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Allocating Departure Time Slot to Optimize Dynamic Network Capacity

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Rijkswaterstaat

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Allocating On-ramp Time Slot to Minimize the Total Travel-Time and Delay on A15 Motorway

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Colophon

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Abstract

Nowadays congestion is a big issue for the road transport. Researchers and engineers have been trying to solve this problem with many innovative ways in dynamic traffic management, such as providing alternative route choice/guidance, improving traffic control, informing travelers, etc. Few have done with regard to departure time to optimize network capacity under the context of dynamic modeling. Based on the traffic situation of A15 motorway through the Rotterdam Port, the concept of departure time slot allocation is applied to solve network congestion.

This thesis aims to get the optimum demand for departure time-slot allocation at on-ramps to alleviate congestion in the network with minimized system travel time and optimized network utilization.

Several related concepts are reviewed such as time-slot, dynamic capacity, corridor control with ramp metering and travel time. Taale (2000) gives an insight of Dutch ramp-metering. Daganzo (2001) analyzes the bottleneck mechanism in traffic streams. Interestingly, capacity in Brilon's paper (2007) is regarded as a random variable, instead of constant-value capacity. These papers offer valuable theoretical supports to consider time slot allocation at on-ramps to minimize system travel time in dynamic traffic management with as less congestion as possible.

Time slot allocation is a type of traffic planning in the time-space dimensions, of which the key characteristic is that infrastructure users have to reserve a 'slot' on the network before departure (Koolstra, 2005). Compared with ramp metering which is a continuous-traffic-loading process for individual travelers, time slot allocation is discrete for group travelers in each time period while ramp-metering brings uncertainty to the travelers. No one knows when and how long they have to wait in the queue. But time slot allocation may offer more certain information. If a traveler is allowed to go through this time slot, no congestion may meet (but no guarantee here, because accidents and other unpredicted issues can produce congestion). Ramp-metering is only used at ramps, while time slot allocation has broader practicability, at on-ramps or even in the network.

The mechanism of time slot allocation follows First-In-First-Out (FIFO) principle and they are controlled by different time slot settings. Vickrey's model is used for a reference to form the initial model concept, and system control concept is applied to make the whole concept integrated. Following an idea by Prof. Henk van Zuylen (2008), minimizing the cost of difference between cumulative desired demand and cumulative optimum demand is the main purpose for the methodology, taking capacity as a constraint. Then situations with (1) late departure only for linear programming and (2) both early and late departure with costs for non-linear programming are considered and mathematical formulations are established.

Then the objective function with the motorway A15 as case study is programmed in Matlab and the corresponding simulation in Dynasmart is carried out. After synchronization between Matlab and Dynasmart, where saturation flow in Dynasmart is made equal to road section capacity in Matlab for instance, linear programming (LP) with only late departure as a test calculation is performed. Optimum demand from LP can solve few congestion and only 0.2% of the corresponding total travel time reduction, not much as expected. For this reason, LP-iteration calculation is pursuit to check whether it reduces congestion to further extent. The main reason is that LP is an algorithm to obtain an optimum solution in one run, which is unable to handle a problem with more than 100 variables as in our case. In order to achieve the global optimum, the genetic algorithm (GA) is further applied. It is very interesting to note that such a global-searching algorithm offers almost average distribution of optimum demand, although values of early and late departure time change a lot. GA can offer the best solution when looking at traffic states. According to the queue observed at the Dynasmart simulation interface, congestion has been reduced much, though there is still congestion showing up in some certain time slots. There are 7.0% of reduction on total travel time and time-space locations of congestion remaining at to 8.9% (5 out of 56 combination of 8 time-slots and 7 locations) from original 19.6% (11 out of 56). Focusing on values of early and late departure, the larger value of late departure is, the less congestion remaining will be. The results demonstrate that departure time slot allocation can reduce congestion to quite some extent, migrating traffic among the time slots and highway sections, as we have expected.

Practically with respect to the socio-economic impacts, travelers' departure profiles can be linked to their value of travel time savings. To this extent, authorities such as Rotterdam Port, motorway operator and urban planner may take measures or design policies to promote time-slot allocation, such as providing subsidies for late departure and reward for early departure. And they may choose to give priority in specific time slots to residential and office areas during rush hours. Outside the rush hours, priority could be given to economic centers, whereas during the weekends a shopping precinct or theme park might be given priority (Rijkswaterstaat, 2003). Additionally, real-time traffic information also has strong influence to travelers' departure profiles (thus time-slot). Taking an example of a real case on 24 November 2008, when there was a heavy snow all around The Netherlands. The broadcast, Internet and other media that day repeatedly announced that there would be a big congestion in The Netherlands in the next morning (25th November). Surprisingly, not much expected congestion showed up, because most of travelers got the traffic information and departed earlier ("*Mensen eerder van huis om aangekondigde drukte voor te zijn*", www.nu.nl). As we can see, valid traffic information from authorities can change and influence the travel pattern and spreading of time-slots of travelers does help alleviate, if not completely solve, the congestion problem.

