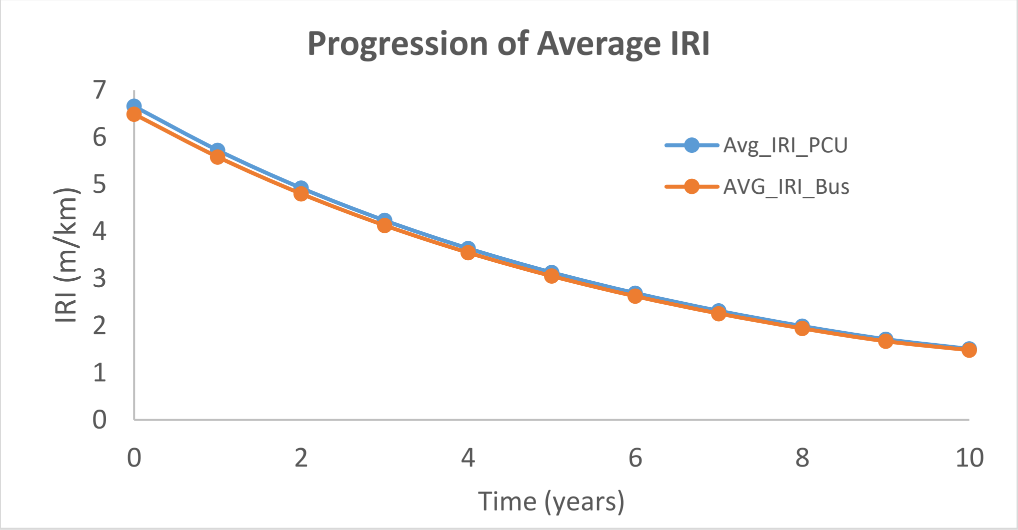


Figure 5-6 Progression of IRI

Similarly, the volume to capacity ratios (VC ratio) of bus routes and non-bus routes (i.e., used by passenger cars) show that daily values of congestion (VC ratio = 1.15) are observed on year zero for bus routes; meanwhile, roads used by cars observe much lower values of VC ratio (nearly 0.74). The implementation of reversible lanes, truck restrictions, and additional lanes aided bus routes to drop to similar levels of congestion as those experienced by non-bus roads.

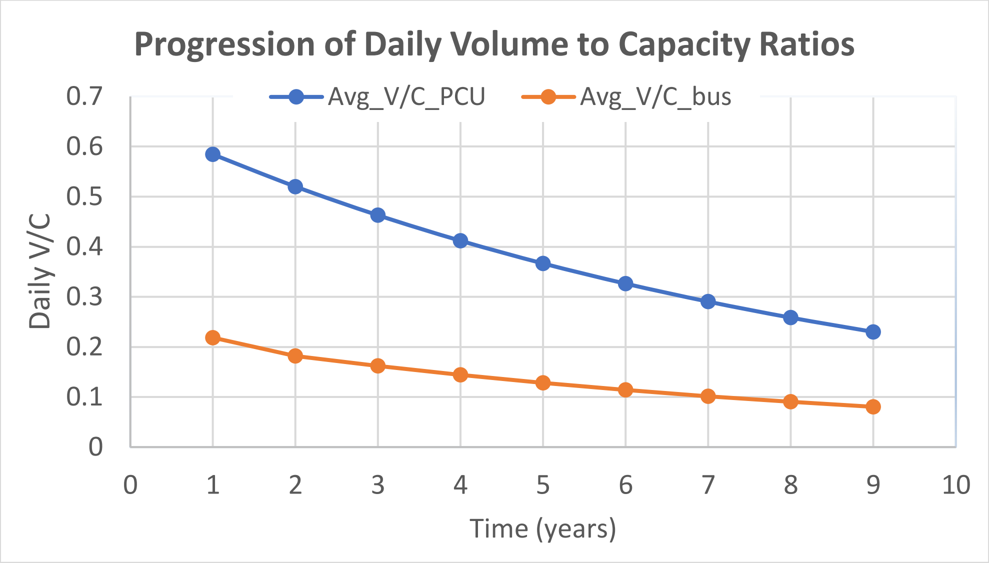


Figure 5-7 Volume to capacity ratios (VC ratios)

Allocation of the pavement surface and structure interventions can be seen in figure 5-8.

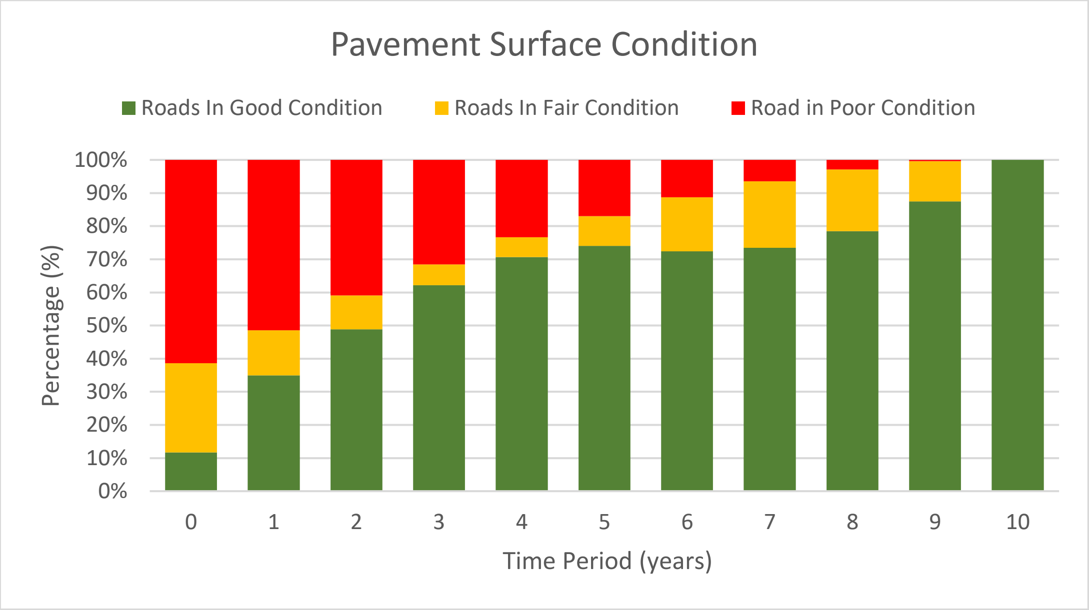


Figure 5-8 Strategies used for congestion

In terms of budget the allocation of strategies and interventions can be seen below in Figures 5-9 and 5-10. The preferred budget level is often left to the government managers but for this research is recommended as $30,000,000

