

# BEDRIJFSECONOMISCHE WETENSCHAPPEN master in de verkeerskunde: mobiliteitsmanagement

(Interfacultaire opleiding)

# Masterproef

Sensitivity analysis of the public transport assignment algorithm in omnitrans

Promotor : Prof.dr.ir Tom BELLEMANS

Joseph Asonganyi Masterproef voorgedragen tot het bekomen van de graad van master in de verkeerskunde , afstudeerrichting mobiliteitsmanagement



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# PREFACE

Public transport in modern life is becoming a more and more sustainable transport mode than the private car. It permits people to move from one country to another in its various forms. The demand to use public transport is high at some periods of the day, week, month or even year. The supply of public transport services is limited at some moments or inappropriately distributed to the market. The task nowadays for public transport companies is to provide an efficient public transport service. This is only possible if enough information is available on the demand for public transport services at specific moments. Decision-making is therefore a strategic tool for public transport companies. Hence, scientific researches such as carried out in this master thesis are of great importance to public transport companies because they will aid decision-making. This master thesis is written, not only as a requirement for a MSc. in transportation sciences, mobility management but also as a tool to aid scientific research. The topic 'Sensitivity analysis of public transport assignment algorithm in OmniTRANS' was selected for this purpose.

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#### SUMMARY

Good decisions are very much needed in the day-to-day running of public transport companies. Decisions made especially in providing efficient public transport services are often long-term investment-based needing short-term demand driven solutions. It is necessary to back these decisions by tangible analysis or information. This thesis topic "sensitivity analysis of public transport assignment algorithms in OmniTRANS" seeks to help in transit assignment by providing information that will or may improve the operation of public transport companies and more specifically for Flanders, Belgium. Just as all changes produce effects, which could be negative or positive, big or small, there is often the problem of understanding the extent to which these effects can be evaluated and used for the good of humanity. Sensitivity analysis is a study in which the effects of changing weights (values) of model parameters or variables are evaluated.

In this master thesis, a partial sensitivity analysis is performed on the parameters of the generalized cost function, the access stop choice model and the transit line choice model as used in OmniTRANS. This is to know if these parameters have an impact on transit assignment. Transit assignment is defined as the manner in which a given origin–destination transit demand is assigned to the various transit routes of this origin-destination pair in order to minimize passenger travel cost. A literature review carried out in the first part of this thesis demonstrates that transit assignment. The algorithm of the Method of Successive Averages (MSA) is recently gaining grounds in transit assignment modeling. This algorithm is used in OmniTRANS for transit assignment.

The data input for the sensitivity analysis is a detail transport network of Flanders-Belgium including transit lines. The data was simulated for a Monday at 8 o'clock but for the partial sensitivity analysis, only transit modes were dealt with, 'walk' was considered the only access-egress mode, and the number of 'transfers' were limited to a maximum of two. The partial sensitivity analyses were performed in OmniTRANS using an all or nothing transit assignment method for the said network.

For the parameters of the transit generalized cost function as used in OmniTRANS, the results showed that as more and more weights (value) are associated to the travel distance ( $\alpha$ m) and the travel time ( $\beta$ m) parameters, the percentage number of transfers, passenger travel distance as well as the percentage travel time keeps on decreasing while the percentage access-egress distance and number of passengers showed an increasing trend. On the other hand, as more and more weights are being associated to the waiting time ( $\gamma$ m) and penalty

 $(\delta m)$  parameters, the percentage number of passengers and the access-egress distance showed a decreasing trend while the percentage passenger travel distance, travel time and number of transfers kept increasing. The parameter value for transit fair ( $\in_m$ ) was not included in the analysis because there was no information in the dataset with regard to it.

Considering average effects on the parameters of the generalized cost function, the travel distance parameter proved to have more influence on other transit assignment outputs (at least 70%) and for the percentage average number of transfers (35%). Though this fact has been established, it should be noted that the combine effect of other factors might outweigh this factor especially as no interaction effect was taking into account in performing the partial sensitivity analyses. In addition, all transit generalized cost factors had more than a 62% influence on the transit assignment output and at least 5% for the average percentage number of transfers.

More so, a partial sensitivity analysis of the access-stop choice model showed that, associating more and more weights to the logit scale factor of this model; the percentage travel distance, travel time, number of passengers, number of transfers, and the access-egress distance keep falling. The access-egress distance showed the highest percentage change (12.5%) meaning that, the logit scale parameter of the access-stop choice model affects more the access egress distance and least the number of transfers (1%). On average, the access-stop choice model proved to have at least 1% influence on all transit assignment outputs. The access-egress distance has the highest percentage effect (8%).

A partial sensitivity analysis of the transit line choice model was also performed in this thesis and the results obtained showed that the transit line choice model does not have any significant impact on transit assignment outputs of this network. There was no variation in these outputs as more and more weights were being associated to the logit scale factor of the transit line choice model. A conclusion could then be arrived at that, the logit scale factor of the transit line choice model may as well have an influence on transit assignment but that, transit assignment of this network is already working at an optimal level in such a way that no further modeling on the transit line choice is necessary.

Key words: Transit assignment, Sensitivity analysis, OmniTRANS.

# DEDICATION

To my sister ASONGASOH DORINE

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## **CHAPTER 1. INTRODUCTION**

# **1.1. Background.**

In real life situations, the supplies of public transport (transit services) are not often geared towards the demand of these services (Y. Zhang et al. 2010). Either more service is supplied at a particular place or time or both place and time or less of it is supplied for an existing transit demand. Transit assignment is an approach derived by public transport managers to model transit demand and supply by either adjusting transit demand to supply or otherwise adapting the supply to the demand (Fisher & Scherr 2009). The scope of transit assignment discussed in this thesis is limited to passengers or transit users and has nothing to do with vehicle assignment. All passengers when making their journeys make a choice of the route(s) to travel (Cepeda et al. 2006). The different routes of a given origin-destination pair often have different generalized cost of travel (Ortuzar & Willumsen 2005). All passengers strive to minimize this generalized cost of travel by choosing routes or journey-legs which are much cheaper (Horn 2003; Horn 2004). The travel cost components of a particular transit route may include: the travel time, the waiting time, the travel distance, the access-egress distance and the number of transfers to be made (Zou & L. X. Zhu 2011).

Transit assignment refers to the manner in which a given origin-destination transit demand is assigned to the transit route(s) of this Origin-Destination (OD) pair to minimize travel cost (Y. Liu et al. 2010). This is to say that, if 10people are travelling from zone A to Zone B using public transport mode (BUS, train, or light rail) and there are three possible routes to travel between zone A and B, transit assignment is the manner in which these 10people will be distributed amongst these various routes making sure that each person travels conveniently and at lowest generalized travel cost.

Transit assignment plays a very important role in transit demand modeling. For instance, it helps to distribute transit demand to the various routes of a given OD pair (N. Otto & Rasmus 2006). This type of transit demand modeling (transit assignment) has already been documented in many works though with diverse opinions or approaches (Cascetta et al. 1996; Lam et al. 2002; D'Acierno et al. 2002; G. Cantarella et al. 2010). The works of Cepeda et al. 2006; Horvath B. 2008; Schmöcker et al. 2010; Nuzzolo et al. 2011; explain some more details about transit assignment and are discussed in the first part of this thesis. Models and software development are very important in modern day transit assignment (Michael Florian 2008). Models constructed to deal with transit assignment get complicated with time giving the growth in complexity of transit demand and multi-modes (Meng et al. 1995; Otto 2000).

According to Horvath B. (2008), transit assignment and modeling are of prime importance in modern day public transport demand and supply analysis. It is now very necessary to increase the efficiency of public transport services based on the fact that existing road infrastructures are fixed and car usage is constantly increasing leading to road congestion, increase in travel cost and pollution (Leao & Elkadi 2011). Car usage, especially in large urban areas, puts more pressure on the demand for parking places, increases road congestion, and institute more pollution to the environment (Cipriani et al. 2012). Public transport can be a suitable option in urban areas to permit the movement of people in the city in a more sustainable way and at lesser social and economic costs (William & Zhou 2007; Beltran et al. 2009; Shimamoto et al. 2010). Despite the certain advantage of public transport over private cars, capacity restraint as well as time variation in transit demand make transit traffic an important issue to deal with (Mesbah et al. 2011). Public transport planners therefore use transit assignment models to forecast transit demand and to analyse the effect of increasing service performance, competitiveness and efficiency on transit demand (Euchi & Mraihi 2012; Wang et al. 2010). The desired level of comfort, quality, and speed are taken into account while modeling transit assignment.

The demand for transit services instigate a supply and both macro and micro approaches are vital (G. Cantarella et al. 2010; Mesbah et al. 2011). The disaggregate approach treats individual performances and characteristics (vehicle and users) while the aggregated approach considers average performances for vehicles on the supply side but groups of users with common characteristics (O-D pairs, departure time) on the demand side.

Transit assignment is an important tool of transit demand modeling. Software packages such as OmniTRANS, transit assignment models, sensitivity analysis are also vital elements in modeling transit traffic. The importance of some of these concepts is highlighted below. For instance, one of the reasons of devoting resources and knowledge in doing transit assignment modeling could be; to understand the variation of transit demand and to be able to put in place a sufficient supply to cope with this demand in space and time (UNESCO 2005). Alternatively, to plant transit infrastructure relative to the predicted service demand or better still, to improve transit planning (Schmöcker et al. 2010). Transit assignment could also be studied in order to test different scenarios before their implementation in real world. To know if these different scenario's produce the desired effects; for instance, increasing service frequency might definitely reduce passengers waiting times at stops, increase the number of passengers using this service line; or produce any unwanted effects: for example, an increase in service capacity resulting to increase congestion.

The need to use software packages such as OmniTRANS in transport modeling is an evidence of the fact that a job performed using a software package is more efficient than that done manually as errors and resources are minimized, and little time is spent using software packages to do operations. OmniTRANS just like TransModeler, PARAMICS, VISSIM, DYNASMART, DynaMIT, CONTRAM is an exceptional software package and as an added advantage, it is built to do transit assignment alongside other transport related modeling (Mahmassani 2001; Taylor 2003; Burghout 2004; Bekir et al. 2006; Jeihani 2007; Jelka et al. 2008; Lu et al. 2010; DTAlite 2012). With OmniTRANS, transit attributes such as the number of access and egress candidates, the number of transfers, the average travel time by passengers, the average travel distance, which are in-build components of the software package could easily be queried and can be compared between scenarios. OmniTRANS just like TransCAD, VISUM, TRANSIMS, EMME/2, QRS II, can do transit assignment (Yu et al. 2003; Horowitz 2004; Parveen Mily et al. 2007; Omnitrans 2011; (Q. Y. Li et al. 2011); Transcad 2012; PTV AG 2012).

The need to perform a sensitivity analysis on the parameters of the generalized cost function, the access-stop choice model and the transit-line choice model are to understand the extent to which transit assignment outputs are affected by the user-defined sizes of the parameters. Sensitivity analysis is an approach in which parameter values in a model are systematically studied to understand their effects on model outputs (Xu 2011). This is because different parameter weights will often produce different effects and may induce results to deviate from expectations. A good sensitivity analysis can then help in the development of policies related to transit traffic such as providing infrastructure, setting schedules, when appropriate values are identified.

With reference to the traditional four step model Ortuzar & Willumsen (2005), Bell et al. (2011) make mention of the importance of trip generation, trip distribution and modal split models in influencing trip assignment model. These models are related one to the other and one model sets the condition for the other (Zhong et al. 2009). For instance, 'the distributional model is conditional on the generation model while the mode choice model is conditional on the distribution model' (Jovicic & Hansen 2003). A recall on these models will certainly throw more lights to the core of this chapter on transit assignment.

# **1.1.1.** Trip Generation: production and attractions

The total number of trips made from an origin (home) to a destination (school, work, shop, and restaurant); trip production is dependent on a certain number of important factors. These factors amongst others may include the trip purpose or motivation (school, work), trip timing (Am peak, Pm Peak), duration and user characteristics such as age, car ownership, marital status (B. David et al. 2010). The zones that attract these trips also possess some important determining factors such as the accessibility, land-use pattern, opening hours of offices (Hyun-Mi & Mei-Po 2003; Konrad et al. 2005). Trip production and attraction are generally known as trip generation (Badoe & C.-C. Chen 2004). All the factors influencing trip generation are equally taken into consideration in transit assignment modeling.

# **1.1.2.** Trip distribution:

While trip generation models try to predict the number of trips produced and attracted by zones, trip distribution models help to explain the destination to any given set of origin trip or otherwise the origin to a given set of destination trip (Ortuzar & Willumsen 2005). Trip distribution models explain how the trips originating from one part of the network are distributed to other destinations of the network and vice versa. Models such as the growth factor model, gravity model are used here (Eric et al. 2011). It is important to note here that trip distribution modeling is also a vital aspect in the choice of the shortest path in trip assignment. This is simply because the assignment of trips to the network depends on the deterrence associated to each travel path and trip assignment seeks to outline possible paths as well as the least cost one (Shrewsbury 2012).

# 1.1.3. Mode choice

At the level of mode choice, many factors do influence the choice of a transport including that of using public transport. These may include amongst others the trip maker characteristics, income, trip length, family situation, transport system (quality, fare levels, accuracy of transit traffic, parking situation), and trip purpose (Michael Florian 2008). In case public transport mode is chosen to make a trip, transport researchers are interested to understand at what stop the passengers are boarding or alighting, which transit line they are using, in other to model their travel path and to provide a fluent service.

# 1.1.4. Trip Assignment

The trip assignment stage of the traditional four-step modeling analyses the problems of transport demand by offering the necessary supply. The problems of transport demand ranges from the demand of road space, problems associated to road accidents, congestion, pollution and most importantly the fluent movement of persons and goods from place to place (Smith 2008). Assignment models take into account transit demand (from origin – destination matrices), the transit network and the route preferences to model user's movement to their destinations, within a given time frame, level of comfort, using the shortest path, and at least cost. The various network dynamics amongst others include the network loads, number of interchanges, stations, and periods. The choice path depends on a transit model in use (Nökel & Wekeck 2007).

# **1.2.** The research goal, aim or objective.

The main goal of this research or its objective is to perform a partial sensitivity analysis on the parameters of the generalized cost function, the access-stop choice model and the transit-line choice model as used in OmniTRANS. This is to know whether the user-defined sizes of these parameters can affect the results of transit assignment. The results and recommendations are presented for a transit network of Flanders-Belgium and could provide good information for decision making in Flanders as well as in public transport related domains. The transit network is made up of around 3332 zones of about five kilometers square each where transit supply is integrated for a Monday at 8 o'clock in the morning.

# **1.3.** Formulation of research questions.

The thesis subject: 'A sensitivity analysis on the parameters used in the algorithm of the software package OmniTRANS' is verified with the help of a simulated transit network of Flanders-Belgium for a Monday 8:00Am. Given this dataset, the thesis seeks to demonstrate the extent to which the results of transit assignment depends on the size of the parameters that are used in the algorithms of the transit assignment module of OmniTRANS. Concisely, this research intends to answer the following questions:-

- 1. What algorithms/concepts are used in general public transit assignments?
- 2. What is a good sensitivity analysis and how can one be performed?
- 3. Why is it necessary to conduct a sensitivity analysis?