Key Words: Departure time slot, Dynamic network capacity, Traffic state, A15 motorway, Generic algorithm, Mecroscopic simulation.

Preface

This report is the final product of my MSc thesis, which can also be taken as a milestone of my two-year study at TU Delft, towards becoming an engineer. The graduation work is executed on behalf of DHV and Dienst Verkeer en Scheepvaart (DVS) of the Dutch Ministry of Transport, Public Works and Water Management (Ministrie van Verkeer en Waterstaat). The research output will be contributed as a reference to get a fresh idea to alleviate network congestion.

I feel indebted and grateful to my supervisor, Prof. Henk van Zuylen, for providing me a good opportunity to manage a quite new topic and giving me support during this work; my daily supervisor, Dr. Yusen Chen, for offering sufficient guidance and patient monitoring; Ir. Wim van der Hoeven, for supporting and providing enough information on my Questor/Dynasmart learning; Ir. Solomon Kidane Zegeye, for great advice on clean Matlab languages; and Dr. Henk Taale, for guiding comments on my thesis.

Especially, I would like to thank Dr. Yusen Chen. He helps me set up the concept of transport modelling/control and lets me experience the requirements as a transport modeller. His critical comments and suggestions enable me to make a progress step by step. With his help, I can make this work better than I could have done by myself.

I would like to extend my heartfelt thanks to my colleagues in DHV, namely, Wim vd Hoeven, Tjeu Giessen, Martijn Meinen, Muriel Verkaik, Ziad Mahmoud AI and in DVS Henk Taale. They help me learning the new software – Questor, Dynasmart and Monigraph, and exchange the ideas of transportation studies. I have a great time to work with them and enjoy the company culture in a Dutch way.

I would like also to extend my heartfelt thanks to Dr. Shuyan Chen, who answered my programming questions helpfully and gave me a lot of useful suggestions; and Benhamin N. Graham, who helps me adjust psychology to a better state in a professional approach.

Thanks to Transport Infrastructure and Logistics department of faculty of Civil Engineering and Geo-Science and TU Delft for providing the graduation platform, letting me form full knowledge about multi-mode transport.

Finally, I would like to thank my family who have always remained supporting me and being concerned about me. I dedicate this thesis to my parents, with love and thanks for all they have done for me throughout my life.

Yinyi Ma

Delft, 18th November 2008

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1. Introduction

Dynamic traffic management (DTM) is a hot topic nowadays, which includes both systems and services such as road side systems, lane control, speed control, vehicle control, incident management, travel information and so on. The purpose of DTM is to inform, induce and, if necessary, direct road users towards a safer and more efficient use of the existing infrastructure while safeguarding the quality of the environment of those living and working in the vicinity of the network (Rijkswaterstaat, 2003). That is to say, the right people, given the right information, will be able to make the right decisions. DTM helps creating the right balance between user needs and technology push, making it possible to fully meet the challenge, implementation and operation of traffic management in a network level, based not only on past events, but also anticipating future traffic conditions (Rijkswaterstaat, 2003).

As we know, all DTM services are to safeguard mobility and accessibility in the network through improving utilization of the available resources. After all, infrastructures bottlenecks tend to become manifest only during the certain times of day, mostly the morning and evening rush hours. If road capacity could be optimized during peak times and traffic flow spread over time, traffic states would improve considerably.

For this purpose, road operators, researchers and engineers can call on a versatile instrument of DTM, which provides such means and measures as route information panels, ramp metering, and rush hour lanes, all of which may be combined with minor infrastructural and traffic planning measures (Rijkswaterstaat, 2003). But few have been done with regard to departure time to optimize network capacity under the context of dynamic traffic modeling, which derives from departure time choice. As we know, departure time is an uncertainty issue, which depends on human behavior and traveler's individual time-table. Obviously it is challenging to use technology to influence and even to force human behavior to change. But it is indeed interesting to see how it works, since the research on departure time is a bridge connecting traffic demand and vehicles activities in the network.

Here departure time slot allocation is brought forward. Based on a case study of the traffic situation at A15 highway through the Rotterdam Port, the concept of departure time slot allocation is applied to solve network congestion (or in other words, breakdown problem, due to flow over a certain percentage of capacity).

1.1 Time Slot Allocation

Slot allocation is defined as the allocation of slots in such a way that capacity constraints are satisfied. It is a type of traffic planning in time-space dimension, of which the key characteristic is that infrastructure users have to reserve a 'slot' on the network before departure (Koolstra, 2005). Maximizing infrastructure utilization is proposed as the primary objective of time slot allocation with regard to absolute infrastructure capacity scarcity. Absolute capacity scarcity occurs when a bottleneck cannot accommodate all traffic demand with an acceptable quality-of-service within the period under consideration (Koolstra, 2005).