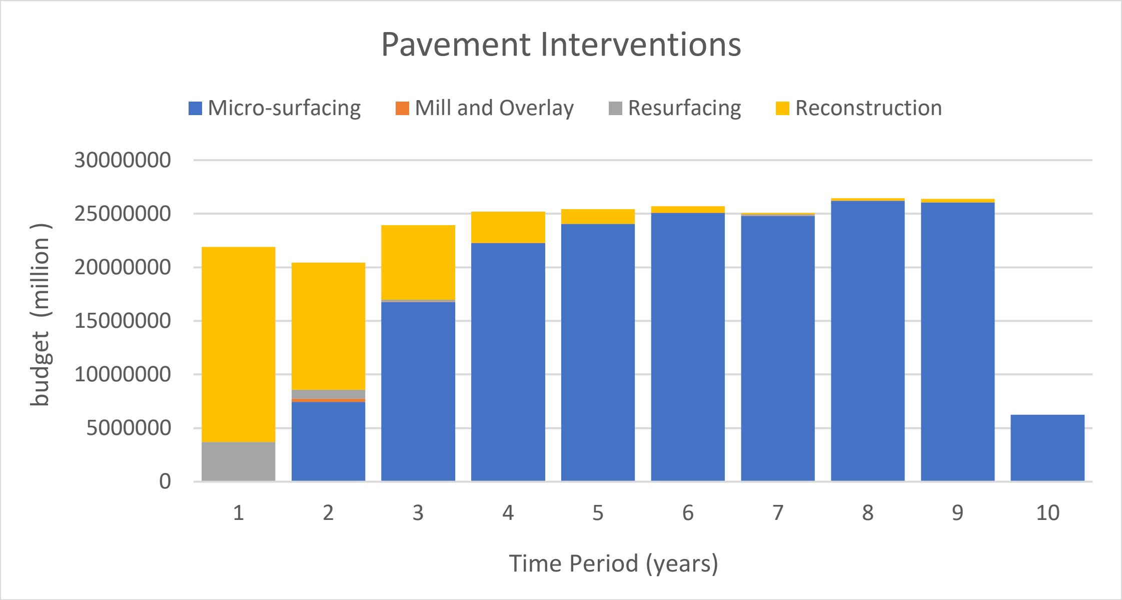


Figure 5-9 Budget allocation to pavement treatment

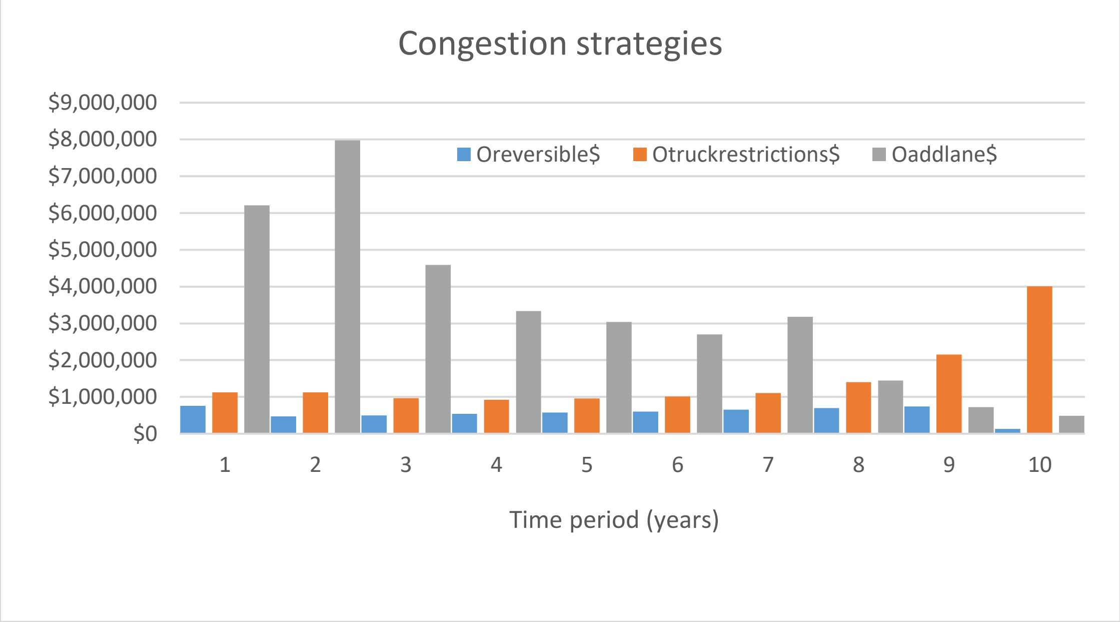


Figure 5-10 Budget allocation to congestion strategies

5.6 Chapter Conclusion

This study proposes an approach to incorporate travel demand into long-term planning of M&R activities of pavements at the network-level considering public transport (buses). This is in line with congestion strategies that have been adopted by several cities around the world to encourage more use of public transportation by reducing congestion levels and travel time on roads that are sharing the same road network as cars. Goal optimization was applied to address the conflicting objectives in the scheduling of interventions; reconstruction, major rehabilitation, preventive treatments, and upgrading. The model was able to reduce travel time significantly, along with the VC ratio. Also, the system was able to take care of the condition of the roads and keep it at an acceptable level of quality. The model dedicated significant resources for adding lanes and also spent consistently year by year on the other two strategies (truck restriction and reversible lanes) because such strategies benefited both cars and buses. Overall the model accomplished its goals: it improved pavement condition, reduced travel time, and reduced VC ratios. Even more, after ten years, the model reduced significantly the need to add lanes and concentrated on other operational strategies to manage congestion. However, only a static linkage was used between the travel demand and the management model. Future research must concentrate on developing a dynamic connection for the VC ratios, which in turn will benefit the travel time for public transportation.

Furthermore, this work employed the capabilities of travel demand models in representing the demand for the entire road network. The results show that implementing truck restrictions applies to the entire network. However, adding a lane and reversible lane is applicable only for some segments due to physical restriction and limited space in the network.

Chapter 6: General Conclusions

This research has presented an extension to road management systems by linking them to travel demand modeling. An approach was proposed to assists policymakers in scheduling strategies that encourage road users to shift from private automobiles into public buses by reducing travel time on the bus network and improving the quality of the ride with smoother surfaces.

The approach presented in this research can be extended in the future to include other modes of transportation, including Metro rapid transit, regional trains, cycling, walking, etc., following the development of travel demand models for such modes and connecting to their corresponding infrastructure management system. In addition, future research can expand and include vehicle operating costs induced by surface roughness, environmental impact from the operation, maintenance, and rehabilitation.

Linking travel demand models and Pavement management systems is feasible as demonstrated in the first case study, where a case study illustrates a simple static approach. In addition, PMS needed to be expanded to consider interventions to increase the network capacity and strategies to handle daily congestion issues. The first requires more significant capital investments, which will likely weaken the government's ability to upkeep infrastructure in general and services running well. Hence as shown on the results of the first case study, strategies are preferred to handle congestion as they are much cheaper and effective, returning increasing improvement of surface and structural condition for the network of pavements. However, these results are specific to the case study and may vary for other applications.

Overall, it was found that it is possible to share a common budget among pavement's M&R with the allocation of strategies to reduce the level of congestion, especially on the bus route without the need to increase the budget. As such, it was concluded that the approach can be tailored to handle improvements in any public transportation network (for the case study, the bus network) and that this will likely encourage more ridership.