- 4. How is public transit assignment working in OmniTRANS?
  - What is OmniTRANS?
  - What algorithms/concepts are used in public transit assignment in OmniTRANS?
  - What are the possible outputs of a public transit assignment in OmniTRANS?
- 5. To what extent are the results of public transit assignment in OmniTRANS affected by the size of the parameters?
  - Which transit attributes are more influential in the generalized cost function of OmniTRANS?
  - To what extent does, the access-stop choice model used in OmniTRANS influence transit assignment outputs.
  - To what extent does, the transit-line choice model used in OmniTRANS influences transit assignment outputs.

# **1.4.** The research methodology.

The research methodology to be applied in this thesis is very simple and straightforward. To answer research questions one to four, a literature study is carried out. This literature study based mainly on scientific papers consulted from well-established journals, documents, dissertations, and books. Moreover, based on the literature study on sensitivity analysis discussed in chapter three of this thesis, a partial sensitivity analysis will be performed to answer research question five. The partial sensitivity analysis will be performed on the parameters of the transit generalized cost function used in OmniTRANS and discussed in section 4.3.1.5, the access-stop choice model discussed in section 4.3.1.2 and the transit-line choice model in section 4.3.1.3. These will help the understanding of the extent to which the user-defined sizes of parameters do have an influence on transit assignment.

In performing a partial sensitivity analysis, the parameters of the generalized cost function as used in OmniTRANS will be investigated one after another by changing their values and studying the effect that each variation has on the assignment outputs (travel distance, number of passengers, passenger travel time, and access-egress distance). For a start, a base scenario is defined specifying the origin values of these parameters and changing these values will help determine the sensitivity of transit assignment to these changes (alternative scenarios). Those parameters which show the highest effect (positive or negative) or which the transit assignment outputs are most responsive to its variation could then be judged as being more influential in transit assignment for the network case in Flanders-Belgium and could be given more attention on any transit policy development. For instance, if the parameter value associated to waiting time is judged from the sensitivity analysis to be most influential in transit assignment, transit policy makers could take this into account in providing a more efficient transit service either through an increase in service frequency, or increasing passengers comfort at waiting points, or better still augment vehicle capacity if waiting could be due to the fact that vehicle crush capacity had been reached for the "just passed" transit vehicle.

To perform a partial sensitivity analysis on the access-stop choice model and the transit-line choice model, the concerned parameters will be varied and its effect study. The parameter used here is known as the logit scale factor for the access-stop choice model and the transit-line choice model. Here, it is a form of a uni-analysis where only one variable is present and studied but higher weights could have a different effect.

Performing a best or worst case sensitivity analysis involves varying the parameters of the generalized cost function simultaneously and doing this many times so as to get a combination of parameters that yields the highest or lowest effect on transit assignment. This could also help in understanding possible percentage combination of these parameters that is necessary to obtain best results or better still worst results in transit assignment. This can aid decision making in the field of transit assignment. This type of sensitivity analysis will not be performed in this thesis giving the enormous work involved but it would be interesting to do such a research in further studies.

A Monte-Carlo sensitivity analysis suggests that all parameter values are coming from a probability distribution or random draws. Given the enormous work already to be done and the fact that many iterations should be performed to have a sufficient sample size, the Monte-Carlo sensitivity analysis will not be performed in this thesis but could be a subject for further research.

The results of the sensitivity analysis would be illustrated by generating reports in OmniTRANS and collecting the queried data. Graphs will also be plotted from the collected data to show trends, effects and deviations of parameter values. The assignment outputs of OmniTRANS are used for this purpose.

# 1.5. Structure of the master thesis.



FIGURE 1 Structure of masters' Thesis

### PART 1. LITERATURE REVIEW

This first part of the thesis consist of two chapters namely chapter two and chapter three. Chapter 2 deals with a literature study on public transit assignment algorithms and chapter three is a literature study on sensitivity analysis. These literature studies will provide a sufficient answer for the first three research questions. Many sources of information have been consulted for this purpose including papers presented at conferences, books, journals, dissertations, and internet sources. Personal introspection and information has equally given an added advantage to this literature study.

#### CHAPTER 2. ALGORITHMS USED IN PUBLIC TRANSPORT ASSIGNMENT.

# 2.1. Introduction

The Literature study on the algorithms used in public transport or transit assignment is extensive but non-exhaustive. The reviews were not constrained to any particular locality: studies from all parts of the world were incorporated. This great unity-in-diversity of ideas about transit assignment is what gives the strength of this review. This chapter discusses current literature on transit assignment, which will help in providing an answer for the first research question. The literature study on this chapter is divided into sub sections. While section 2.2 discusses the possible transit assignment methods, section 2.3 discusses the different assignment models. Section 2.52.4 highlights on some used transit assignment algorithms and section 2.5 provides a case study of transit assignment using software package MILATRAS. Section 2.6 demonstrates that different cost functions have different effects on transit assignment while Section 2.7 concludes this chapter by stating that passengers strive to minimize their travel cost and public transport operators seek to provide them with sound solutions.

# 2.2. Transit assignment methods

There are three main groups of transit assignment methods; static transit assignment, Dynamic transit assignment and Emerging approach (Y. Liu et al. 2010). These assignment methods are discussed below.

### 2.2.1. Static transit assignment

Static transit assignment is an assignment method in which no time component of passenger transit demand is taken into account for transit assignment (Ortuzar & Willumsen 2005). This is to say that, passenger transit demand is considered fixed or non-varying at all time-periods. Sub-classes of this assignment method include; All or nothing assignment,

stochastic transit assignment with random utility maximization route choice models, and user equilibrium based assignment (Y. Liu et al. 2010). Each of these sub transit assignment method is discussed below.

#### 2.2.1.1. All or nothing transit assignment

In an all or nothing transit assignment, all transit passengers are assumed to have a good understanding of the transit system and uses this knowledge to define their shortest route or optimal path between each OD pair (Q. Y. Li et al. 2011). The shortest path is normally the cheapest route (lowest generalized cost of travel) and all passenger transit demand are assigned to it leaving nothing for the inferior or more expensive paths (Spiess 1993). In situations where a transit stop is served by many transit lines serving a given OD pair, this assignment method can face the usual 'common line problem' in which passengers are faced with the decision of boarding the first arriving line or waiting for the next transit line (Kurauchi et al. 2003; Guido et al. 2005). In this case, the probability of using a transit line does not so much depend on the all or nothing shortest path analysis but on the vehicle arrival pattern, service frequency, and passenger arrival pattern (BingFeng et al. 2009).

# 2.2.1.2. Stochastic transit assignment

This is a transit assignment method in which the perception of transit users to transit conditions are taken into account to assign passenger transit demand on the transit network (Luigi et al. 2010; Cinzia et al. 2011). In stochastic transit assignment, random utility maximization (RUM) choice modeling is used for passenger transit-demand analysis (Castillo et al. 2008). RUM models assume that every passenger has a discriminating ability to choose amongst alternatives an alternative with the maximum perceived utility (F. Mark 2011). Because the information provided by public transport companies on transit conditions are often incomplete for the passengers or perceived and interpreted differently, there is bound to be uncertainties. For instance; the subjectiveness of utility, unequal knowledge about the transit network, variability of transit demand and travel time (Denis & Thierry 2011; Burkhard 2012). Therefore, the OD passenger transit demand is not assigned only to the cheapest route but also to sensible routes for the given OD pair (BingFeng et al. 2009). Though utility maximization models assume that passengers have a perfect discriminating ability, other studies show that individuals are less organized, more adaptive and very imitative (Y. Liu et al. 2010; Ellen R. A. De et al. 2012). The work of Otto (2000) demonstrates how a stochastic transit assignment model is used taking into account the differences in road users utility functions in transit assignment.

#### 2.2.1.3. User equilibrium based transit assignment.

A user equilibrium transit assignment refers to that transit assignment in which all transit passengers have full knowledge of transit conditions (congestion, travel time, operators etc.) and chooses for the least cost path (Lian-Ju & Zi-You 2007). Nigel & Agostino (2004) are of the opinion that the chosen path varies depending on whether the frequency of the service is low or high. At equilibrium, all sensible paths of each OD pair have the same generalized travel cost and no passenger can reduce his/her generalized travel cost simply by changing routes (Castillo et al. 2008; Fernando & Nicolás 2010). This is the backbone of this assignment model. Normally, all transit users will often travel using the shortest path between each origin destination pair, but with changes in network conditions; for instance congestion related effects on bus capacity, waiting time, travel time, in-vehicle discomfort, other competitive routes become attractive and transit demand is assigned throughout all sensible OD pairs in such a way that each and every passenger cannot further reduce his/her generalized travel cost (Holden 1989). Hamdouch & Lawphongpanich (2008) states that passengers use different travel strategies and are time adaptive to travel conditions, which institutes user equilibrium. The static nature of this user equilibrium is questionable and it is assumed that this equilibrium is a moving equilibrium with day time-dependent transit demand (Cascetta 1989).

# 2.2.2. Dynamic transit assignment

Dynamic transit assignment refers to transit assignment in which a time dependent OD transit demand is considered as an important component for transit assignment (Nigel & Agostino 2004; Poon, Wong, et al. 2004; Jeihani 2007). Categories of this assignment method are; within-day dynamics in transit user's route choice and transit network formulation types.

# 2.2.2.1. Within-day dynamics in transit users route choice

Because transit demand varies within-day time periods; congested and uncongested periods, it is needful to institute a dynamic assignment method for transit demand over the different time periods for each OD pair (Fisher & Scherr 2009). This is basically an overcrowding problem at particular time periods or transit lines when transit demand is greater than service capacity; seat or crush capacity (Shimamoto et al. 2008; Donald & Rahman 2010). This assignment method takes into consideration the dynamics of passenger stop arrival time; (assumes it follows a random distribution especially when the stop is served by a much shorter headway or when there is much unreliability of the service); departure time changes during peak congestion periods caused by either lack of seat availability or crush

capacity; and acts for a short term with more precision in transit assignment (Fisher & Scherr 2009).

## 2.2.2.2. Transit network formulations.

The transit network formulation approach to dynamic transit assignment considers two network formulation types; a schedule based and a frequency-based transit networks (Z. Wu & Lam 2006; Cepeda et al. 2006). Frequency-based and schedule-based transit assignment models are discussed in sections 2.3.3 and 2.3.3 respectively. For the frequency-based type, each transit line is assumed to operate under fixed frequencies and the travel time along a link depends on the volume/delay function (Y. Liu et al. 2010). In this case, the waiting time to board a sensible transit line for all passengers is a probabilistic function of the passengers' arrival time at the stop and the line frequency. In congested situations, passengers might not be able to board the available service but are obliged to wait for the next transit line.

According to Schmöcker et al. (2010), passengers choice of a hyperpath between a given OD pair is conceived at two levels; at a strategic level where all possible paths between each OD pair are defined by the passenger and a tactical level where a choice path amongst the strategic choice set is chosen to make a trip assuming existing transit conditions remain stable. In a schedule-based network formulation type, the waiting time to board a sensible transit line for all passengers is a deterministic function of the line schedule and the passengers' arrival pattern at the stop (Poon, Wong, et al. 2004). A schedule-based optimal path is deterministic by specifying the possible lines used for a particular period of time and assigns transit demand for each OD pair to each and every schedule vehicle run during the period of analysis (Poon, Tong, et al. 2004; Kurth et al. 2008).

# 2.2.3. Modern approaches

Emerging approaches to transit assignment do handle behavioral complexities, Realtime Transit information, day-to-day and real time dynamics in transit users' route choice (Y. Liu et al. 2010). This approach tries to predict passenger's behavior and their assimilation of information, which does, influences their decision processes. These approaches are:behavioral complexities, real-time transit information, and the day-to-day dynamics in passengers route choice.

### 2.2.3.1. Behavioural complexities

Just as utility maximization approach assumes that passengers have optimal rationality in decision making processes and often choose the optimum or shortest path in transit travel, the approach of behavioral COMPLEXITY counteracts the concept of rationality and even further state that individuals have bounded rationality and tend to seek for satisfying choices (T.-L. Liu et al. 2007; Samantha Schmeh 2009). Hence, this approach tries to incorporate bounded rationality, risk attitude, habit effects, learning and adaptation in transit assignment (Bogers et al. 2005; Cassey 2011). According to Feng & Duangao (2008), the risk attitude of individuals could be categorized into three groups; risk-averse, risk-prone, and risk-neutral groups which affects their decision choices and consequently their travel. Risk-averse passengers are those transit users that fear risk and would often make their trips ahead of time. Risk prone and risk-neutral passengers are those that belief in transit schedules and may be worse-off when delays are encountered.

# 2.2.3.2. Real-time transit information

The approach of real-time transit information considers the use of intelligent transport systems or advanced public transportation information systems (APTIS) in the provision of real-time information to transit users, bus drivers, related to the network conditions; transit lines, schedules, departure time, occupancies, number of transfers (Adler 2001; H. Nick & Graham 2002). This real-time information could be made available to passengers at stops or in-transit via media such as internet, telephone or audio-visual messages (L. Zhang et al. 2011). Research works on the effects of traveler real-time information on route choice through APTIS and ATIS can be found in Hato et al. 1999; Hussein 2002; F. Zhang 2010; Fries et al. 2011. Pratt (2003) discussed the concept of traveler response to transportation system changes due to provided information. Such real-time information can also help passengers in reducing uncertainty in waiting, reducing the perceived waiting time and to improve their decision processes for each OD pair. It also has a consequence on the route choice and departure time choice for each traveler. It may help 'late arriving' passengers at stop to go earlier or penalize 'on-time' passengers to go late considering a given OD pair and a late arriving bus service. When real-time information is provided at a boarding stop, passengers may not just board the first arriving service or may do otherwise depending on the information given about other possible transit lines between each OD pair (F. Zhang et al. 2008).

#### 2.2.3.3. The Day-to-day real-time dynamics in passengers route choice.

This approach to transit assignment considers the day-to-day variation of service and user route choices. This is because transit users are constantly 'learning' the transit network either based on information provided or by coherence and adapting to its dynamics (Wahba & Shalaby 2006; Tian et al. 2010). During the learning process, users can unilaterally change

their route choices but when this is no more possible, the learning process is said to have converged. Wahba & Shalaby (2011) discussed a micro simulation based learning approach in transit assignment for MILATRAS. This approach considers a multi-dimension of the transit path choice problem; departure time choice, access stop choice and run choice in transit assignment. MILATRAS models' each passenger's reaction (from learning the transit system) as a single entity to the transit system and triggers a dynamic system performance as a response to passengers behavior. Thus, the learning process for today has an effect for each passenger's departure time, access stop, and run choice for the next day. Passengers learn today to plan for tomorrow. The provision of real-time information can have an effect in passenger's learning process (Fries et al. 2011). The perception updating for each passenger depends on the trip purpose and how frequent that user make use of transit network (Wahba & Shalaby 2011).

The review on the transit assignment methods demonstrates that much work has been put forth in modeling transit assignment. The basic problems affecting transit service supply include; passenger demand forecast, predicting passengers assimilation and reaction to realtime information, and understanding passenger learning processes and behaviour (Wen-Tai & Ching-Fu 2011).