Normally, two types of time slot allocation exist – static and dynamic time slot allocation. The former one has fixed time-sliced periods, properly based on a forecast or pre-evaluation. All slot requirements are collected before the final time slot allocation decision is made. In contrast, dynamic time-slots are allocated according to the real-time traffic demand. All slot requests are evaluated sequentially with flexible slot periods. In this thesis, time slot is assumed as the static one but with a dynamic modeling approach.

Compared with ramp-metering which is based on signal controllers to regulate the flow of traffic entering freeways according to current traffic situation, time slot allocation has the same purpose to ameliorate traffic situation through controlling demand. But from the mechanism perspective, ramp-metering is a continuous-traffic-loading process for individual travelers, while time slot allocation is discrete for group or individual travelers in each time period. And ramp-metering brings uncertainty to the travelers. No one knows when and how long they have to wait in the queue. But time slot allocation may offer certain information. If you are allowed to go through this time slot, no congestion will meet. In addition, ramp-metering is only used at ramps, while time slot allocation has broader practicability, at on-ramps or even in the network.

It is because of the board practicability as a group solution that time slot allocation has attracted more and more attention of policy-makers and road operators. They would like to see how effective time slot allocation is in several levels: national level (socio-economic evaluation), program level (effects on a regional or national scale), measures level (effects of a specific measure on a specific location) (Taale, 2003).

Policy-maker considers more about socio-economic aspects in national level. They make polices based on the results of cost-benefit analysis or cost-effectiveness analysis. If time slot allocation can improve social welfare, improving accessibility and making travelers to reach their destinations in a shorter time, they will make a strong policy to realize it.

On the other hand, road operators should do some research on Willingness-to-Pay (WTP), which generally refers to the value of a good to a person as what they are willing to pay, sacrifice or exchange for it. WTP is the maximum monetary amount that an individual would pay to obtain a good (Wikipedia). They need to know how much and when the travelers are willing to pay for a certain time slot. In the measurement aspect, road operators in regional level may sell time slots with different prices on a certain website according to optimum demand quantity. This is suitable for the travelers who are willing to wait at the initial departure places such as home and offices and have much experience to know the exact travel time between home or offices and the entrance of time-slot allocation network. For the travelers who are on the road and will enter the time-slot-allocation network, on-line navigation system can offer time-slot information, letting travelers choose the time slots with suitable time periods and affordable prices. Therefore all these behaviors can be abstracted as a choice model of willingness-to-pay that depends on the value of travel time for travelers. Travelers with low value of travel time would take prices more into account and choose cheaper time slots. Travelers with high value of travel time care less about prices and may pay for a certain time slot.

1.2 Problem Statement

Traffic congestion is a big issue for each city around the world. Authorities have executed a large quantity of policies to solve the problem, keeping the road traffic as fluent as possible and increasing traffic capacity as much as possible, such as expending more lanes and installing more ramp metering. Meanwhile they have to take social effectiveness into account, making sure that travelers can reach their destinations within defined time. Here the defined time is a quantities concept. In the document "Towards a Reliable and Predictable Accessibility", the quantitative target for the transport policy with respect to reliability is that for trips longer than 50km over freeway 95% of the trips arrive within the time interval of the median travel time plus or minus 20%. For shorter trips the target is that 95% of the trips will be between the median travel time plus and minus 10 minutes (VW, 2005). How to combine these two aspects is a challenging topic.

It is well-known that increasing highway capacity by building more infrastructures is time consuming and costly, which is never a sustainable method. Road operators prefer carrying out dynamic traffic management (DTM) to ameliorate network congestion efficiently. Taking ramp-metering for instance, it is widely used and works well in plenty of cities solving the congestion on highways. But travelers have to wait in a long queue at on-ramps, increasing their total travel time.

With respect to these problems, time slot allocation at on-ramps is introduced. Time slot allocation is a discrete concept, which has the similar functions as continuous ramp metering to control the traffic demand. It is because of the discrete that time slot management can be abstracted or transplanted as an OD-matrix time-slot problem in dynamic traffic modeling. On the other hand, from the traveler's perspective, being discrete means that travelers can have their preferred time slots to departure certainly, so the waiting time can be migrated from one road section to other places or from one time slice to another.

The character of time slot, based on the A15-motorway corridor to the Port of Rotterdam, is examined by allocating time-slots at on-ramps of A15. There is no route choice in this corridor, so the new concept can be tested independently. Additionally, A15 motorway's congestion problem lasts for longer hours, especially in the peak hours Bottleneck situation always shows up in A15 motorway, depicted in Figure 1-1.