As a consequence of the models, developer in this research, it is evident that initial models will likely require some degree of simplification and/or employ some assumptions in light of the data gaps. This is true for both the development and calibration of travel demand models and road management systems.

As recommended for future research, for the rail, cycle, or sidewalk management systems, there will be a need to secure minimum information related to the degree of deficiency, its dynamic behavior, and to characterize the strategies or actions that can be employed, their effectiveness and cost. In the future the system presented in this research should be expanded to consider the entire transportation system including future infrastructure schemes Fact network is incomplete mention some regions within island belong to other municipalities.

References

AASHTO. (2010). AASHTO LRFD Bridge Design Specifications. Inhttps://doi.org/10.1111/febs.12237

Abane, A. M. (2011). Travel behavior in Ghana: Empirical observations from four metropolitan areas. *Journal of Transport Geography*, *19*(2), 313–322. https://doi.org/10.1016/j.jtrangeo.2010.03.002

Abdel-Aal, M. M. M. (2014). Calibrating a trip distribution gravity model stratified by the trip purposes for the city of Alexandria. *Alexandria Engineering Journal*, *53*(3), 677–689. https://doi.org/10.1016/j.aej.2014.04.006

Abdul Majid, J., Sulaiman, M., Zailani, S., Shaharudin, M. R., Saw, B., Wu, C. L., … Challoumis, C. (2015). Deployment Strategies of Managed Lanes on Arterials. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, *16*(2), 39–55. https://doi.org/10.1377/hlthaff.2013.0625

Abu-Samra, S and Amador, L. (2019). *resilience preparedness-based optimization framework for water and combined sewer pipes : town of Kindersley*. *2056*, 1–10.

Advani, M., & Tiwari, G. (2006). Review of Capacity Improvement Strategies for Bus transit service. *Indian Journal of Transport Management*, *30*(4), 363–391.

Amador-Jiménez, L., & Amin, M. S. R. (2013). Simulating freight traffic between Atlantic Canada and québec to support pavement management on new Brunswick's regional highways. *Journal of Infrastructure Systems*, *19*(3), 343–350. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000126

Amador-Jiménez, L. E. (2011). Relating land use and transport modeling with transportation asset management. *T and DI Congress 2011: Integrated Transportation and Development for a Better Tomorrow - Proceedings of the 1st Congress of the Transportation and Development Institute of ASCE*, (Nams 2006), 957–965. https://doi.org/10.1061/41167(398)91

Amador-Jiménez, L. E., & Afghari, A. P. (2013). Non-monetized multi-objective decision-making system for road management. *International Journal of Pavement Engineering*, *14*(7), 686–696. https://doi.org/10.1080/10298436.2012.727995

Amador-Jiménez, L. E., & Mrawira, D. (2009). Roads performance modeling and management system from two condition data points: a Case study of Costa Rica. *Journal of Transportation Engineering*, *135*(12), 999–1007. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000074

Amador-Jiménez, L., & Mrawira, D. (2011a). Reliability-based initial pavement performance deterioration modeling. *International Journal of Pavement Engineering*, *12*(2), 177–186. https://doi.org/10.1080/10298436.2010.535538

Amador-Jiménez, L., & Mrawira, D. (2011b). Roads Performance Modeling and Management System from Two Condition Data Points: Case Study of Costa Rica. *Journal of Transportation Engineering*, *135*(12), 999–1007. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000074

Amador-Jimenez, L., & Willis, C. J. (2012). Demonstrating a correlation between infrastructure and national development. *International Journal of Sustainable Development and World Ecology*, *19*(3), 197–202. https://doi.org/10.1080/13504509.2011.644639

Amin, M. S. R. (2015). *Pavement Management Systems: Integration of Transportation Modeling, Land Use, Economy and Indicators of Development*. (October), 216.