# 2.3. Models used in transit assignment.

Two main types of models are developed and used in transit assignment modeling; a frequency-based transit assignment model and a schedule-based transit assignment models (Y. Zhang et al. 2010). A third could be incorporated known as a process-based transit assignment models (Horvath B. 2008). Most of these transit assignment models are often adaptations of traffic assignment model to transit traffic (Nigel & Agostino 2004). Traffic assignment is clearly different from transit assignment though Schmöcker et al. (2010) are of the opinion that they could be considered the same since transit traffic comes from more than a single mode. The basic difference between transit and traffic assignment is that the network in transit assignment is more complex; that is, having a series of access-egress modes, transfer nodes, depends on fixed schedules and frequencies, and encounter more interaction effect with other road users (Horvath B. 2008). Models are available for used in traffic assignment but according to Horvath B. (2008), no specific models exist for transit traffic. Existing models are often adapted to this type of study and used under strict limitations resulting to outcomes, which are not often expected.

Model development in the field of transit assignment seems to have started around the late sixties (J. H. Wu et al. 1994; Horvath B. 2008). The old models avoided the concept of 'capacity restraint' in transit assignment of which more recent models do incorporate this concept (Lam et al. 1999). Capacity restraint in transit assignment modeling refers to the manner in which assignment models do take into consideration congestion (limited seat availability, crush capacity) of the transit vehicle and its effect on transit assignment (Schmöcker et al. 2010). If capacity restraint is not taken into consideration in assignment models, it will simply mean that any transit user can travel through a given OD pair at all moments and at the same general travel cost. This is not true.

Drawing generalizations from some of these transit assignment models is often problematic as some of the models are better-off in specific localities, larger networks; mass transit (numerous lines and passengers); high frequency; lots of direct lines; small amounts of transfer and the steady flow of passengers to the boarding stops, compared to smaller networks (Schmöcker et al. 2010). Ortuzar & Willumsen (2005) are of the opinion that transit assignment models should be developed taking into consideration two main factors: the role of data (from cross sectional and time series, revealed and stated preferences) and that of a monitoring function (to help model changes in model parameters) for better prediction and transit assignment. This section proceeds with a discussion of the basic transit assignment problem (capacity restraint) and will further discuss a frequency-based as well as a schedulebased transit assignment modeling.

# 2.3.1. Capacity restraint in transit assignment.

Many studies on transit assignment acknowledge the fact that transit assignment faces the problem of capacity restraint (Lam et al. 1999). This could either be in the form of seat availability or crush capacity of the transit vehicle. Many recent studies try to explain the concept of capacity restraint in transit assignment. For more insights on how capacity restraint is discussed with respect to transit assignment, it would be interesting to have a look at the works of Cepeda et al. (2006), Shimamoto et al. (2010), and Nuzzolo et al. (2011).

Throwing highlights on the works of Cepeda et al. (2006), emphasis is made of the fact that waiting time at boarding stops and the travel time are important factors in determining the route choice of any transit passenger. In their study, the effect of bus capacity restraint, road congestion and congestion at boarding points was taken into account for any user travelling from an origin i to a destination d. Their model considers the risk aversion of passengers to over-crowded stops thereby leaving the boarding probability to be determined

by the residual of the transit vehicle. Cepeda et al. (2006) assumed that in travelling between a given origin-destination pair, each passenger considers non-empty subsets of lines s  $\underline{C}$  A called the attractive line or strategy. s refers to the best strategy of travelling from O to D and s is also a subset of A (A=a<sub>1</sub>, a<sub>2</sub>, ..., a<sub>n</sub>), meaning that they equally exist other possible routes from O to D in the transit network (William & J. Zhou 2007). Given a  $\in$  A, the probability of using strategy s  $\in$  A and boarding line a  $\in$  s can be given by

Where  $f_a$ ,  $f_b$  are line frequencies and  $v_a$ ,  $v_b$ , their respective flows. The type of probability distribution used in their analysis is not clearly spelt out but it is believed that, this model uses a continuous probability distribution since it seems obvious that many lines may exist for any origin destination pair. It could be concluded from their study that bus frequencies and flows which are somehow affected by road congestion, congestion at boarding points and capacity restraint determines the route choice of passengers. While travelling between an origin-destination pair and arriving at an intermediate point z, their model assumes that a passenger could exit from z and use arcs a  $\in A_z^+$  to arrive at node  $j_a$ . Considering the travel time  $t_a(v)$  and the transit time  $t_{ja}^d$  from  $j_a$  to d. This passenger faces a decision problem at node z known as the 'common line problem' with travel times  $t_a(v) + t_{ja}^d$  and the effective frequency or service operation on the arcs a  $\in A_z^+$ .

Cepeda et al. (2006) suggest that all passengers are faced with a decision at each stage (stop) of his travel and it is necessary to offer him with a path to his destination that is less costly from each stop. This same analogy is presented by Veitch & Jamie (2011, p.32) as depicted by the figure below.



FIGURE 2. Sensible paths between a given OD pair. Source: Veitch & Jamie (2011)

Cepeda et al. (2006) further develops that, if any transfer is to be made along a trip leg, the cost of travel for a particular strategy s  $\in$  *y* equals

In their model, two special scenarios where verified; a situation of no congestion characterized by constant travel times  $t_a(v)=t_a$  and constant effective frequency  $f_a(v)=f_a$  and the second scenario of semi congestion considering the frequencies to be constant but where the travel times are used to model the effects of congestion. This is because bus frequencies are usually planned to be fixed or constant though relative to the seasons but only the travel times or departure times of users often vary due to congestion effects of certain parts of the network. The second scenario is a minimization problem of the function P(1) given by;

$$P(1) = \min_{v \in Vo} \sum_{d \in D} \sum_{a \in A} ta(V) V_a^d + \sum_{i \neq d} w_i^d - \sum_{i \neq d} g_i^d t_i^d(v) \dots (3)$$
  
s.t 
$$V_a^d \leq \sum w_i^d f_a \forall d \in D, i \neq d, a \in A_z^+.$$

In which  $V_a^d = \sum w_i^d f_a$  must be satisfied as equality for at least one a  $\in A_z^+$  otherwise, the value of the objective function could be reduced by the corresponding variable  $w_i^d$ . However, in the un-congested case (first scenario),  $t_i^d(v)$  is constant and thus the third term in the objective function is reduced resulting to

$$P(1) = \min_{v \in Vo} \sum_{d \in D} \sum_{a \in A} ta(V) V_a^d + \sum_{i \neq d} w_i^d \dots (4)$$
  
s.t  $V_a^d \leq \sum w_i^d f_a, \ d \in D, \ i \neq d, \ a \in A_z^+.$ 

With  $w_i^d$  equating the waiting time at node i for passengers going to d.

More so, they equally considered a third situation in which the effect of congestion is only sensed on a particular crowding section leading to an increase in cost of travelling through this arc. They represented this as an example of a convex cost minimization problem as shown below.

Using equation (4), and considering the effects of congestion and un-congestion, it is possible to draw valid conclusions of these effects on transit networks with available data. To obtain the optimum path, Cepeda et al. (2006) used the algorithm of the method of successive averages (MSA). This approach computes transit network equilibrium by adjusting the travel

times and the frequencies of the current flow and updating these flows by averaging the previous iterations and the newly computed solutions.

The EMME/2 software package was used in their project with the aid of the MSA to compute an optimal hyper-path with linear costs and fixed frequency on the transit network. Boarding a service by a passenger could depend on whether there is still residual capacity for that service. The residual capacity is the sum total of the number of available seats and the vehicle's crush capacity. This development considered a constant travel time  $t_a(va)=t_a$  and an effective frequency = $\infty$ , but for boarding arcs, the frequency was given by the relation;

$$f_{a}(v) = \{u[1 - (\frac{va}{uc - va + va})^{\beta} \text{ if } va < uc \dots (6).$$

$$0 \qquad \text{otherwise}$$

Where u denotes the norminal frequency of the corresponding line,

c= the physical capacity of buses

 $v\dot{a}$  = On-board flow right after the stop ( $v\dot{a} \ge v_a$ )

uc- vá is the expected residual capacity after stop. This residual capacity is important because it shows the level of on-board congestion on that particular line. Cepeda et al. (2006), constructed a similar representation of a transit point as seen in FIGURE 3 below. An example of their study was verified in the transit network of Stockholm, Winnipeg, and Santiago, Chile, which proved that, capacity restraint, traffic flow, and congestion at boarding points influences the transit assignment.

The work of Nuzzolo et al. (2011) demonstrates that congestion through vehicle capacity restraint influences user departure time, run choice and the point of network access. They used joint choice models (Ettema et al. 2007) to model this effect and to define the space-time path of users taking into consideration a dynamic network loading process. Congestion effect on a transit network refers to the decrease in on-board comfort as load reaches vehicle capacity and new users are not allowed to board but to wait for the next available service. Nuzzolo et al. (2011) states that, transit users have a full predictive information and uses this to create their route choices in order to minimize their generalize cost of travel (waiting time, travel time, fair).

The findings of J. H. Wu et al. (1994) based on a transit equilibrium assignment problem (TEAP) in modeling route choice of passengers in a congested network highlights the notion of 'strategy' that passengers use to arrive at a least cost hyper path of their route choice. This study just like that of Horvath B. (2008) also states that transit assignment models that assume constant travel times are good for small networks but certainly not for larger ones. The model of J. H. Wu et al. (1994) is built on an asymmetric cost function approach (Piercarlo 2006) modeling both the waiting time and in-vehicle travel time costs as functions of transit flow. This model constructs two scenarios; one considering no congestion and the other considering a congestion effect. Apart from this development, their study stressed on the fact that a general network contains four types of arcs; Walk arcs, Wait arcs, in-vehicle arcs, and transfer or alight arcs in which each arc has two attributes; a travel cost function and a frequency. This network structure is presented in appendix 1 of this thesis. Their work is in line with the studies of Cepeda et al. (2006), Schmöcker et al. (2010) in establishing the fact that passenger discomfort increases with vehicle crowding (congestion) and then demonstrating the existence of an equilibrium in a congested network.

Many other works have been written to show the need to take into consideration bus capacity restraint while building modern days transit assignment models (Schmöcker 2006; Shimamoto et al. 2010). Szeto et al. (2011) developed a model showing the effect of invehicle travel time, waiting time, capacity constraint as simultaneous stochastic variables in the formulation of a risk-aversion stochastic transit assignment problem.

Studies including those of Cepeda et al. (2006), Nuzzolo et al. (2011); Schmöcker et al. (2010) make mention of the fact that many models used in transit assignment are either schedule-based or frequency based. The basic difference between these two models is that while frequency-based assignment models deals with average loads and average head-ways, schedule-based models are run-based, timetable-based (Horvath B. 2008). These models are discussed below in sections 2.3.3, and 2.3.4 respectively and a process-based transit assignment approach included in section 2.3.4.

### 2.3.2. A Frequency Based Transit Assignment model.

A frequency-based transit assignment model tries to model transit route user choices and their travel path by taking into account their knowledge of routes, travel time and the frequencies of transit lines (Nökel & Wekeck 2008). Many authors have written on this type of transit assignment and which more could be consulted from Nökel & Wekeck (2007), Cepeda et al. (2006), Schmöcker et al. (2010). In the works of Y. Liu et al. (2010), random utility models in which all passengers have the ability of choosing a travel path that yields maximum utility or has the lowest possible cost is discussed and this path choices may be influenced by the frequency of each transit line.

The good thing is that, most of these frequency-based transit assignment models do incorporate the problem of capacity restraint in transit assignment. Passenger loads on transit

networks do vary from time to time and from one point to another (Hai Yang et al. 2000). In overcrowding situations, passengers are often unable to board transit lines as pre-planned especially if the vehicle does not have available space and have to wait for the next vehicle (Schmöcker 2006). The capacity of any transit service greatly affects its performance and this performance is even exacerbated when transit demand constantly fluctuates (Ferrari 1997; J.-S. Zhu & N. Zhang 2008; A. Chen & Kasikitwiwat 2011). Frequency-based transit assignment models try to model this effect of passenger transit demand fluctuations, capacity restraint, on the frequency of the transit line.

As far as the network structure is important to J. H. Wu et al. (1994), Ziyou et al. (2004), Lee (2006); Schmöcker et al. (2010) are of the opinion that the transit network design problem is basic in transit assignment. This fact was also seriously taken into account in solving the network problem in the city of Rome as stated by Cipriani et al. (2012). A good transit network design will certainly have fewer number of transfer between OD pairs, reduction in total travel time, reduction in congestion (G. E. Cantarella & Vitetta 2006; Bernhard & Ulrich 2011; Szeto & Y. Wu 2011; Miranda et al. 2011).

FIGURE 3 below is a schematic representation of a transit network according to (Schmöcker et al. 2010).



FIGURE 3. Network Representation Of A Transit Stop. source: (Schmöcker, Shimamoto, et al. 2010)

# 2.3.3. Schedule-based transit assignment model

Transit modeling seems to have been the first field that witnessed a schedule-based modeling approach (Nigel & Agostino 2009). This approach to transit assignment modeling takes into consideration the number of transit lines or vehicle runs serving a given OD pair in transit assignment. Many studies have documented describing this type of transit modeling (Nigel & Agostino 2009; Normen et al. 2010). These studies may differ on the specific aspect modeled in transit assignment. For instance, Tong & Wong (1999) presented a stochastic transit assignment model using a dynamic schedule-based approach, Hamdouch & Lawphongpanich (2008), Hamdouch et al. (2011), Nuzzolo et al. (2011) discussed a schedule-based transit assignment model taking into account vehicle capacity constraint. This thesis will highlight on a few strongholds of these model approaches.

Unlike frequency-based transit assignment models where transit services are represented by lines and the effect of single vehicle loads are not totally taken into account but simply approximated, and in which high variation in transit demand especially at peak hours will worsen this approximation and hence the results, a schedule-based approach is evident (Nigel & Agostino 2004). A schedule-based transit assignment can check the congestion in a transit network as each run and its vehicle capacity could be considered as well as the changes in the demand profile. Schedule-based transit assignment just like activity based models does take into account space-time measures (Hyun-Mi & Mei-Po 2003). All transit trips between a given OD pair are modeled as a sequence of activities (Doherty & E. Miller 2000). A schedule-based transit assignment approach is more accurate as the vehicle or passengers' arrival/departure times at stops are taking into account in modeling (Nigel & Agostino 2004). In this light, the stops, departure/arrival times and other transit processes of the transit vehicle as well as passengers are effectively taken into account in transit assignment. The figure below is an illustration of a schedule-based assignment model.



FIGURE 4: Schedule-based Transit assignment network. Source: (Nigel & Agostino 2004)

# 2.3.4. A process-based transit assignment model

This is a transit assignment model in which transit travel is considered to be made up of a series of processes. Understanding these processes even at local scale can help transit assignment at the global scale (Horvath B. 2008). A process-based transit assignment model is timetable-based, capacity restraint simulation-based model in which all elements (users and vehicles) are considered discrete. This type of transit assignment modeling shows the flow of passengers at a given stop and the functionality or the disorder at a given transfer point. It can help to generate user demand and a dynamic route choice in parts, which works separately but not independently. That is, the availability of a particular route choice will depend on the possibilities of a connecting line(s) or a transfer point(s). If this transfer line is no longer available, this route choice is deleted and another one looked for. This does not mean that public transport has fixed routes but the choice of a route may depend on the network's existing dynamics.

The demand of a process-based model is dynamic information about transit demand and the transit network. Dynamic means taking into consideration model inputs that represent reality. For instance, a certain transit line for De Lijn in Belgium (bus 68) exist between Houthalen in the Limburg province of Flanders via Leuven between 6:00Am till 8Am. A process-based model will use this information to assign trips to this line within this period and after which, this bus line will no longer be considered in further trip assignment over the network. Origin–Destination matrices of groups and sub groups of users such as pupils, students, workers, are needed for a good transit assignment since these are transit demands, which are highly demanded at particular time periods. The result is a model, which helps in the analysis of a probable effect of a transit network development; support the aims of transport policy and as an educational tool. The figure below is a schematically represented process-based transit assignment model according to (Horvath B. 2008)



FIGURE 5. A Process-Based Transit Assignment Model.

### 2.3.5. Limitations of these models

Capacity restraint frequency-based assignment models are limited especially when the frequency on the transit network are low or when the transit facility is operating at almost full capacity. Frequency-based transit assignment models use average number of passengers at boarding or transfer points. Transit users cannot be modeled as averages.

Most of the models were built and tested in specific localities with specific characteristics. Generalizing the results obtained and using them for some other localities will not produce the desired effects. Hence, schedule-based and frequency-based assignment models are result-based.

In a frequency-based assignment approach, transit services are represented by lines and the effect of single vehicle loads are not totally taken into account. Frequency based transit assignment models only consider average waiting time and constant vehicle travel time but fail to account properly for the variability of capacity and congestion (Szeto et al. 2011).

In order to solve these problems, Horvath B. (2008) insinuates that it is necessary to simulate transit traffic both at the level of the runs as well as the demands of every user. The data collected for particular lines or stops, should never be generalized for the entire network because the transit demand certainly varies from one part of the network to another. Thus, models that predict the 'process' running on a public transit network are encouraged. This is why, Horvath B. (2008) is of the opinion that a process-based assignment model is of much importance because beside providing common results (for a particular network), it can also show transit processes that do occur on a transit network.

Transit processes are those steps involved in making a trip; the access mode, boarding stop, travel link(s), number of transfer(s), destination stop, egress mode (Cepeda et al. 2006). Furthermore, according to Horvath B. (2008), frequency-based and schedule-based assignment models are result-based by pointing out the results for a particular transit network whereas a process-based assignment model using simulation-based assignment methods to follow the processes involved in a transit network; the access stop choice, the transit line choice, the transit transfer choice stop.

Schedule-based networks are often used in dynamic transit assignment whereas frequency-based networks are used for static transit assignment. Schedule-based assignment is more demanding than frequency-based assignment because the former needs large databases, more detail information on transit demand, more simulation run times (Nigel & Agostino 2004). Schmöcker et al. (2008) compares schedule-based and frequency-based transit assignment models but states that an approach that complements them is necessary.

# 2.4. Algorithms used in transit assignment

An algorithm can be defined as "a set of detailed instructions which results in a predictable end-state from a known beginning" (wiseGEEK 2012). This means that any failure to follow the instructions will result to faulty end-products. This type of reasoning has been developed and used in public transport assignment. Different studies of transit assignment tend to adopt inspiration from other fields such as biological science to create their own proper algorithms to execute transit assignment models. For instance, while Szeto et al. (2011) proposed a column generation based algorithm to solve the non-linear complementarity problem of the risk aversive stochastic transit assignment, Wahba & Shalaby (2011) used a genetic algorithm (GenoTrans) in the transit assignment module of

MILATRAS. Szeto & Y. Wu (2011) used Genetic Algorithms (GA) to solve a route design problem of their model. Some other works in transit assignment such as those of Cepeda et al. (2006), Schmöcker (2006), N. Otto & Rasmus (2006), Schmöcker et al. (2010), Nuzzolo et al. (2011), Hamdouch et al. (2011), described and used the method of successive averages (MSA) in their studies. This is because the MSA easily accounts for the effects of congestion on a transit network. The congestion effect is a response of the passenger loads to the vehicle capacity (volume/capacity ratio).

Tong & Wong (1999) used a time dependent optimal path algorithm which consisted of three steps; 'forward pass of quickest path, backward pass of quickest path and a branchand-bound method' in their study. Some authors are of the opinion that network algorithms such as minimum spanning tree, maximum spanning tree, shortest path algorithms, branchand-bound techniques are used to determine the hyperpath within a transit network (Ruihong & Zhong-Ren 2002; Friedrich et al. 2007). Ruihong & Zhong-Ren (2002) are of the opinion that for transit networks, forward-search, backward-search, and minimal transfer path search algorithms are used for a pre-determined departure time, arrival time and number of maximum transfers respectively.

# 2.5. Case study: Transit network assignment in MILATRAS

This section discusses transit assignment using an assignment module MILATRAS as discussed in Wahba & Shalaby (2011). *FIGURE 6* below illustrates the processes involved when passengers travel between OD pairs. The structure of the mental model in MILATRAS is assumed fixed but each passenger is modeled singly based on his/her experience and learning. Pre-trip information gathered from learning processes pushes passengers to develop an original or tentative travel plan which includes the departure time, access stop, run choice, and this plan will be realized if 'en-route' conditions matches with their perception (Adler 2001; Nigel & Agostino 2009). Wahba & Shalaby (2011) demonstrated that transit stops and route choices of passengers are associated to the departure time choice and all in steps. Given an OD pair, the path engine used in MILATRAS searches for possible access stop, destination stop, possible paths, within this pair. The access/destination stop choice model for this package considered a maximum distance of 1.000m within the search radius and used three access/ egress modes; walk, auto-passenger, and auto-driver (Wahba & Shalaby 2011).

The travel cost or the generalized cost structure used in MILATRAS is dependent on seven choice levels; origin O, Departure time T, access stop G, run choice V, off stop F, onstop N, and the destination stop D. There is a skim or cost associated to each and every choice and the sum total of these make up the travel cost (Veitch & Jamie 2011). Also, the generalized cost of making any choice depends on the immediate reward of such a decision and the expected return from the choice 'sub-tree' of alternatives (Wahba & Shalaby 2011). These cost components could either be fixed (origin, access stop, destination) or variable (waiting time, in-vehicle travel time). The variable cost components are considered as a random variable in MILATRAS as its value changes for each passenger's choice depending on the transit network conditions.

Because the Toronto Transit Commission (TCC) using MILATRAS for transit assignment operates within the Greater Toronto Area (GTA), there existed some interaction with neighboring transit systems along its boundaries and it was necessary to consider them. Hence, the entire network was made up of surface route services (SUR) and that of the Government of Ontario and subway services (RT). Nine parameters where then calibrated to find those that minimized the generalize cost of travel for each passenger. These parameters where  $\beta$ RT,  $\beta$ SUR,  $\beta_{waiting}^{RT}$ ,  $\beta_{waiting}^{SUR}$ ,  $\beta_{Transfer}$ ,  $\beta_{InvehicleT}^{RT}$ ,  $\beta_{SD}^{HBW}$ ,  $\beta_{fare}^{HBS}$ . Since HBW and HBS trips were considered to be recurrent and influence the learning adaptation process much faster, they were taken into account in the analysis. The calibration procedure for the nine parameters was possible using a genetic algorithm approach (GenoTrans) in which out of a possible parameter population, parameters that minimized the objective function are selected. A total of n-1 parameters were estimated with the nth parameter being fixed. A best-fit solution is obtained based on a pre-defined stopping and conversion criterion being satisfied.

Care is often taken into account when assigning different values to different parameters in a model (Salvatore et al. 2010; Salvatore et al. 2011). For MILATRAS, it was assumed that,  $\beta_{\text{InvehicleT}}^{\text{RT}}(0.8) < \beta_{\text{InvehicleT}}^{\text{SUR}}(1.0)$  i.e. passengers perceive a minute spent on the subway lesser than that spent on the bus. Also,  $\beta_{\text{waiting}}^{\text{RT}}(1.4) > \beta_{\text{InvehicleT}}^{\text{RT}}(0.8)$ ,  $\beta_{\text{waiting}}^{\text{SUR}}(5.0) > \beta_{\text{InvehicleT}}^{\text{SUR}}(1.0)$ ,  $\beta_{\text{SD}}^{\text{HBW}} > \beta_{\text{SD}}^{\text{HBS}}$  i.e. the value of time for a work trip is higher than that of a service trip etc. Transit assignment outputs were built for the run loads, stop run records and travelers' behavior.

Because of the unavailable transit demand data for each route load, the model used the total route loads which was different from the total trips modeled and this had its effect on the assignment output; underestimation and overestimation of transit demand for certain routes, institute congestion on particular routes which does not exist (Wahba & Shalaby 2011). An indication of passengers learning was introduced through overcrowding which declined as learning and adaptation increased (number of iterations in the model increased).


## FIGURE 6. A Mental Model For Transit Assignment as Used in MILATRAS. Source: (Wahba & Shalaby 2011)

MILATRAS transit assignment has been applied to the multi-modal transit network of Toronto operated by the Toronto transit commission (TTC) which incorporated passenger learning process. Their conclusion was that, passengers learn the transit network and uses this knowledge to make their journeys. A comparative study of MILATRAS, EMME/2, and MADITUC software packages is demonstrated in (J. Wang et al. 2010).

## 2.6. Cost of transit movement

Cost functions are important in transit assignment and have their different impacts. The following section discusses the different types of cost functions used in transit assignment as well as the generalized cost of passenger's movement.

#### 2.6.1. Transit assignment cost functions

All the above discussion has demonstrated that, people do travel and ensure a cost in making their journeys. The general cost of travelling or making a trip always act as a disutility or disincentive to travel and many passengers do seek to reduce their travel cost. This travel cost could be network related (Waiting time, travel time, traffic flow, number of transfers) or purely monetary (fares). The deterrence or disutility to travel can take many forms and may include (Spiess 1993; Ortuzar & Willumsen 2005):

- A linear cost function
- A Non-linear cost functions e.g Ca= Ca(Va)

- A power cost function e.g  $f(Cij) = Cij^n$
- An exponential cost function e.g  $f(Cij) = \exp(-\beta Cij)$

Though it could be said that due to difference in passenger perception, different transit users perceive different cost functions while travelling from the same origin to the same destination. Knowing the different characteristics of transit users (perception of cost) will aid in the adoption of a single assignment cost function. In most cases, transit assignment models can only hold grounds under the assumption of 'rational traveler'.

However, the works of Veitch & Jamie (2011) show that OmniTRANS has its own specific cost functions and these include;-

- An Exponential distribution cost function of the form e.g;  $f(Cij) = \alpha \exp(\beta Cij)$
- A log-normal distribution cost function of the form e.g;  $f(Cij)=\alpha \exp(\beta ln^2(Cij+1))$ .
- A Top log-normal distribution cost function e.g;  $f(Cij) = \alpha \exp(\beta ln^2(fracCij\gamma))$ .

- and others (power function, combined power and exponential function).

Each of these cost functions and their parameter influences the cost of travel differently. For instance, the graph below demonstrates that an exponential cost function will punish less for higher levels of impedances when compared to the log normal cost functions (Veitch & Jamie 2011, pp.60–61). The x-axis represents the travel impedance Cij and the y-axis represents the parameter values.





Moreover, using the notion of 'cost flow functions', the cost of using a transit link is directly related to the traffic flow on that link and on the network;  $C_a = C_a(V)$  or  $C_a = C_a(V_a)$ where  $C_a$  refers to the link cost, V equals the network traffic flow conditions and  $V_a$  refers to the flow on link a (Ortuzar & Willumsen 2005). Though this may be looked as an external factor influencing the transit vehicle, it should certainly be taken into account while doing transit assignment since the flow on a particular link makes that link more expensive than other links of same dimension.

#### 2.6.2. The generalized cost function for transit assignment

According to Schmöcker et al. (2010), the cost of travel for any transit user varies depending on the distance, in-vehicle travel time, waiting time at the stops, fares, number of transfers to be made, the probability of travelling seated or standing, a penalty factor and fare. Travel distance may play a very important role in the determination of travel cost alongside the waiting time, travel time, number of transfers, travel penalty, fare and Schmöcker et al. (2010) clearly point out that seat availability is also a paramount factor in transit travel cost. A simple linearized generalized cost for public transport according to Ortuzar & Willumsen (2005) is given as follows

$$C_{ij} = a_{1}t_{ij}^{\nu} + a_{2}t_{ij}^{w} + a_{3}t_{ij}^{t} + a_{4}t_{ij}^{n} + a_{5}F_{ij} + a_{1}\delta_{ij}^{n} \dots (9)$$

$$t_{ij}^{\nu} = \text{vehicle travel time between i and j.} \qquad t_{ij}^{w} = \text{waiting from and to stops}$$

$$t_{ij}^{t} = \text{waiting times between stops} \qquad t_{ij}^{n} = \text{interchange time}$$

$$F_{ij} = \text{travel cost or fair price} \qquad \delta_{ij}^{n} = \text{interchange deterrence}$$

 $a_1$ ,  $a_2$ ,  $a_3$ ,  $a_4$ , are parameter estimates in time value with  $a_2$ ,  $a_3$ ,  $a_4 > a_1$  because a minute of waiting time is usually perceived more than that in in-vehicle travel time.  $a_4$  and  $a_5$  are monetary value estimates. A necessary question to pose at this juncture is 'should cost be evaluated in monetary terms or time?' It is certainly more practical to measure the generalized cost of travel in time units rather than money value. This is true considering the effect of a change of a or some parameter(s) in the prediction model such as an income effect on the generalized cost of travel as explained by (Ortuzar & Willumsen 2005). However, it is more efficient to use all the attributes associated with the disutility of a trip as outlined in the generalized cost function above.

### 2.7. Conclusion

It could be concluded that the above developments show deep-routed knowledge in transit assignment and that the reality is still to be modeled. Just like origin-Destination forecast models such as the growth factor model, gravity model, and proper transit assignment necessitate the putting in place of models that will forecast transit demand and institute the corresponding service assignment. Without such models, transit traffic will often face uncertainties; congestion, lack of seats, service unreliability, and increase in waiting times etc. Quality data is needed to build such models that can forecast properly future transit demand

and the growth in transit and then use this information to adapt transit assignment to passenger demand (Ortuzar & Willumsen 2005).

Transit assignment involves building models that will assign transit demand to the possible travel paths while moving from one zone to another. Therefore, it can be concluded that doing transit assignment refers to;-

- Identifying a set of routes (lines) which might be considered attractive to users
- Assigning a suitable proportion of trips to these routes resulting to the flows on the links of the network
- Looking for a convergence

Conclusively, just like traffic assignment, transit assignment could be performed using the algorithm of Dijkstra but supper-imposing a travel cost function rather than just considering distance effect on the network (Ruihong & Zhong-Ren 2002; Horn 2003). This is the operational background of many transit assignment algorithms. All passengers strive for a least travel cost hyper path when making a journey. The transit system owes passengers the duty to provide the needed information about the transit network and schedules. Many reasons such as the subjectivity of learning by different individuals, capacity restraint in its various dimensions make transit assignment a difficult task.

#### **CHAPTER 3. LITERATURE STUDY ON SENSITIVITY ANALYSIS**

## **3.1.** Introduction

This chapter discusses literature studies on how to do a sensitivity analysis. In this chapter, a definition of sensitivity analysis will be stated, types of sensitivity analysis will be discussed and the procedure of doing and analyzing the results of a good sensitivity analysis will be explained. The importance of doing a sensitivity analysis will then be highlighted. All these will provide a sufficient answer to the second and third research questions of this thesis as discussed in section 1.3. It will further set the framework to answer the fifth research question.