Amin, M. S. R., & Amador-Jiménez, L. (2015). Pavement management with dynamic traffic and artificial neural network: a case study of Montreal. *Canadian Journal of Civil Engineering*, *43*(3), 241–251. https://doi.org/10.1139/cjce-2015-0299

Amin, Md Shohel Reza, & Amador-Jiménez, L. E. (2015). Pavement management with dynamic traffic and artificial neural network: A case study of Montreal. *Canadian Journal of Civil Engineering*, *43*(3), 241–251. https://doi.org/10.1139/cjce-2015-0299

Ashalatha, R., Manju, V. S., & Zacharia, A. B. (2013). Mode choice behavior of commuters in Thiruvananthapuram city. *Journal of Transportation Engineering*, *139*(5), 494–502. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000533

Beltrán, G., & Romo, M. (2014). Assessing artificial neural network performance in estimating the layer properties of pavements. *Ingenieria e Investigacion*, *34*(2), 11–16. https://doi.org/10.15446/ing.investig.v34n2.42158

Birdsall, J., & Hajdin, R. (2008). Vulnerability assessment of individual infrastructure objects subjected to natural hazards. *Transportation Research Circular*, (October), 339–355. Retrieved from files/3260/Birdsall and Hajdin - 2008 - Vulnerability assessment of individual infrastruct.pdf

Bliemer, M., Raadsen, M., & De, E. (2013). *working paper itls-wp-13-16 Requirements for traffic assignment models for strategic transport planning : A critical INSTITUTE of TRANSPORT and LOGISTICS STUDIES The Australian Key Centre in Transport and Logistics Management The University of Sydney*.

Booz Allen Hamilton. (2011). Relationships Between Asset Management and Travel Demand: Findings and Recommendations from Four State DOT Site Visits. *Growth (Lakeland)*.

Brazilian National Association of Urban, & Transport. (2013). *BRT Studies in Brazil*. Brazilian National Association of Urban Transport Companies - NTU.

Canadian Automobile Association. (2017). *Grinding to a Halt: Canada's Worst Highways*. 81. Retrieved from www.cpcs.ca

Carmona, M., & Sieh, L. (2008). Performance measurement in planning - Towards a holistic view. *Environment and Planning C: Government and Policy*, *26*(2), 428–454. https://doi.org/10.1068/c62m

Cascetta, E. (2009). Transportation Systems Analysis, Models and Applications. In *Transportation Research*. https://doi.org/10.1016/0041-1647(76)90008-3

Castiglione, J., Bradley, M., & Gliebe, J. (2014). Activity-Based Travel Demand Models: A Primer. In *Activity-Based Travel Demand Models: A Primer*. https://doi.org/10.17226/22357

Chaverri J., Ghobadpour R., Amador L., Alecsandru C. (2020). Demand modeling calibration for a developing country under limited data: challenges and opportunities of improvement. [*manuscript in progress]

Celik, H. M. (2010). The sample size needed for calibrating trip distribution and behavior of the gravity model. *Journal of Transport Geography*, *18*(1), 183–190. https://doi.org/10.1016/j.jtrangeo.2009.05.013

Charlotte, C., Helene, L. M., & Sandra, B. (2017). Empirical estimation of the variability of travel time. *Transportation Research Procedia*, *25*, 2769–2783. https://doi.org/10.1016/j.trpro.2017.05.225

Chin, M. J., Babashamsi, P., & Yusoff, N. I. M. (2019). A comparative study of monitoring methods in a sustainable pavement management system. *IOP Conference Series: Materials Science and Engineering*, *512*(1). https://doi.org/10.1088/1757-899X/512/1/012039

Chiou, Y. C., Jou, R. C., & Yang, C. H. (2015). Factors affecting public transportation usage rate: Geographically weighted regression. *Transportation Research Part A: Policy and Practice*, *78*, 161–177. https://doi.org/10.1016/j.tra.2015.05.016

Communaute Metropolitaine de Montreal. (2016). *Portrait of Greater Montreal - 2016 Edition*. (September). Online: http://observatoire.cmm.qc.ca/observatoire-grand-montreal/produits-cartographiques/donnees-georeferencees/

De Grange, L., Fernández, E., & de Cea, J. (2010). A consolidated model of trip distribution. *Transportation Research Part E: Logistics and Transportation Review*, *46*(1), 61–75. https://doi.org/10.1016/j.tre.2009.06.001

Duncan, C., Landau, S., Cutler, D., Alstadt, B., & Petraglia, L. (2012). Integrating transportation and economic models to assess the impact of infrastructure investment. *Transportation Research Record*, *2297*(617), 145–153. https://doi.org/10.3141/2297-18

Evren, G. (2005). *Transportation Planning Problems in*. 796–804.

Faghih-Imani, A., & Amador-Jimenez, L. (2013). Toward Sustainable Pavement Management. *Transportation Research Record: Journal of the Transportation Research Board*, *2366*, 13–21. https://doi.org/10.3141/2366-02

Federal Highway Administration. (2018). *Highway Safety Benefit-Cost Analysis Guide*.

Federal Highway Administration. (2019). *Integrating Asset Management into the Transportation Planning Process - A Case Study*. (May).

FHWA. (2018). *Computation Procedure for the Pavement Condition Measures*. (April).

France-Mensah, J., & O'Brien, W. J. (2019). Developing a Sustainable Pavement Management Plan: Tradeoffs in Road Condition, User Costs, and Greenhouse Gas Emissions. *Journal of Management in Engineering*, *35*(3), 1–13. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000686

Fwa, T. F., & Farhan, J. (2012). Optimal Multiasset Maintenance Budget Allocation in Highway Asset Management. *Journal of Transportation Engineering*, *138*(10), 1179–1187. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000414

Gao, L., Xie, C., Zhang, Z., & Waller, S. T. (2012). Network-Level Road Pavement Maintenance and Rehabilitation Scheduling for Optimal Performance Improvement and Budget Utilization. *Computer-Aided Civil and Infrastructure Engineering*, *27*(4), 278–287. https://doi.org/10.1111/j.1467-8667.2011.00733.x

Government of Canada. (2019). *Investing in the Middle Class – Budget 2019*. 1–460. Retrieved from https://www.budget.gc.ca/2019/home-accueil-en.html

Haas, R., Hudson, W. R., & Falls, L. C. (2015). Pavement Asset Management. In *Pavement Asset Management*. https://doi.org/10.1002/9781119038849

Hammond, P. J. C., & Dot, W. S. (n.d.). *REPORT 716 Travel Demand Forecasting: Parameters and Techniques*.

Han, D., & Kobayashi, K. (2013). Criteria for the development and improvement of PMS models. *KSCE Journal of Civil Engineering*, *17*(6), 1302–1316. https://doi.org/10.1007/s12205-013-0142-2

Hess, S., Rose, J. M., & Polak, J. (2010). Non-trading, lexicographic and inconsistent behaviour in stated choice data. *Transportation Research Part D: Transport and Environment*, *15*(7), 405–417. https://doi.org/10.1016/j.trd.2010.04.008

Horak, M., Sancton, A., Goswami, R., Ali, U., Horak, M. ;, Sancton, A. ;, … Umera, A. (2017). *Municipal Resource Guide to Leading Practices in Costs Savings*. Retrieved from https://ir.lib.uwo.ca/urbancentre-reportshttps://ir.lib.uwo.ca/urbancentre-reports/1

Husein, R. (2017). *Scholarship at UWindsor Travel Demand Modeling for London , Ontario , Canada ONTARIO , CANADA*.

Irfan, M., Khurshid, M. B., Bai, Q., Labi, S., & Morin, T. L. (2012). Establishing optimal project-level strategies for pavement maintenance and rehabilitation - A framework and case study. *Engineering Optimization*, *44*(5), 565–589. https://doi.org/10.1080/0305215X.2011.588226

J. Javid, R., & Jahanbakhsh Javid, R. (2018). A framework for travel time variability analysis using urban traffic incident data. *IATSS Research*, *42*(1), 30–38. https://doi.org/10.1016/j.iatssr.2017.06.003

Janssens, D., & Wets, G. (2005). *the Presentation of an Activity-Based Approach for*. *32*(november).

Javanmardi, M., Langerudi, M. F., Shabanpour, R., & Mohammadian, K. (2015). Mode Choice Modelling Using Personalized Travel Time and Cost Data. *14th Conference of International Association on Travel Behavior Research (IATBR)*, (2117).

Jeong, J. H., Lim, J. S., Suh, Y. C., & Nam, J. H. (2014). Development of performance criteria for Korean pavement warranty specifications. *Journal of Performance of Constructed Facilities*, *28*(2), 402–411. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000405

Amin, M. S. R., & Amador-Jiménez, L. E. (2015). *Pavement Management with dynamic traffic and ANN: a case study of Montreal*.

Karoonsoontawong, A., & Lin, D. Y. (2015). Combined Gravity Model Trip Distribution and Paired Combinatorial Logit Stochastic User Equilibrium Problem. *Networks and Spatial Economics*, *15*(4), 1011–1048. https://doi.org/10.1007/s11067-014-9279-x

Kittelson, W. K., Rouphail, N. M., Williams, B. M., & Zhou, X. (2011). Analyzing operational improvements as an alternative to traditional highway construction. *Transportation Research Record*, (2223), 18–25. https://doi.org/10.3141/2223-03

Kulkarni, & Miller. (2003a). *Past, Present, and Future*. (03), 65–71.

Kulkarni, R. B., & Miller, R. W. (2003b). Pavement Management Systems: Past, Present, and Future. *Transportation Research Record*, (1853), 65–71. https://doi.org/10.3141/1853-08

Li, N., Haas, R., & Huot, M. (1998). Integer Programming of Maintenance and Rehabilitation Treatments for Pavement Networks. *Transportation Research Record: Journal of the Transportation Research Board*, *1629*, 242–248. https://doi.org/10.3141/1629-27

Lindhjem, H., & Navrud, S. (2011). Using the internet in stated preference surveys: A review and comparison of survey modes. *International Review of Environmental and Resource Economics*, *5*(4), 309–351. https://doi.org/10.1561/101.00000045

Lucas, K., Marsden, G., Brooks, M., & Kimble, M. (2007). Assessment of capabilities for examining long-term social sustainability of transport and land use strategies. *Transportation Research Record*, (2013), 30–37. https://doi.org/10.3141/2013-05

MARTIN, W. A., MCGUCKIN, N. A., & Barton-Aschman Associates, L. (1998). *Report 365 Travel Estimation Techniques for Urban Planning*. Retrieved from http://www.nas.edu/trb/index,html

McNally, M. G. (2007). *The Four-Step Model*. https://doi.org/10.1108/9780857245670-003

MEHRAN, B., & NAKAMURA, H. (2009). Considering Travel Time Reliability and Safety for Evaluation of Congestion Relief Schemes on Expressway Segments. *IATSS Research*, *33*(1), 55–70. https://doi.org/10.1016/s0386-1112(14)60237-5