## **3.2.** Defining sensitivity Analysis.

As a response to the question; what is sensitivity analysis? Anthony et al. (2006) defines sensitivity as a study in which the uncertainty of some predicted or unpredicted impacts are verified. Uncertainties are outcomes or events that cannot be predicted with certainty (UNESCO 2005). This can be done by setting and testing different scenarios. These scenarios could be the result of changing values or weights associated to the parameters of a model. Values or weights can be numerical; often associated to a model or its parameter or a social value that may be attached to a particular object (Bock & Ruyter 2011). Sensitivity analysis is performed to understand uncertainty (Avineri & Prashker 2003). According to UNESCO (2005), Broadhead et al. (2004), sensitivity analysis is a study in which a change in a model output is studied with respect to changing input values. A sensitivity analysis can be performed to validate a model, warn of unrealistic model behaviour, point out important assumptions, help in the formulation of a model structure, give room for further research, model simplification, adjust numerical values of model parameters, allocate resources, detect very important model parameters (Shengtai & Linda 2004; Terry 2009).

## **3.3.** Types of sensitivity analysis.

Hamby (1994) and Anthony et al. (2006) identifies three type of sensitivity analysis: Partial sensitivity analysis, best or worst case sensitivity analysis and Monte-Carlo sensitivity analysis. These are discussed below.

#### 3.3.1. Partial sensitivity analysis

Partial sensitivity analysis is a study in which one or more model parameters or assumptions are modified to study a certain model output or prediction (Canada mortgage 2004). This type of sensitivity analysis will be performed in this thesis. The sensitivity of the parameters of the access stop choice model, the transit line choice model and those of the generalized cost function as used in OmniTRANS will be verified. This will be in line with the works of (William & J. Zhou 2007) who performed a partial sensitivity analysis to know the optimal fare structure that should be charged by public transport companies to attract the highest number of customers and to provide an efficient service while making profits. Some assumptions preceded their analysis: that transit fare structure significantly affects passengers demand and route choice; that there exist a fixed line frequency, a known origin destination pair, an elastic demand & capacity restraint, and a monopoly transit market. This is to show that making assumptions is necessary in doing sensitivity analysis and a variation of these assumptions can offer the opportunity to discover new trends (Shengtai & Linda 2004).

#### 3.3.2. Worst or Best case sensitivity analysis

Worse or Best case sensitivity analysis is a study in which a combination of variables or model parameters which feat a model best or worst are verified (Shengtai & Linda 2004). Contrary to conducting a partial sensitivity analysis where only one parameter can be varied at a single moment in a model while keeping others constant, a best or worst case sensitivity analysis involves varying more than a single parameter at a time. In the process of varying these model parameters, a combination of parameter values that predicts optimum results may be obtained known as 'best case sensitivity results'. On the other hand, a combination of model parameter values producing the worst results is known as the 'worst case sensitivity analysis'. The results of a worst case sensitivity analysis are often conservative while those of a best case sensitivity analysis are optimistic (Kristina & Jurgen 1999).

Best or worst case sensitivity analysis is very similar to some statistical methods of data analysis using simple regression procedures in statistical software packages such as R console and SAS enterprise with the aid of tools such as AIC, Mallow's CP (H. K. Michael et al. 2005). Best or worst case sensitivity analysis can be performed by varying a few

assumptions or parameter values of a model to a given minimum or maximum, halved or even doubled (Canada mortgage 2004). Compared to partial sensitivity analysis, best or worst case sensitivity analysis is better because the behaviour of a model is known relative to the variation in parameter values as model interactions are taken into account in their outputs (Herman & Ryan K. 2010; Chang 2012). Best or worst case sensitivity analysis is only possible in a model where there are at least two variables or parameters to be estimated. This is why, a best or worst case sensitivity analysis can only be performed on the parameters of the transit generalized cost function as used in OmniTRANS and not on the access stop choice model or transit line choice model. Taking into account the enormous amount of work involved in this thesis, best or worst case sensitivity analysis has not been performed.

#### 3.3.3. Monte-Carlo Sensitivity Analysis

The Monte Carlo sensitivity analysis is a type of sensitivity analysis which involves generating random variables from probability distributions of a form that best suit them (Braun & Murdoch 2007). The Monte Carlo computer based simulation of random variables is a better approach to doing sensitivity analysis as bias is reduced (Ghazala 2002; Kyle & Sander 2004). The analyst though instituting the input conditions, has no control over the output as it is computer based (Mooney 1997). This means that, a computer based Monte Carlo simulation generates random variables which resemble real values and permits the use of these generated variables for making predictions. The values are generated based on the chosen probability distribution. The Monte Carlo simulation approach assumes that any value that falls within plausible values are likely to occur (Jennifer et al. 2006). For instance; the total bus wait time at a stop varies from the first person coming to the stop and the last passenger. In is light, depending on the bus frequency, the passenger wait time at a bus stop varies infinitely from when the last bus departed till when the last passenger arrives the bus stop to board the next bus service.

Generating random draws from model parameters based on their respective probability distributions is a better approach to model estimation (Song et al. 2003). Random distribution draws are better from those of a Bernoulli distribution because the latter takes only two values except when this is the case; a parameter that can take only two values (board or not, seating or standing) (Reza 2011; Kohji et al. 2012). More so, repeating these random draws many times produces a large number of realizations and thus good samples for prediction. Due to the fact that a partial or best case sensitivity analysis goes alongside with some form of fixity of parameters of which certainty is questionable, Monte Carlo sensitivity analysis can correct

this. To perform a Monte Carlo sensitivity analysis, the probability distribution of all model parameters should first of all be defined. Then, random draws should be generated based on the probability distribution to obtain a sufficient sample for the analysis (Pavlos & F. Nick 2012). Considering the complexity of performing a good Monte Carlo sensitivity analysis and given the amount of work to be done, a Monte Carlo sensitivity analysis will not be carried out.

## **3.4.** Performing a good sensitivity analysis

A good sensitivity analysis can be performed by stating different scenarios or assumptions and testing the variability obtained from the results using a model. For this to be done, an acceptable variation level for the model parameters (coefficients) should be set at the beginning be it a +-5%, +-10% (Canada mortgage 2004; Radulescu et al. 2008). This is known as setting the benchmark criteria for a proper sensitivity analysis (Elam & Rearden 2003). Broadhead et al. (2004) states that, sensitivity coefficients should be defined in a way that they represent a percentage effect on some system response due to a percentage change in some input parameters. In this way, a 50% change should have a 50% effect on the response variable for a robust parameter. The variation of the parameter values in a model should be related to a range of plausible values (Jennifer et al. 2006). Doing a partial sensitivity analysis refers to varying each parameter in a prediction model and studying its impact on the model output. This is to know how sensitive the prediction model will react to variation in assumptions or some of its parameters. If the model output does not change, then it is said to be 'robust model' and greater confidence could be attributed to it. To do a good sensitivity analysis, it is important to:

- Specify a set of alternative assumptions. In this thesis, this will involve describing the various iterations that will be performed in the algorithms of OmniTRANS. One hundred scenarios were created for a partial sensitivity analysis of the generalized cost function, thirty iterations each for the partial sensitivity analysis of the access stop choice and the transit line choice models.
- Decide on whose benefits or costs counts. This involves stating what type of results that are expected. In this thesis, a partial sensitivity analysis is performed to understand the variability of transit assignment outputs to changing weights associated to the different parameters of the generalized cost function, the access stop choice model and the transit line choice model. The results obtained will aid decision making

by policy makers or public transport companies with respect to how they may influence public transit assignment (William & J. Zhou 2007).

- Cataloguing the impacts and selecting measurement indicators. Impacts here imply both inputs and out puts (Anthony et al. 2006). Impacts are outlined from a cause and effect relationship. In fact, what cause? (Input, value changes) will produce what effect? (Output, decision). For example, changing the values of the parameters of the algorithm of OmniTRANS and performing assignment produces certain effects. These effects have to be studied to know the trend in which the model behaves.

It will also be worthwhile stating that, making important assumptions are necessary for every model and this equally holds for doing sensitivity analysis (Estache & Gómez-Lobo 2005; Jiefen 2010). Results are liable to deviate with changing assumptions (Álvaro & Ruben 2012).

## **3.5.** Importance of performing sensitivity analysis.

A well conducted sensitivity may aid the verification of important assumptions of a model, identify key parameters affecting a model or to test the extent to which the parameters are important in a model (Canada mortgage 2004; Singler 2005). Sensitivity analysis can be a tool to evaluate projects (Marijke et al. 2006). It could also help to develop predictions where uncertainties are common (Avineri & Prashker 2003; Jyri et al. 2006). In this light, from the literature study discussed in section 2.6.2, it was established that many factors do influence the transit generalized cost of travel. Performing a sensitivity analysis on the transit generalized cost function will help in the prediction of those factors which are more influential in transit assignment. The applications of sensitivity analysis are varied (Caldeira et al. 2003; Strydom 2010). Ziyou et al. (2004) performed a sensitivity analysis to solve a bilevel model problem by considering changes in link flows resulting from changes in the line frequencies of the transit network. Sensitivity analysis can be carried out to ascertain the risk involved in real-estate development projects (Pavlos & F. Nick 2012).

## **3.6.** Conclusion

Performing a sensitivity analysis gives an added value in the decision making process of any project. Sensitivity analysis helps to reduce the uncertainty that may result from certain decision making processes and pushes the analyst to be more confident in decision making. This is why, performing a sensitivity analysis on the parameters of the algorithms of OmniTRANS, the access stop choice model, the transit line choice model, will have an added value for policy makers or public transport companies who seek to know those factors that influence transit assignment. This will give room for developing measures to increase service performance and to make profits especially for public transport companies operating in Flanders, Belgium.

#### PART TWO. PERFORMING SENSITIVITY ANALYSIS IN OMNITRANS.

The second part of this thesis is going to provide insights on the software package OmniTRANS and will also describe the manner on which sensitivity analysis is performed in OmniTRANS. These will provide answers for the fourth and fifth research questions stated in section 1.3. General conclusions and questions for further research are developed in chapter 6.

# CHAPTER 4: WHAT IS OMNITRANS AND WHAT ALGORITHMS ARE USED IN OMNITRANS?

Chapter four gives an overview of the software package OmniTRANS. This overview will discuss the SWOT characteristics of OmniTRANS and highlight the transit attributes used in this package, the algorithms and their properties, the outputs of OmniTRANS alongside discussing how congestion effects are modeled in this package through the use of the crowding function and the BPR function. The discussions in this chapter will provide a good answer to the fourth research question cited in section 1.3 and also set a framework for performing sensitivity analysis in OmniTRANS.

## 4.1. Introduction

OmniTRANS is a transport planning software used to improve the quality and productivity of transport planning and modeling (Omnitrans 2011). It was developed by Goudappel Coffeng, a consultancy company in the Netherlands (Omnitrans 2007). The software package offers;-

- a good visual interface for model development and analysis
- a strong data management and planning information system
- An efficient, flexible, fast and reliable job engine for running task.

Just like MILATRAS (Wahba & Shalaby 2011), OmniTRANS is multi-dimensional especially in providing guidance on travel purpose, mode choice, time, land-use system, and users characteristics in the project set-up (Veitch & Jamie 2011). This software package uses network, matrices, planning and socio-economic data as input to model situations of transit demand and supply. This is why, in this thesis, the data input is the transport network of Flanders-Belgium.

The OmniTRANS job engine offers the possibility to create, edit, process and monitor jobs within an interactive graphic user interphase. One hundred jobs were created and ran to obtain the data needed to perform sensitivity analysis on the generalized cost function of OmniTRANS and thirty jobs each were created for performing a sensitivity analysis on the access stop choice model and the transit line choice model.

The OmniTRANS desktop contains vital elements such as a project manager, project set-up, network display, matrix cube, database job engine, graphical and report design which are important in managing all the information associated with model scenarios (Omnitrans 2011). The project manager is a tool that manages the generation, storage, display and reporting of associated scenario data. It's associated with a project template to facilitate model development and avoid building models from scratch while offering user-defined characteristics for model building (Omnitrans 2011).

The OmniTRANS transit manager is of utmost importance by allowing the possibilities to define the transit system and its attributes: fare systems, and other system-wide information (Omnitrans 2011). OmniTRANS can be used to perform a schedule-based and frequency-based transit assignment (Veitch & Jamie 2011). Detail OD matrices are needed in doing a schedule-based transit assignment to provide very detail results which may be difficult to process effectively. The single-class assignment performed by schedule-based assignment permits the modeler to gain insights of transit occurring at different time periods or zones and to concentrate resources where necessary rather than wasting time and resources on very un-important areas. OmniTRANS can perform only a static transit assignment as discussed in section 4.6.

## 4.2. Transit attributes used in OmniTRANS

A short-list of Transit attributes used in OmniTRANS is given as follows (Veitch & Jamie 2011);

- 1. Transit network attributes;
- Links
- Nodes
- Centroids
- Transit lines
- Transit stops
- Transit schedules
- 2. Project set up dimensions;
- Public transport mode
- Other modes (bike, walk, car)
- 3. Transit transfers;

- Default Access and egress modes, transfer penalties
- Alternative Access, egress and transfer modes (bike, walk, car)
- Transit fares
- 4. Transit line attributes;
- Transit mode
- Transit line schedule
- Transit line per hour frequency
- LOS (reliability, speed)
- Seat capacity

-	Crush capacity under congestion	-	Stop type based fares				
	conditions	-	Stop to stop fares				
-	Travel time on this line	-	Stop type to stop type based fares				
5.	Stop attributes;	8.	Space accessibility constraints;				
-	Boarding	- Stops					
-	Alighting	-	Lines				
-	Egress, access and transfer links	-	Links				
-	Egress, access and transfer modes	-	Nodes				
6.	Transit transfer attributes;	9.	Time accessibility constraints:				
-	Wait time	-	Frequency				
-	Penalty	-	Operating hours				
-	Maximum wait time	10	. Behavioural constraints				
-	Egress, access and transfer links	-	Access distance				
7.	Transit fare attributes;	-	Number of transfers				
-	Distance based fares	-	Maximum detour				
-	In-vehicle time based fares						

## 4.3. Algorithms used in OmniTRANS

According to Veitch & Jamie (2011), two types of algorithms are used in OmniTRANS for transit assignment;-

- A Path building algorithm &
- An Assignment algorithm

OmniTRANS path building algorithm searches through the network and determines the possible paths for each origin destination pair. This algorithm begins its search procedure at the destination node and moves backward taking into account all possible stops and transit lines linked to the destination zone (Veitch & Jamie 2011). This is the same algorithm behaviour discussed in (Tong & Wong 1999; Ruihong & Zhong-Ren 2002). The path finding algorithm equally calculates the generalized cost involved in making a step backward from the destination zone i.e from one backward stop to another. Upon arriving the origin node, it computes the generalize cost of travel between origin destination pair (Veitch & Jamie 2011).

The path building algorithm determines the possible paths to arrive at each destination zone and the OmniTRANS assignment algorithm then uses these calculated paths to assign transit demand (passengers) between each origin destination pair. A detail description of these algorithms is discussed by Veitch & Jamie (2011, pp.62–67). However, these algorithms have some important properties worth highlighting.

#### 4.3.1. Properties of algorithms used in OmniTRANS

The algorithms used in OmniTRANS are endowed with some important properties and these properties demonstrate its strength and uniqueness. The properties include; the determination of the Access, Egress and walk transfer candidates, the Access stop choice model, the transit line choice model, the schedule-based path building algorithm, the generalized cost function, and transit fares. These properties help model the decision choice set often faced by passengers and transit and presented in appendix 2. Each of these properties is explained below.

#### 4.3.1.1. Determination of the access, egress, walk and transfer candidate(s)

A set of possible boarding stops a passenger can use at the origin of their trips is known as the access candidate set of that trip in OmniTRANS. The access candidate(s) is determined by the access mode (walk or car) based on an allowable distance (in kilometers) depending on each of these modes and set by the user. In OmniTRANS, the *otTransit.searchRadius property* is used to determine the set of access candidates. This property is set in such a way that at least one possible stop is found depending on the type of network (rural or urban).

At the destination node, OmniTRANS determines a set of stops which are possible egress points. These egress stops depend on the egress mode (walk, car). The egress candidate(s) is a set of possible alighting stop(s) that a passenger can use. The *otTransit.searchRadius* script is used in OmniTRANS to determine at least one possible egress stop depending on the type of egress mode and the network.

OmniTRANS can also determine a set of possible transfer stops in a transit network for any user making a trip between OD pairs. The default transfer mode used here is the walk transfer mode. Thus, a set of possible walk transfer distances is taken into account in the algorithms of OmniTRANS to determine the walk transfer candidates.

More so, the specification of other properties such as *OtTransit.minfind* permits the specification of a minimum number of candidates to be determined by the algorithm. The property *OtTransit.minfind* is different from *otTransit.searchRadius* because the latter could be specified for each access, egress mode but the former could be applied for the whole search procedure. Specifying the property *OtTransit.mustfindModes* and setting the modes permits the algorithm to include stops in which the specified mode exist. Specifying

*OtTransit.mustfindStop* permits the algorithm to include the specified stop(s) irrespective of the origin or the destination. The property *OtTransit.mustfindStopType* permits the algorithm to provide stops of a specified stop type in the candidate set. This property is very important because it helps to include car-pool locations (park & ride) into the candidate set. Setting the property *OtTransit.candidatesmustProvideCheaperOption=True* permits the algorithm to determine a stop that offers a least travel cost (Veitch & Jamie 2011).

#### 4.3.1.2. Access stop choice model

The access stop choice model is used in OmniTRANS to determine the proportion of passengers to board at a given set of access candidates. In an urban bus routing problem of a Tunisian case study, the set of access stops determines the routes to be visited as well as the generalized cost of travel (Euchi & Mraihi 2012). An access stop is chosen so as to minimize the generalized travel cost (Nökel & Wekeck 2007). There are two access stop choice models used in OmniTRANS (Veitch & Jamie 2011);-

An *Optimal access stop choice model* which is the default stop choice model set in OmniTRANS. Using the optimal stop choice model, all passengers will board at a stop that offers the lowest travel cost from the origin to the destination. Using the optimal access stop choice model approach and looking at the figure below, all passengers will board at candidate A.



#### FIGURE 8. Access Stop Choice Model. Source; (Veitch & Jamie 2011)

On the other hand, there is equally a *logit access stop choice model* used in OmniTRANS. The logit stop choice model allocates a proportion of the transit demand to each candidate while taking into account the fact that, passengers will always favour an access

candidate that yields a lower generalized travel cost. A logit Parameter is used by the logit stop choice model to determine the degree to which users will favour access candidates of lower generalized cost. This parameter can be set by the users themselves. From *FIGURE 8* above, using the logit stop choice model, the proportion of passengers to be assigned to candidate A can be calculated as follows (Veitch & Jamie 2011);

Where

- P<sub>a</sub> is the proportion of passengers boarding at candidate A
- Ca is the total generalized cost of boarding at candidate A
- Ø is the logit scale factor

If the access candidate contains many stops, then then logit stop choice model could be written as

Where

S is the set of access candidate stops for the given area.

The effects of the logit scale parameter are varied. A scale parameter of zero will share transit demand equally between two access candidates. A positive scale parameter will assign more passengers to a cheaper access candidate and vice versa. FIGURE 9 below (Veitch & Jamie 2011) clearly represents the effect of different values of the scale parameter of the logit stop choice model. A partial sensitivity analysis has been performed in this thesis in section 5.3.2 to understand how the logit parameter of the access-stop choice model can influence transit assignment outputs.



FIGURE 9. Effect of the Logit Scale Factor On the Access Stop Choice Model.

The access stop choice model in OmniTRANS can be specified using the property *OtTransit.logitParameters*. A value of *nil* in the code implies that an optimal stop choice model should be used while a value other than *nil* means a logit model is applicable.

#### 4.3.1.3. Transit line choice model

The access-stop choice model discussed above showed how a passenger makes a choice concerning the stop to board a transit service but does not tell us which service he or she will board considering that the chosen stop is served by many transit lines. The Transit line choice model explains this. It tries to;- outline a set of possible transit lines for an origin destination pair and also estimates the demand for each transit line taking into account its frequency and the generalized cost of travel using each transit line (Veitch & Jamie 2011).

The OmniTRANS transit line choice model in determining the set of possible transit lines takes into account the number of interchanges to be made, the generalized cost of travel through the specified transit line, and the expected level of service for a particular transit line. The *OtTransit*.minServiceUsage property is used to specify the minimum acceptable level of service for a particular transit line (Veitch & Jamie 2011).

To estimate the demand for a particular transit line, two transit line choice models are used in OmniTRANS (Veitch & Jamie 2011);-

- *The optimal (indifferent) transit line choice model* in which all passengers are expected to board the first possible departing transit line between each origin destination pair. This approach is often set to be default in OmniTRANS and passengers are assigned to each transit line in proportion to its frequency. In this light, the probability to board a given transit line (P<sub>a</sub>) equals

With F<sub>a</sub> being the frequency of transit line A

T is the set of sensible transit lines between each origin destination pair and

- The logit transit line choice model which assumes that passengers do not board only the first sensible transit line but a transit line that yields the lowest generalized cost of travel either in the form of reduced travel time, reduced number of transfers or reduced fare charge. According to this formulation, the probability to board a given transit line ( $P_a$ ) equals

With  $\lambda$  being the logit scale factor of the transit line choice model.

Ca is the generalized cost of traveling using transit line A

The logit transit line choice model demonstrates that the degree to which passengers will take transit lines of lower generalized cost depends on the transit line logit scale factor  $\lambda$ . The higher the value for  $\lambda$ , the more people will board a transit line with lower generalized cost. Consider an example in which a stop is served by two transit lines A & B with respective frequencies 1 & 2 per hour. The generalized costs are 15 and 25 for A & B respectively. Using the optimal transit line choice model, 66.7% of passengers will use line B despite its higher cost. This corresponds to setting the scale parameter of the logit model to zero. Increasing the value of the logit scale factor  $\lambda$ , more passengers will tend to use the cheaper transit line A. The graph below better illustrates this approach.



FIGURE 10. Effect of the Logit Scale Factor on the Transit Line choice model.

A partial sensitivity analysis is performed in this thesis and discussed in section 5.3.3 to understand the effect of the logit scale factor of the transit line choice model on transit assignment output.

#### 4.3.1.4. Schedule Path Building Algorithm

In OmniTRANS, the determination of the travel path(s) is controlled by the schedule path building algorithm made up of six parameters. These six parameters are;  $\alpha_{cost}$ ,  $\beta_{cost}$ ,  $\alpha_{time}$ ,  $\beta_{time}$ ,  $\alpha_{transfer}$ ,  $\beta_{transfer}$ . Setting these parameters in OmniTRANS is done using the property *schedulePathFactors* and by default, their values respectively are [1.3, 0, 1.5, 0, 1, 1]. Literally, this means only paths with cost falling within 30% of the cheapest option, whose time is 50% of the fastest option, with extra one transfer compared to the most direct option should be determined. This algorithm uses a branch and bound technique to find the optimal path(s) through the network (Tong & Wong 1999; Ruihong & Zhong-Ren 2002). For any path to be included in the path choice set, it is necessary that these parameters obey the following conditions from a give origin S (Veitch & Jamie 2011).

- $C_p < \alpha_{cost}C_s^{min} + \beta_{cost}$
- $T_p < \alpha_{time} T_s^{min} + \beta_{time}$
- $N_p < \alpha_{transfer} N_s^{min} + \beta_{transfer}$ .

Where  $C_p$  is the cost of using path P and  $C_s^{min}$  is the current minimum cost to the stop S. Altering the values of these parameters will definitely alter or change the travel paths included in the choice set. In this light, it will be very important in future studies to do a sensitivity analysis (partial, Best or Worst Case) on these parameters to understand which parameters affect significantly the path choice set.

To build travel paths more efficiently, OmniTRANS also considers the possibility of having walk-only paths in which no access, transfer and egress legs are necessary. This is sensible especially in situations where it is less costly to walk between centroids rather than using transit path. Setting the OmniTRANS property; *walkbBetweencentroids=True* permits the inclusion of walk-only paths. Otherwise, by default this property is set to *false* and OmniTRANS has as duty to search for paths with have an access, transfer and egress leg and which may even be more costly.

<u>N.B.</u> Path-choice results obtained from NMBS-mobility (2012) shows that, limiting the number of transfer in an assignment module such as OmniTRANS does not certainly lead to optimal path choices. However, striking a balance between the gain in travel time by permitting many transfers and travel discomfort due to these many transfers is important. This is one of the possible experiments to be performed in sensitivity analysis.

#### 4.3.1.5. The Generalized cost function in OmniTRANS

The transit generalized cost of travel used in OmniTRANS is a weighted sum of five variables. These variables are: - Travel distance, Travel time, waiting time, Penalty and the transit fare. OmniTRANS calculates the cost of travel for each mode be it in transit, access and egress mode. Not all variables of the generalized cost function are used in determining the cost of travelling through a given mode e.g. waiting time; penalty and fare are often related to the transit mode. The figure below clearly defines the cost variable associated to each travel mode (Veitch & Jamie 2011).

									@ Transfer Stop						
	Access		@ Access Stop		In-transit-vehicle		Walk Transfer		(point of reboarding)		@ Egress Stop		Egress		
	Travel time	Distance	Waiting time	Penalty	Travel time	Distance	Fare	Travel time	Distance	Waiting time	Penalty	Waiting time	Penalty	Travel time	Distance
Generalised cost *															
Travel time															
Distance															
Waiting time															
Penalty															
Fare															

#### FIGURE 11 Components of the Generalized Cost Skims.

The generalized cost function used in OmniTRANS as defined by Veitch & Jamie (2011) is given thus:

Where

- C is the generalized cost of travel
- m is the transit mode
- n is the non-transit mode used for access and egress

 $D_m$ ,  $T_m$ ,  $W_m$ ,  $P_m$  and  $F_m$  refer to travel distance, travel time, waiting time, penalty (in hours) and fare incurred on mode m respectively during the journey. Their respective weights are  $\alpha_m$ ,  $\beta_m$ ,  $\gamma_m$ ,  $\delta_m$ ,  $\epsilon_m$ . These weights are introduced in omnitrans using the property *OtTransit.routeFactors* with default values [0, 0.0, 60.0, 60.0, 60.0, 1.0]. A sensitivity analysis will be carried on the parameters of the generalized cost function.

<u>N:B.</u> In OmniTRANS, all variables are converted to monetary units (V=12). Thus, an hour is equivalent to 12monetary units. Also, walking time and waiting time are assumed to have higher values of time; double and one-half times their default values respectively (Veitch & Jamie 2011).

#### 4.3.1.6. Fares

Fares used in transit travel depend on each and every transit system and OmniTRANS permits a more flexible approach in the definition of transit fares. The following fare systems could be used in OmniTRANS; Distance based fares, In-vehicle time based fares, stop type based fares, stop-to-stop type based fares (Veitch & Jamie 2011). The OmniTRANS project setup permits the inclusion of multi-fare systems but only one fare system is advisable for a single run. This is in line with the works of William & J. Zhou (2007) where one or more fare systems are allowable for transit assignment. The fare system can be incorporated in OmniTRANS using the property *OtTransit.farescheme* especially when multi-fare schemes

exist but if only one fare scheme is available, OmniTRANS automatically adopt it for the travel fare.

## 4.4. The outputs of OmniTRANS

Two main types of outputs can be obtained from OmniTRANS; Skim outputs and assignment outputs (Veitch & Jamie 2011).

## 4.4.1. Skim outputs in OmniTRANS

Skims in OmniTRANS refer to costs tables for each origin destination pair. These skims are created for each travel leg; access, transit, transfer and egress. Skims are important to OmniTRANS and are used by the algorithms to assign transit demand. The skim matrix for each and every leg depends on the generalized cost variables associated to the leg as described in FIGURE 11 above. Aggregated skims contain attributes of an entire OD trip while disaggregated skims contain attributes of each and every transit leg. An example is shown in appendix 3.

## 4.4.2. Assignment outputs.

Assignment outputs in OmniTRANS are made up of; link output, stop output, and Transit line output (Veitch & Jamie 2011). OmniTRANS displays the result of these outputs using designers such as pie charts, bandwidths, compare variants and reports. These various outputs are explained below.

## 4.4.2.1. Link Outputs

Link outputs display the total passenger flow on a link. The fields of this output are many and may require a combination of two fields to obtain the desired results. For instance, *load\*length* will produce the total number of passenger distance travel for walk as the accessegress mode. Some other link output fields include:

- *Sum(load)* field which stores the total number of passengers travelling on a specific link.
- *Sum(cost)* field which stores the generalized cost of travelling on the specified link.
- *Sum(length)* field which stores the total passenger distance travel on a particular link.

## 4.4.2.2. Stop Output

The stop output in OmniTRANS shows the passenger flow at a specific stop. The fields of the stop output table depends on the template used. Some of the output fields include:

- *Sum(changeboarding)* field which stores the output of the total number of passenger transfers made at a particular stop.
- *Sum(dwelltime)* field which indicates the total number of service time spent on a particular stop.
- *Sum(changealighting)* field which stores the total number of passengers alighting at a particular stop.
- *Sum(Walkboarding)* and *sum(walktalighting)* fields indicates the total number of passengers walking to another stop to board a service and who just alighted from the previous stop.

The total boardings and Alightings can be calculated as; *Total Boardings=Boarding + Changing + Walkboardings Total Alightings= Alighting + changing + walkalighting.* 

## 4.4.2.3. Transit line output

The Transit line output stores the number of passengers using a defined transit line. It can also store the total number of passengers travelling in a transit network, the total passenger travel distance as well as the total passenger travel time. These results can also be determined for each and every transit line in the network.

Some of the o

utput fields used are:-

- *Sum(Passengers)* field which store the total number of passengers who board a specific transit line or using transit services.
- *Sum(Passdistance)* field which stores the total number of passenger distance units travelled on a specified transit line.
- *Sum(passtime)* field which stores the total number of passenger time traveled in a particular transit line.
- *Sum(seats)* field which stores the total number of passenger seats available for a given transit line.