Mishra, S., Welch, T. F., & Jha, M. K. (2012). Performance indicators for public transit connectivity in multi-modal transportation networks. *Transportation Research Part A: Policy and Practice*, *46*(7), 1066–1085. https://doi.org/10.1016/j.tra.2012.04.006

Mitran, G., Ilie, S., & Nicolae, V. (2010). *The Calibration Of Macroscopic Transport Sub-models Through Traffic Counting*. 8. Retrieved from http://metrocount.com/downloads/science/ICTTE.pdf

Moeckel, R., Fussell, R., & Donnelly, R. (2015). Mode choice modeling for long-distance travel. *Transportation Letters*, *7*(1), 35–46. https://doi.org/10.1179/1942787514Y.0000000031

Mohammadi, A., Amador-Jimenez, L., & Nasiri, F. (2019). A multi-criteria assessment of the passengers' level of comfort in urban railway rolling stock. *Sustainable Cities and Society*, *53*(September 2018), 101892. https://doi.org/10.1016/j.scs.2019.101892

Moreira, A. V., Fwa, T. F., Oliveira, J. R. M., & Costa, L. (2017). Coordination of User and Agency Costs Using Two-Level Approach for Pavement Management Optimization. *Transportation Research Record: Journal of the Transportation Research Board*, *2639*, 110–118. https://doi.org/10.3141/2639-14

Múčka, P. (2017). International Roughness Index specifications around the world. *Road Materials and Pavement Design*, *18*(4), 929–965. https://doi.org/10.1080/14680629.2016.1197144

National Research Council Transportation Research Board. (2000). HCM 2000, Highway Capacity Manual. In *Freeway Facilities, Adverse Weather Capacity Reduction*.

Ortúzar, J. de D., & Willumsen, L. G. (2011a). Modelling Transport. In *Modelling Transport*. https://doi.org/10.1002/9781119993308

Ortúzar, J. de D., & Willumsen, L. G. (2011b). Modelling Transport. In *Modelling Transport*. https://doi.org/10.1002/9781119993308

Papageorgiou, M., Diakaki, C., Dinopoulou, V., Kotsialos, A., & Wang, Y. (2003). Review of road traffic control strategies. *Proceedings of the IEEE*, *91*(12), 2043–2065. https://doi.org/10.1109/JPROC.2003.819610

Papinski, D., Scott, D. M., & Doherty, S. T. (2009). Exploring the route choice decision-making process: A comparison of planned and observed routes obtained using person-based GPS. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(4), 347–358. https://doi.org/10.1016/j.trf.2009.04.001

Paulssen, M., Temme, D., Vij, A., & Walker, J. L. (2014). Values, attitudes and travel behavior: A hierarchical latent variable mixed logit model of travel mode choice. *Transportation*, *41*(4), 873–888. https://doi.org/10.1007/s11116-013-9504-3

PTV AG. (2018). *PTV VISUM 18, Manual*. 3054.

Ramaekers, K., Reumers, S., Wets, G., & Cools, M. (2013). Modelling Route Choice Decisions of Car Travellers Using Combined GPS and Diary Data. *Networks and Spatial Economics*, *13*(3), 351–372. https://doi.org/10.1007/s11067-013-9184-8

Rasouli, A. (2018). *Calibrating the Distance-Deterrence Function for the Perth Metropolitan Area*. (January). Retrieved from https://espace.curtin.edu.au/handle/20.500.11937/59663

Recommendations, P., Secretary-general, U. N., Group, H. A., & Transport, S. (2016). Transport for Sustainable Development. *Transport for Sustainable Development*. https://doi.org/10.18356/2c1884f4-en

Replogle, M., & Fulton, L. (2014). *A Global High Shift Scenario: Impacts and Potential for More Public Transit, Walking and Cycling With Lower Car Use*. (November). Retrieved from https://www.itdp.org/wp-content/uploads/2015/11/A-Global-High-Shift-Cycling-Scenario_Nov-2015.pdf

Rich, J., Holmblad, P. M., & Hansen, C. O. (2009). A weighted logit freight mode-choice model. *Transportation Research Part E: Logistics and Transportation Review*, *45*(6), 1006–1019. https://doi.org/10.1016/j.tre.2009.02.001

Roorda, M. J., & Miller, E. J. (2005). Assessing transportation policy using an activity-based microsimulation model of travel demand. *Proceedings, Annual Conference - Canadian Society for Civil Engineering*, *2005*, 1–10.

Saha, P., & Ksaibati, K. (2017). Developing an Optimization Model to Manage Unpaved Roads. *Journal of Advanced Transportation*, *2017*, 1–11. https://doi.org/10.1155/2017/9474838

Schrank, D. T. L., Tim Lomax, & Bill Eisele. (2019). 2019 urban mobility report. *Published by The Texas A&M Transportation Institute with Cooperation from INRIX*, (August), 4–7.

Shen, Q., Chen, P., & Pan, H. (2016). Factors affecting car ownership and mode choice in rail transit-supported suburbs of a large Chinese city. *Transportation Research Part A: Policy and Practice*, *94*, 31–44. https://doi.org/10.1016/j.tra.2016.08.027

Sociéte de transport de Montréal. (2010). Strategic Plan 2020. *Wines of Chile*, (November), 1–120.

Stopher, P., FitzGerald, C., & Xu, M. (2007). Assessing the accuracy of the Sydney Household Travel Survey with GPS. *Transportation*, *34*(6), 723–741. https://doi.org/10.1007/s11116-007-9126-8

Street, D. S., Adamson, P., Yo, Y., & Hoy, S. (2005). Final report Final report. *The National Audit of Violence (2003 - 2005)*, (May), 1–74.