## 4.5. The Crowding function as used in OmniTRANS

In-vehicle crowding has the tendency to increase the generalized cost of travelling: travel time & comfort (Zheng & Hensher 2011). As more passengers aboard a transit service, its capacity is reduced and this may get to a point where passengers begin to sense an increased cost of traveling using this transit line. The crowding function is used in OmniTRANS to perform an iterative assignment given that transit line assignment is inversely related to its load. This is necessary in providing more accurate results especially when the transit infrastructure operates at above capacity (transit demand > supply). The reason behind the usage of the crowding function is to associate a component of the generalized cost function to be directly related to the loads on a given transit line. This is achieved in OmniTRANS by introducing a 'crowding factor' on each road segment.

The crowding factor takes into account the passenger load on the road segment; the sitting and the crush capacity of the transit line. A crowding factor of 0.0 is used for an empty vehicle, 1.0 for a transit line with loads being equal to seat capacity and 2.0 for a transit line with loads being equal to crush capacity. Multiplying the crowding factor with the travel time of each route segment produces an additional cost which could be included in the generalized cost of travel. As the loads on a transit line increases, the crowding factor also increases and this may cause passengers to switch to alternative transit lines or use different modes because the cost of using this transit line increases (Veitch & Jamie 2011). This increase in cost could either be an increase in travel time or an increase in the discomfort of using a particular transit line (Cepeda et al. 2006; Schmöcker et al. 2008).

The crowding function f can be defined as

 $F_{\text{crowding}} = F(V_c)$ 

#### Where

 $F_{\text{crowding}}$  is the crowding factor, V<sub>c</sub> is the volume capacity ratio and F is the crowding function. The *FIGURE 12* below illustrates the effect of the crowding factor (Veitch & Jamie 2011).



FIGURE 12. The Crowding Function in OmniTRANS.

<u>N.B.</u> The Bureau of Public Roads (BPR) function is used in OmniTRANS to model the effect of congestion. This function is given by

$$t_{a}(q_{a}) = \frac{la}{V_{a}^{max}} 1 + \alpha \left(\frac{qa}{ca}\right)^{\beta} \qquad (15)$$

Where la is the length of link a,  $V_a^{max}$  is the maximum speed on link a,  $C_a$  is the capacity of link a.  $\alpha$  and  $\beta$  are parameters of the function which do vary for each link.  $t_a$  is the travel time on link a which depends on the link load  $q_a$ .

## 4.6. Transit Assignment Methods Applicable in OmniTRANS

Unlike PARAMICS, VISUM, which can perform both static and dynamic assignment, OmniTRANS can perform only static transit assignment (Jeihani 2007). This assignment method is made up of; an all or nothing assignment, Stochastic assignment, deterministic or volume averaging assignment, and a stochastic equilibrium assignment. A detail discussion about these assignment methods has been given in section 2.2.1. and can be summarized by the figure below.

		Congestion Effect modeled?			
Random component		No	Yes		
in route cost?	NO	All or Nothing Assignment	Deterministic equilibriu		
			Assignment		
	Yes	Stochastic Assignment	Stochastic	Equilibrium	
			Assignment		

Figure 13 Assignment methods performed in OmniTRANS.

In a nutshell, the all or nothing assignment is performed in OmniTRANS by writing and running the property transit.assignMethod=AON in the job engine. For a deterministic or volume averaging assignment which takes into account crowding; passenger loads (volume) and the capacity of the transit vehicle, the property transit.assignMethod='VOLAVG' or transit.assignMethod='VOLUMEAVERAGING' is written and executed in the OmniTRANS job engine (Veitch & Jamie 2011).

### 4.7. Conclusion

Conclusively, OmniTRANS has its strengths, Weaknesses, Opportunities and Threats (SWOT). As its strength, OmniTRANS can do both traffic and transit assignment. More to this, it is multi-dimensional, has an adaptable job engine to suit the needs of different users, a RDBMS to manage the objects and data, a graphical user interface, etc. It has the capacity to automatically update task performed in an older version when running them in a newer version but the reverse is not true.

As its weakness, OmniTRANS do not compute on its own trip productions and attractions and this data is imported from other packages. The simulation run times for a single job for the network used in this thesis are almost unbearable using an Intel® core TM i5 CPU with 4.00 GB RAM. The transit network of Flanders-Belgium used in this thesis consisted of about 3332 zones of about five kilometers square each and running a single iteration with an all or nothing transit assignment method took about 20 minutes. Also, files stored in distant directories in a computer are difficult to be accessed by OmniTRANS.

For its opportunities, OmniTRANS easily works with data processed in other packages such as FEATHERS (Janssens et al. 2007). The data input for this thesis was a product of FEATHERS. Just like TRANSIMS, MATSIMS, TASHA, OmniTRANS can also export data to other processing packages (Ramaekers et al. 2012). In addition, it has an in-built report manager permitting the automatic generation of reports for analysis.

As a threat, OmniTRANS can easily scratch when the network size is too large. It should be noted that, all these comments are based on the OmniTRANS version 6.0.1.

#### **CHAPTER 5: DATA EXPERIMENTATION & ANALYSIS IN OMNITRANS**

## 5.1. Introduction

This chapter discusses how sensitivity analysis is carried out in OmniTRANS and brings out the result of the sensitivity analysis. Only partial sensitivity analysis has been performed in this thesis and on the parameters of the generalized cost function, on the access stop choice model and the transit line choice model. This analysis will help provide a sufficient answer for the fifth research question of this thesis cited in section 1.3. This chapter begins with an exploratory analysis of the dataset and goes forth to explain the experiments and the results obtained.

## 5.2. Exploratory analysis of the dataset.

The Input data for the experiments is a transport network of Flanders-Belgium on a Monday at 8 o'clock morning. Data was available for all travel modes but only transit modes (Train, Light-rail and bus) were included for the experiments. The transit network constitutes of a transit demand of about 3332 zones of about five square kilometers each. Sensitivity analysis of this network involves performing a number of transit assignments in OmniTRANS. One hundred iterations were generated to perform a partial sensitivity analysis on the parameters of the generalized cost function and thirty iterations each were made for the sensitivity analysis on the access stop choice model and the transit line choice model.

For the sensitivity analysis, walk was considered as the only access-egress mode or nontransit mode. The One hundred iterations for the sensitivity analysis of the generalized cost function were performed starting from a base scenario in which all parameters of the generalized cost function were assumed a fixed weight of 2.5 each. The various parameters represent travel distance, travel time, waiting time, transit penalty and transit fare and were denoted respectively by the following symbols  $\alpha m$ ,  $\beta m$ ,  $\gamma m$ ,  $\delta m$ ,  $\in m$ . The parameters of the generalized cost function used by OmniTRANS had been discussed in section 4.3.1.5. Weights were equally introduced for the access-egress distance ( $\alpha n$ ) but no weight was attributed to the access-egress walk time ( $\beta n$ ). A maximum of 2 transfers was considered for the experiments. A simple script for the experiments on the generalized cost function is shown in appendix 4.

To perform a partial sensitivity analysis of the generalized cost function as used in OmniTRANS and discussed in section 4.3.1.5, a maximum of 5 weights were given to each and every parameter of the generalized cost function starting at 0.2 weight per parameter. 25 experiments were performed for each parameter with a constant ratio of 20% for every new

simulation using an all or nothing transit assignment method. Since no information from the dataset was available for the transit fare parameter ( $\epsilon_m$ ), this parameter was attributed a null value in the experiments. These weights were introduced in OmniTRANS using the property *my\_transit\_assignment.routeFactors*.

## **5.3.** The Experiments.

The results of the experiments explained below help to demonstrate the extent to which the size of the parameters of the generalized cost function has on transit assignment. This will help provide a sufficient answer to the fifth research question of this thesis and discussed in section 1.3. The experiments are explained in the following sub-sections. Apart from the experiments conduction on the generalized cost function, section 5.3.2 and 5.3.3 also discusses a partial sensitivity analysis of the access-stop choice model and the transit line choice model respectively which are intended to provide a sufficient answer to the sub questions of the fifth research question.

#### 5.3.1. Partial sensitivity analysis of the generalized cost function

This section discusses the partial sensitivity analysis performed on the parameters of the generalized cost function. It should be recalled that performing a partial sensitivity involves keeping some parameters constant and varying a few. This is exactly what has been done for the experiments.

#### 5.3.1.1. Varying αm (distance parameter) and keeping other parameters constant

Assuming that all other parameter weights are kept constant at 2.5 and only  $\alpha$ m (value for distance parameter) is being varied from 0.2 to 5.0 at the rate of 20%, the following outputs were obtained in OmniTRANS.

A close look at FIGURE 14 below shows the marginal percentage effect of varying weight values for the distant parameter on the assignment outputs. It should be recalled that the assignment outputs discussed here are the percentage passenger travel distance, travel time, number of transfers, total number of passengers, and the passenger access egress distance. The distance parameter portrays a normal distribution on the percentage number of transfers but on the opposite. The travel distance marginally decreases as more weights is being associated to the distance parameter but this is no longer evident when weights reaches a value of 2.6. More so, the marginal percentage number of passengers almost remains constant while varying the weights but the margin is highest when weight values are 2.6. The marginal number of transfers witnesses the highest variation (-150%) when the distance

parameter weights are being modified as depicted in the graph below. The most significant variation is when weights of 2.6 are used for  $\alpha$ m.

Also, the marginal Access-Egress distance is highest (about 20%) when weights of  $\alpha$ m are 2.6 and goes down to almost 0% afterwards. This shows that any weight associated to the distance parameter below 2.6 has a better impact on the passenger access-egress distance than weights greater than 2.6. It can therefore be concluded at this level that weights of  $\alpha$ m=2.6 yield an optimal solution while keeping other factors constant.



FIGURE 14. Marginal Percentage effect of varying weight value for distance parameter  $(\alpha m)$ .

The cumulative plot below in FIGURE 15 explains the trend of varying the distance parameter ( $\alpha$ m). The percentage number of passenger distance traveled decreases as more weights are being associated to  $\alpha$ m and is almost constant at weight value equal 2.6 and more. The percentage number of passengers is fairly constant for each and every weight introduced. The percentage travel time decreases and is almost constant when weights of 2.6 are introduced. The percentage number of transfers reduces drastically as more and more weights are being associated to  $\alpha$ m but the decrease in the number of passenger transfers is no longer acute when weights of 2.6 or more are introduced in the module. In economic terms, the passenger travel distance, the passenger travel time, the number of transfers, undergo a decreasing and then constant returns to the parameter value  $\alpha$ m of the generalized cost function while keeping other factors constant. The access-egress distance undergoes an increasing and then constant returns to the variable factor  $\alpha$ m of the generalized cost function.



FIGURE 15. cumulative % effect of varying weight value for distance parameter ( $\alpha m$ )

#### 5.3.1.2. Varying βm (Travel time parameter) and keeping other parameters constant.

Assuming other parameter weights are held constant except for travel time parameter ( $\beta$ m) of the transit generalized cost function as used in OmniTRANS, and considering the marginal effects of each weight variation, FIGURE 16 below shows that the marginal percentage travel distance varies at an almost constant rate. The percentage changes on the number of passengers, the passenger travel time, and the access- egress distance keeps fluctuating. This portrays that there could be many optimal and sub-optimal situations (weight values). For instance, a weight value of  $\beta$ m=2.6 and  $\beta$ m=4.2 yields an almost equal marginal percentage effect on the number of transit passengers. The access-egress distance is marginally minimum when  $\beta$ m=1.2. The number of transfers fluctuates violently at each variation of the value of  $\beta$ m but is most sensitive when  $\beta$ m=2.2.



FIGURE 16. Marginal % effect of varying weight value for Travel time parameter ( $\beta m$ ).

The cumulative plot below shows the trend of varying  $\beta m$ . The Percentage passenger travel distance and travel time decreases as more and more weight is attributed to  $\beta m$  while the percentage transit passengers and the access-egress distance increases. The number of transfers keep fluctuating but decreasing as shown in FIGURE 17 below. It could be concluded at this point that  $\beta m$  affect the number of transfers but not significantly the travel distance, the number of passengers, the travel time and the access-egress distance taking into account the slope of their respective curves.



FIGURE 17. Cumulative effect of varying weight value for travel time parameter (βm).

## 5.3.1.3. Varying γm (Waiting time parameter) and keeping other parameters constant

Assuming other parameter weights are held constant at 2.5 each and varying the weight value for waiting time parameter ( $\gamma$ m), FIGURE 18 below shows that the percentage difference of each variation of  $\gamma$ m is not significant for the marginal percentage travel distance, number of passengers, the travel time, and the access-egress distance and is really fluctuating for the passenger number of transfers.





A look at FIGURE 19 below is a cumulative plot of the waiting time parameter ( $\gamma$ m) which shows that the percentage passenger distance traveled and travel time increases as more and more weight is attached to  $\gamma$ m. The percentage access-egress distance and the number of passengers decrease as more weight is associated to  $\gamma$ m. The number of transfers keeps fluctuating given any additional weight associated to  $\gamma$ m but portrays much more an increasing trend. From figure 19 below, it could be concluded that the percentage number of transfers is much more affected by associating different weight values to  $\gamma$ m but not significantly the travel distance, travel time, number of passengers or even the access-egress distance given the slope of their respective graphs.



FIGURE 19. Cumulative % effect of varying weight value for waiting time parameter (ym)

## 5.3.1.4. Varying δm (penalty) and keeping other parameters constant

Assuming all parameter weight values are held constant at 2.5 except for that of the penalty factor ( $\delta$ m), FIGURE 20 below shows that there is no significant marginal percentage variation realized for the total percentage passenger travel distance, number of passengers, travel time, and the access-egress distance except for the number of transfers. It could be concluded that varying  $\delta$ m effects significantly the number of transfers made and this effect is even more critical when weights of 2.6 and 3.4 are associated to the transit parameter  $\delta$ m while keeping other factors constant.



FIGURE 20. Marginal % effect of varying weight value for penalty parameter ( $\delta m$ )

More so, the cumulative plot in FIGURE 21 below shows that as more and more weight is associated to  $\delta$ m, the percentage number of passengers and the access-egress distance decreases. The percentage travel time and the travel distance keeps increasing but the percentage number of transfers portrays no specific trend.



FIGURE 21. Cumulative effect of varying weight value for penalty  $(\delta m)$ 

## 5.3.1.5. General effect of changing the parameter values of the generalized cost function.

FIGURE 22 below shows that except for the distance parameter ( $\alpha$ m) which response significantly to the percentage passenger travel distance when weights are introduced, other parameters influence less though having at least about 70% effect on the passengers travel distance. There exist an intersection of all parameter weights at value 2.6 and this can be considered a critical value for travel distance since even the influential distance parameter becomes less significant.





It can also be seen in FIGURE 23 below that the total percentage effect of varying weight values do not have the same impact on the number of passengers. While there is an increasing trend on the number of passengers when more and more weights are being attributed to the travel time parameter, there is equally a decreasing trend when more weight is attributed to the penalty parameter and waiting time parameter. The percentage number of passengers decreases when more and more weights are attached to the travel distance parameter but when these weights attain the value 2.2, the percentage number of passengers increases rapidly and then begins to stagnate when weights of about 3.4 or more are associated. Most importantly, parameter weights of 2.6 yields an almost equal (91%) number of passengers for all parameter values.


FIGURE 23. Total effect of varying all weight values on the number of Passengers

Furthermore, FIGURE 24 shows that except for the distance parameter which shows a significant variation on the travel time as more weights are introduced to this parameter, other parameter values portray little or no effect (almost constant at about 63% of the travel time). However, all parameter values produce an almost equal effect on the travel time when weights of 2.6 are attributed.



FIGURE 24. Total effect of varying all weight values on passenger Travel time

In addition, FIGURE 25 illustrates that only the distance parameter significantly influences the number of transfers though all parameters produce the same effect when weights are equal to 2.6.





More so, FIGURE 26 clearly shows that the access-egress distance is affected by about 90% of the parameters of the generalized cost function with little fluctuations by the distance parameter. As more and more weights are attributed to the distance parameter ( $\alpha$ m), the access-egress distance increases, reaches a set maximum and then remains almost constant.



FIGURE 26. Total effect of varying all weight values on the Access-Egress Distance

# 5.3.1.6. Average effects of varying all weight values on transit assignment.

In a nutshell, the percentage average travel distance, travel time, number of transfers, number of passengers as well as the access-egress distance are influenced differently by the parameters of the generalized cost function as shown in FIGURE 27 to FIGURE 31 below.



FIGURE 27. Average percentage effect of varying all parameter weight values on travel distance

About 76% of the travel distance is influenced by the distance parameter value while about 70% of the travel distance is influenced by the travel time, waiting time and penalty parameters respectively.





On average, about 73% of passenger travel time is influenced by the distance parameter value while about 63% of the passenger travel time is influenced by the travel time, waiting time and penalty parameters respectively.



# FIGURE 29. Average percentage effect of varying all weight values on the total number of passengers

On average, about 96% of the number of passenger is influenced by the distance parameter value while about 91% of the number of passengers is influenced by the travel time, waiting time and penalty parameters respectively.



FIGURE 30. Average percentage effect of varying all parameter weight values on the number of transfers

On average, about 32% of the number of transfers is influenced by the distance parameter value while only about 5% of the number of transfers is influenced by the travel time, waiting time and penalty parameters respectively.



FIGURE 31. Average percentage effect of varying all weight values on passenger accessegress distance travel

On average, about 70% of passenger access-egress distance is influenced by the distance parameter value while about 90% of the passenger access-egress distance is influenced by the travel time, waiting time and penalty parameters respectively.

Considering the average effect of varying all parameter values on transit assignment, it is noticed as shown in FIGURE 27 to FIGURE 30 above that the travel distance parameter plays a very big role on transit assignment. About 76% of the passenger travel distance is influenced by this parameter while other parameters (travel time, waiting time, penalty) have an almost equal effect of about 70%. More so, the travel distance parameter has about 96% influence on the average number of passenger travelling but the travel time, waiting time and the penalty parameters has only about 91% influence on the number of passengers. Also, the travel distance parameter affects about 73% of the travel time used by passengers but the other parameters in the module has only about 63% effect on the passenger travel time. About 32% of the transfers is being influenced by the distance parameter whereas only about 5% of the transfers is influenced by any of the other parameters.

On the other hand, the travel distance influences less the access-egress distance (about 70%) while the other parameters (travel time, waiting time, penalty) has about a 90% influence each on the passenger access-egress distance.

#### 5.3.2. Partial sensitivity analysis of the access stop choice model (logit scale factor).

Under default transit assignment conditions, OmniTRANS considers an optimal access stop choice model in which all passengers are assigned to routes with lower generalized cost of travel. On the contrary, the logit scale parameter of the access stop choice model assumes that some passengers will access the transit service at specific stops yielding a lower generalized cost (Veitch & Jamie 2011). A partial sensitivity analysis is performed on the access stop choice model logit scale factor discussed in section 4.3.1.2. The results are only valid for the dataset used in this thesis (transport network of Flanders-Belgium on a Monday at 8 o'clock). A simple job script written and executed in OmniTRANS for the various iterations of this sensitivity analysis is shown in appendix 5. The results are presented in FIGURE 32 below. This figure shows that as more and more weight is associated to the logit scale factor of the access stop choice model, the percentage travel distance, number of passengers, travel time, number of transfers, and the access-egress distance keep reducing. This decrease is an explanation of the fact that the generalized cost of travel reduces. The percentage access egress distance reduces from about 100% to about 87.5% with scale factor variation from zero to about three units. The percentage number of transfers is least affected when varying the value for the logit scale factor.



FIGURE 32 Effect of the Access stop choice logit scale factor on transit assignment

FIGURE 33 below shows that at least 1% of transit assignment is influenced by the access stop choice logit scale factor. The access-egress distance is most affected by the logit scale factor (8%). On average, about 99% of transfers are obtained which shows that the access stop choice model logit scale factor influences this output least.



FIGURE 33. Average percentage effect of varying the access stop choice logic scale parameter on transit Assignment outputs.

It is equally realized as shown in FIGURE 34 below that, the cumulative marginal difference on transit assignment outputs between subsequent variations of the logit scale factor of the access stop choice model tends to be lower as more and more weights are associated to this factor. This decrease is more felt by the access-egress distance.



# FIGURE 34 Marginal effect of changing the logit parameter of the access stop choice model on transit assignment

Hence, it can be concluded at this level that, the logit access-stop choice model actually affects transit assignment. The access egress distance tends to reduce more significantly with the consideration of the access stop choice model logit scale factor in transit assignment. This stop choice model equally shows that the number of transfers least affects transit assignment (1%). The percentage travel time, travel distance and the number of passengers equally proof to be affected by the logit scale factor of the access stop choice model. This partial sensitivity analysis of the access-stop choice model shows that, giving more weights to the logit scale parameter of the access-stop choice model, the access-egress distance is more affected in transit assignment than any other assignment output.

#### 5.3.3. Partial Sensitivity analysis of the transit line choice model (logit scale factor).

A partial sensitivity of the logit scale factor of the transit line choice model in FIGURE 35 shows that the logit scale factor of the transit line choice model does not affect transit assignment outputs at all. This partial sensitivity analysis was performed in other to provide and answer for the sub-question of the fifth research question. The conclusion is that the logit scale factor of the transit line choice model may have an influence on transit

assignment and also that transit assignment of this network is already working at an optimal level in such a way that no further modeling on the transit line is necessary.



FIGURE 35 Total percentage effect of the transit line choice model (logit scale factor) on transit assignment outputs

## 5.4. Conclusion.

Conclusively, it can be said that on average, about 70% of passenger travel distance is influenced by the parameters of the generalized cost function irrespective of the weights but for the travel distance parameter which exhibits much variation at lower weights (see FIGURE 26). Also, except for the distance parameter, all other parameters affect about 91% of the number of travel passengers, about 65% of the percentage travel time, and about 5% number of transfers. In addition, about 90% of the access-egress distance is being influenced by these parameters. This shows that, associating weights to the parameters of the travel distance, travel time, number of passengers but not the percentage number of transfers. This leads to a conclusion that, the travel distance, travel time, waiting time and penalty parameters greatly influence transit assignment outputs but not the number of transfers. This is in line with studies discussed in section 4.3.1.4 which demonstrated that reducing the number of

transfers in an assignment module does not necessarily lead to optimal path choices or reduced cost of travel. All transit assignment solutions were optimum or converging at parameter weights of 2.5.

As a whole, the results presented shows that the passenger travel distances influences more significantly transit assignment, that the logit scale factor of the access-stop choice model affects significantly transit assignment and that the logit scale factor of the transit line choice model does not influence transit assignment of the said network, can help decision making in many domains. For instance, reducing the passenger travel distance through reduce activity space, reducing access-egress distances to boarding points, instituting missing links where necessary to reduce passenger travel distances and better urban planning.

#### **CHAPTER 6. GENERAL CONCLUSION.**

### 6.1. **Observations**

It has been observed throughout this research work that, much scientific research has been carried out on traffic assignment than transit assignment. Because of this, finding sufficient scientific papers on important issues were difficult to come by. In this respect, it was difficult finding scientific documents in which a sensitivity analysis has been carried out in the algorithms of a transit assignment software package talk less of OmniTRANS. Many studies made in the domain of transit assignment have shown interest in understanding the problem of capacity restraint in transit assignment. This thesis contributes its quota to many research works by successfully demonstrating that the travel distance, travel time, waiting time and penalty parameters of the generalized cost function greatly influence transit assignment. Though this may contradict some studies, the fact remains valid for Flanders-Belgium in which the dataset was obtained for a Monday at 8 o'clock. This conclusion was arrived at based on the assumptions made in conducting the experiments.

Furthermore, just as discussed in section 2.3.1 in which many studies are of the opinion that waiting time and travel time are very important factors influencing transit assignment, it has equally been demonstrated in this thesis that higher weights associated to these parameters affect more on transit assignment (section 5.3). More so, just as highlighted in section 4.3.1.4, this thesis has also proven that limiting the number of transfers in an assignment module such as OmniTRANS does not certainly lead to optimal path choices. It has been proven that the numbers of transfers are less influenced by the parameters of the generalized cost of travel. However, striking a balance between the gain in travel time by permitting many transfers and travel discomfort due to these many transfers is important. It will even be important to study the optimal number of transfers in OmniTRANS by performing a sensitivity analysis in further studies.

### 6.2. Further Research

Further research on sensitivity analysis could be:

To perform a Monte-Carlo sensitivity analysis on the access stop choice model and the transit line choice model and to understand an optimum or minimum values on the respective parameters yielding optimal or minimal results.

To perform a Partial sensitivity analysis on the crowding function used in OmniTRANS. This could be to understand the effect of changes in the usage of different value(s) of the crowding function given different transit load levels or to know whether this crowding factor could have the same value for the different transit demand levels over the network. In this type of analysis, the road network can be segregated into two types; an urban road segment (high transit demand) and a local road segment. This kind of analysis will help in transit policy developments such as changes in the bus frequencies depending on the road segments.

To perform a Partial sensitivity analysis on the various fare schemes applicable in OmniTRANS and comparing their effects on the generalized cost of travel. In this light, distance based fare scheme can be compared with in-vehicle time based fare scheme and so on. This can help policy development in setting fare schemes that are more profitable to public transport companies as well as transit users. It will also be of interest to ascertain the accuracy of OmniTRANS by conducting a comparative study with other software packages such as MILATRAS or EMME/II as shown in Kucirek (2012). This could just be by repeating the experiments carried out in this thesis using other transit assignment software packages.

To perform a partial sensitivity analysis on zoning systems. This type of study will involve performing transit assignment on two different types of transit networks of Flanders-Belgium. A detail transit network (the one used in this thesis) which consists of transit zones of about five kilometers each and a sub-level transit network in which transit zones will be made up of zones of about three kilometers square each. The sensitivity analysis will help our understanding of the impact of the zoning system on transit assignment. The transit assignment outputs of OmniTRANS can be used for such a comparative study. Also, the transit generalized travel cost for a given origin destination pair can be studied assuming that these OD pair lie in different zones of the sub-level zoning systems as well as in the same zone of the detail zoning system. A comparison of this generalized travel cost could show if the zoning system have an effect on transit assignment. An access stop choice model and a transit line choice model could also be studied for the different zoning systems and their effects on transit assignment verified because it seems more likely that the access stop as well as the transit line choice will differ given different zoning systems. Well, this could be determined in a further study.

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# Appendix

 Representation of a transit stop in a general network (J. H. Wu et al. 1994; Nigel & Agostino 2004).



2. <u>Sequential network choices</u>



#### 3. Aggregate and disaggregate skims



4. <u>A simple Script for the simulated experiments for partial sensitivity analysis on the</u> generalized cost factors

# define mode numbers (from the dimensions)
Walk = 40
# create instance of OtTransit and set the modes property
my\_transit\_assignment = OtTransit.new
my\_transit\_assignment.modes = [[Walk,Walk]]
# define the parent transit mode number (from the dimensions)
PT = 30
# define the time period number (from the dimensions)
AM = 108
# create instance of OtTransit and set the network property
my\_transit\_assignment.network = [PT,AM]
# define mode numbers

CAR = 10WALK = 40TRAIN = 32*BUS* = *31* LRT = 33# define the sets of weighting factors for both transit (distance, time, wait, penalty, fare) and non-transit modes used for access/egress/transfer (distance, time, linkCost, fixedCost). rfTrain= [TRAIN, 2.5, 2.5, 2.5, 2.5, 0] *rfBus*= [*BUS*, 2.5, 2.5, 2.5, 2.5, 0] *rfLRT*= [*LRT*, 2.5, 2.5, 2.5, 2.5, 0] *rfWALK*= [*WALK*, 2.5, 0, 0, 0] *# define the PMTU of the trip matrix to be assigned* purpose, mode, time, user = 1,30,108,1my\_transit\_assignment.searchRadius = [[Walk,3.0]] *my\_transit\_assignment.maxInterchanges* = 2 *my\_transit\_assignment.routeFactors* = [*rfTrain, rfBus, rfLRT, rfWALK*] *my\_transit\_assignment.numberOfThreads* = 2 *my\_transit\_assignment.minFind* = [[Walk,1]] *my\_transit\_assignment.odMatrix = [purpose, mode, time, user]* # define the PMTURI where the output passenger loads should be saved purpose = 1mode = 30time = 108user = 1*result* = 1081 *iteration* = 1*# Create instance of OtTransit and set the load property my\_transit\_assignment.load = [purpose,mode,time,user,result,iteration] my\_transit\_assignment.execute* 

5. A ruby script for the simulated experiments for a partial sensitivity analysis on the access-stop choice model and the transit line choice model. *# define mode numbers (from the dimensions)* Walk = 40*# create instance of OtTransit and set the modes property my\_transit\_assignment = OtTransit.new my\_transit\_assignment.modes* = [[Walk,Walk]] *# define the parent transit mode number (from the dimensions)* PT = 30*# define the time period number (from the dimensions)* AM = 108*# create instance of OtTransit and set the network property my\_transit\_assignment.network = [PT,AM] # define mode numbers* CAR = 10WALK = 40TRAIN = 32*BUS* = *31* LRT = 33# define the sets of weighting factors for both transit (distance, time, wait, penalty, fare) and non-transit modes used for access/egress/transfer (distance, time, linkCost, fixedCost). rfTrain= [ TRAIN, 0.0, 1.0, 1.5, 0.1, 0.2 ] rfBus= [BUS, 0.0, 1.5, 2.5, 0.2, 0.2] rfLRT= [LRT, 0.0, 1.0, 2.0, 0.2, 0.2] rfWALK= [ WALK, 0.0, 2.0, 0.0, 0.0] *# define the PMTU of the trip matrix to be assigned* purpose, mode, time, user = 1,30,108,1*my\_transit\_assignment.searchRadius = [[Walk,3.0]] my\_transit\_assignment.maxInterchanges* = 2 *my\_transit\_assignment.routeFactors* = [*rfTrain, rfBus, rfLRT, rfWALK*] *my\_transit\_assignment.numberOfThreads* = 2 *my\_transit\_assignment.minFind = [[Walk,1]] my\_transit\_assignment.odMatrix = [purpose, mode, time, user]* 

my\_transit\_assignment.logitParameters = [0.0, nil, nil]
# define the PMTURI where the output passenger loads should be saved
purpose = 1
mode = 30
time = 108
user = 1
result = 1081
iteration = 1
# Create instance of OtTransit and set the load property
my\_transit\_assignment.load = [purpose,mode,time,user,result,iteration]
my\_transit\_assignment.execute

# Auteursrechtelijke overeenkomst

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