Texas Transportation Institute. (2005). Final report of the safety assessment of methacrylate ester monomers used in nail enhancement products. *International Journal of Toxicology*, *24 Suppl 5*, 53–100. https://doi.org/10.1080/10915810500434209

The California State University. (2019). *CSU Fact Book 2019*. 23. Retrieved from https://www2.calstate.edu/csu-system/about-the-csu/facts-about-the-csu/Documents/facts2019.pdf

Tighe, S., Li, N., Falls, L. C., & Haas, R. (2000). Incorporating road safety into pavement management. *Transportation Research Record*, (1699), 1–10. https://doi.org/10.3141/1699-01

Torres-Machí, C., Chamorro, A., Videla, C., Pellicer, E., & Yepes, V. (2014). An iterative approach for the optimization of pavement maintenance management at the network level. *TheScientificWorldJournal*, *2014*, 524329. https://doi.org/10.1155/2014/524329

Transportation Research Board. (2000). Highway capacity manual 2000 (HCM 2000). In *Environmental Protection*. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000746.

TRB. (2018). Cell Phone Location Data for Travel Behavior Analysis. *Cell Phone Location Data for Travel Behavior Analysis*, 0–4. https://doi.org/10.17226/25189

Trip Generation Manual, 10th Edition © 2017. (2018). 0–12.

Uddin, W. (2005). Pavement management systems. In *The Handbook of Highway Engineering*. https://doi.org/10.1201/b17219-35

Unidas, N. (2003). Traffic Congestion - The Problem and How to Deal with it. In *United Nations : Economic Commission for Latin America and the Caribbean, Deutsche gesellschaft für Technische Zusammenarbelt (GTZ) GmbH* (Vol. 1). https://doi.org/10.1017/CBO9781107415324.004

Usyukov, V. (2017). Methodology for identifying activities from GPS data streams. *Procedia Computer Science*, *109*(2016), 10–17. https://doi.org/10.1016/j.procs.2017.05.289

Van Dam, Thomas J., John Harvey, Stephen T. Muench, Kurt D. Smith, Mark B. Snyder, Imad L. Al-Qadi, H. O. et al. (n.d.). *Towards Sustainable Pavement Systems :*

van den Berg, P., Arentze, T., & Timmermans, H. (2011). Estimating social travel demand of senior citizens in the Netherlands. *Journal of Transport Geography*, *19*(2), 323–331. https://doi.org/10.1016/j.jtrangeo.2010.03.018

Vanier, D. J., & Rahman, S. (2004). *MIIP Report : A Primer on Municipal Infrastructure Asset Management*. 71. https://doi.org/10.4224/20377283

Ville de Montréal. (2018). *plan local de déplacements*.

Wang, T., Gan, A., & Alluri, P. (2013). Estimating annual average daily traffic for local roads for highway safety analysis. *Transportation Research Record*, *5*(2398), 60–66. https://doi.org/10.3141/2398-07

Webb, M., Fulton, G. A., Ph, D., Grimes, D. R., Ph, D., Lisa, M., … Arbor, A. (2008). *Evaluating the Economic Benefits to Michigan of Alternative Road-Bridge Investment Mixes FINAL REPORT Prepared for Michigan Department of Transportation Prepared by Institute of Labor and Industrial Relations RC-1518 Evaluating the Economic Benefits to Mi*. (March).

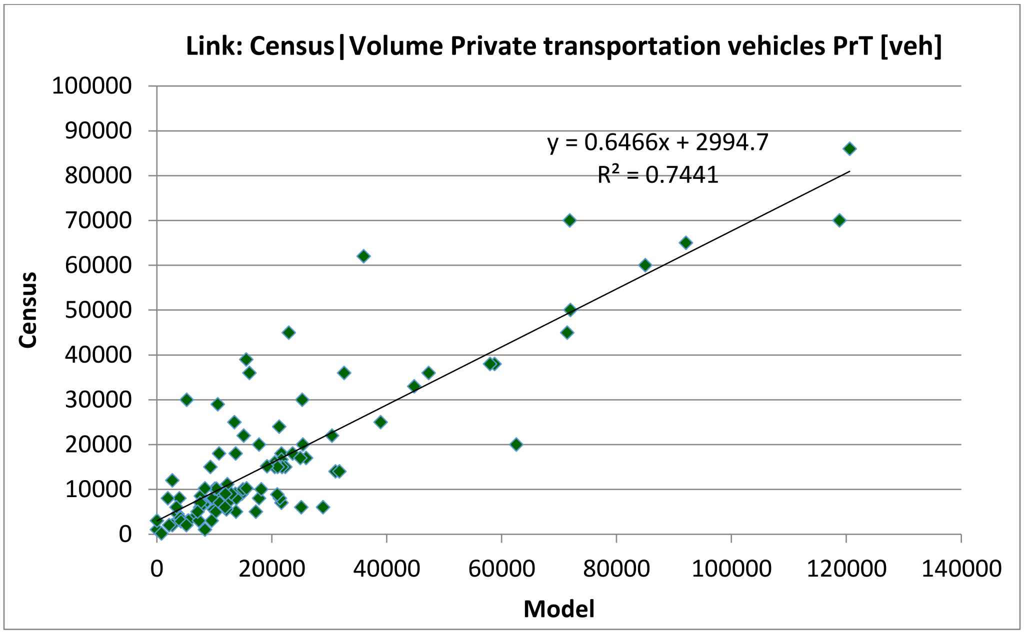
Yousefi, S., Abbasi, T., & Anvari, Z. (2014). Transportation routing in urban environments using updated traffic information provided through vehicular communications. *Jiaotong Yunshu Xitong Gongcheng Yu Xinxi/Journal of Transportation Systems Engineering and Information Technology*, *14*(5), 23–36. https://doi.org/10.1016/s1570-6672(13)60142-7

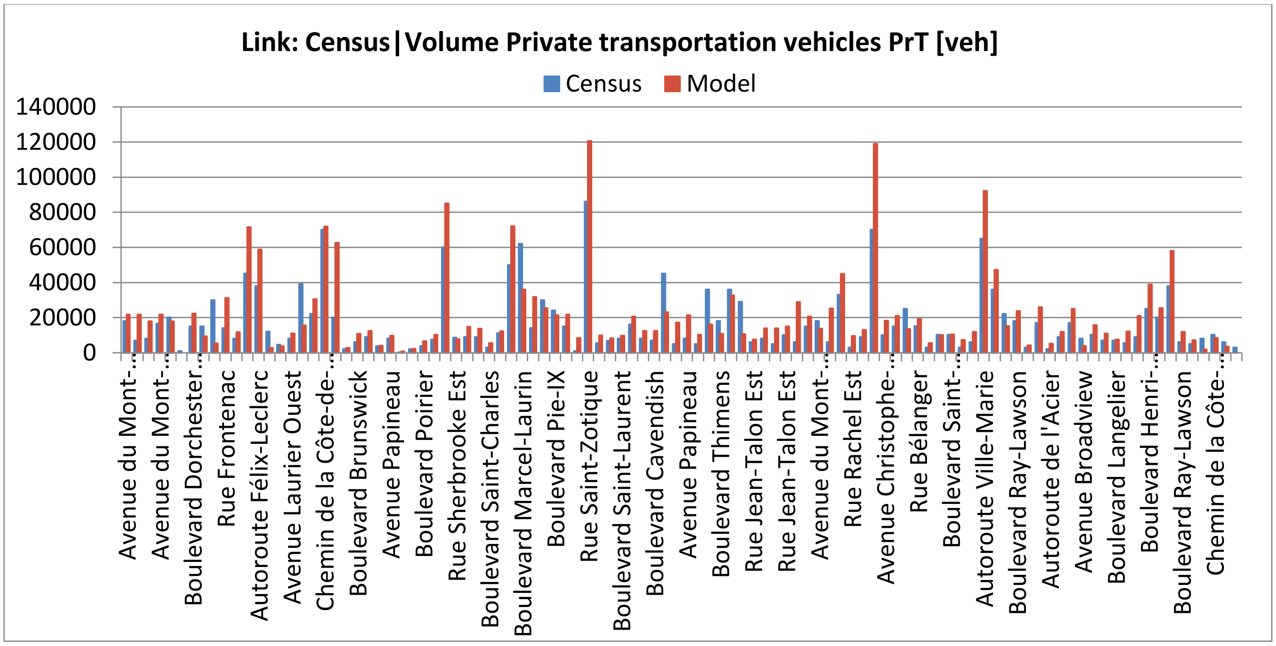
Zenina, N., & Borisov, A. (2014). Regression Analysis for Transport Trip Generation Evaluation. *Information Technology and Management Science*, *16*(1). https://doi.org/10.2478/itms-2013-0014

Zhou, G., & Wang, L. (2012). Co-location decision tree for enhancing decision-making of pavement maintenance and rehabilitation. *Transportation Research Part C: Emerging Technologies*, *21*(1), 287–305. https://doi.org/10.1016/j.trc.2011.10.007

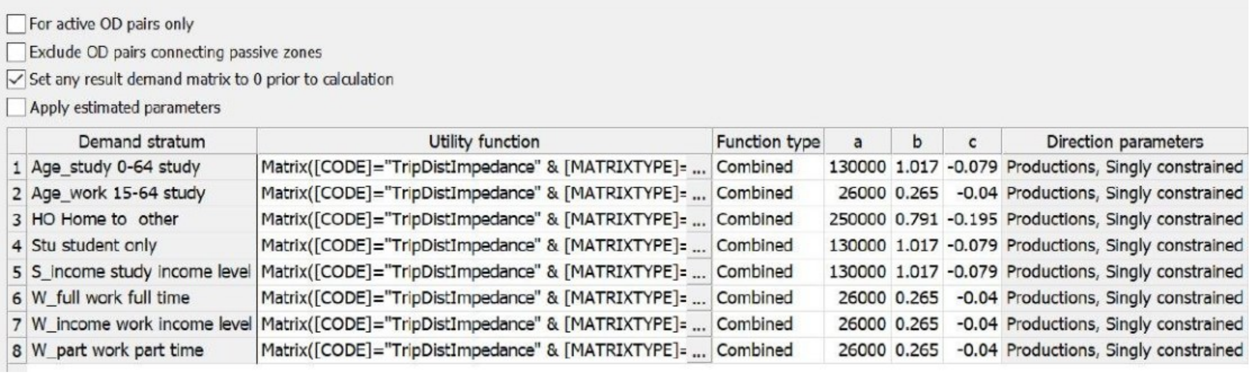
Appendix

Travel Demand model validation (Montral case study)





Gravity Model parameters for Montreal case study (NCHRP report 716)



☐ For active OD pairs only

☐ Exclude OD pairs connecting passive zones

☑ Set any result demand matrix to 0 prior to calculation

☐ Apply estimated parameters

	Demand stratum	Utility function	Function type	a	b	c	Direction parameters
1	Age_study 0-64 study	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	130000	1.017	-0.079	Productions, Singly constrained
2	Age_work 15-64 study	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained
3	HO Home to other	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	250000	0.791	-0.195	Productions, Singly constrained
4	Stu student only	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	130000	1.017	-0.079	Productions, Singly constrained
5	S_income study income level	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	130000	1.017	-0.079	Productions, Singly constrained
6	W_full work full time	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained
7	W_income work income level	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained
8	W_part work part time	Matrix([CODE]="TripDistImpedance" & [MATRIXTYPE]= ...	Combined	26000	0.265	-0.04	Productions, Singly constrained