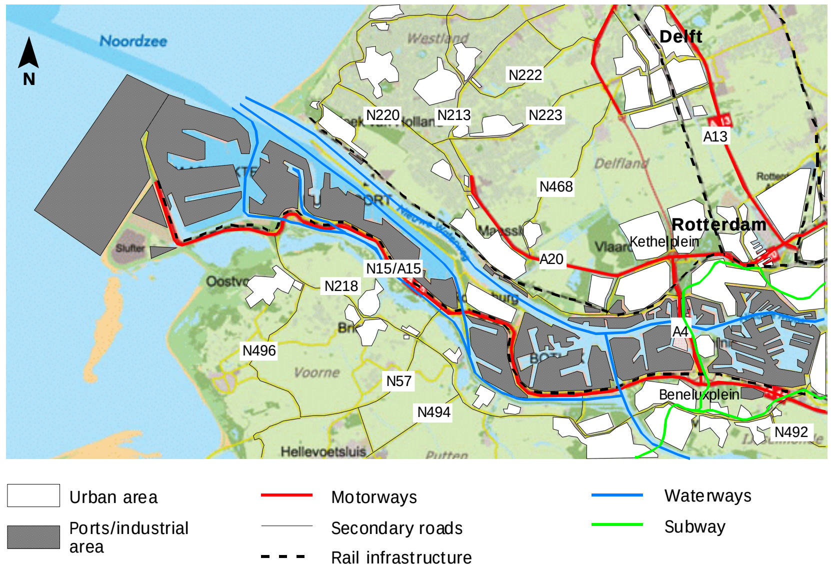


Figure 1-1: Airscape of Rotterdam Port with A15 Motorway (Van Zuylen, 2008)

Given the importance of the topic, it is therefore motivating to see how and to what extent the time slot allocation can influence the network capacity optimization in A15 motorway, and how to design the time slots.

1.3 Research Goal

Following the problem statement, this thesis will develop and test a new concept -- allocating time slots at motorway on-ramps. In the space perspective, the road capacity should be used as much as possible to optimize network utilization. And in the time perspective, system travel time is required to be minimized.

The final output of this thesis is a time-slot allocation at on-ramps, aiming at minimizing system travel time and optimizing network utilization.

Main Research Questions with this can be formulated as follows:

- Is it feasible to allocate discrete time-slots at on-ramps to solve congestion problem on the motorways?
- Does shifting traffic demand in time slots improve traffic states?
- Which algorithm is the most suitable for this case?
- Will time slots selling influence travelers' departure?

1.4 Thesis Outline

The structure of this thesis will be as follows:

Chapter 1 introduces the concept of time-slot allocation, its relationship with DTM, problem statement and research goal.

Chapter 2 is the literature review, including topics in time-slot allocation, Ramp Metering/Corridor Control, and Network Capacity Optimization. These are all individual concepts while the underlined analysis tries to integrate each of these ideas and to serve to the time-slot concept.

Chapter 3 analyzes the traffic states of A15 motorway network and the surroundings based on the monitoring data and simulation. The analysis tries to find whether there is more room left in some highway sections from time and space perspectives, and whether it is possible to use these available time slots for accommodating extra traffic to solve congestion in the network.

Chapter 4 presents the methodology and mathematical formulation. Late departure only with linear programming; and late and early departures with costs based on non-linear programming are taken as two formulation cases. Meanwhile dynamic traffic simulation is carried out to get the traffic states. Both analytical formulation and dynamic simulation are performed and combined to search for an optimum time-slot allocation.

Chapter 5 starts with a small test case to see whether the proposed methodology and framework can work and can explain the whole process in time-slot allocation. Algorithm comparison gives an idea of advantages and disadvantages of three algorithms.

Chapter 6 answers the research questions, draws useful conclusions, gives some suggestion to road authorities and main stakeholders, presents the main conclusions and proposes the future research direction.

2. Literature Review

Several state-of-art concepts are reviewed in this thesis, such as time-slot allocation, dynamic network capacity, corridor control with ramp metering and travel time. Few papers consider time slot allocation for the ramp metering to minimize system travel time in dynamic traffic management with as less congestion as possible. Fortunately, some researches do give the ideas separately about ramp metering/corridor control, time slot allocation, travel time and network dynamic capacity respectively, which have the closest relationship with the thesis topic.

2.1 Time Slot Allocation

Slot allocation is defined as the allocation of slots to departure time requests in such a way that capacity constraints are satisfied. It is a type of dynamic traffic planning in time-space dimension, of which the key characteristic is that infrastructure users have to reserve a 'time-slot' on the network before departure (Koolstra, 2005). It can be regarded as an instrument to solve conflicting traffic demand corresponding with different infrastructure users, helping to avoid traffic congestion. The main objective of slot allocation is to solve capacity conflicts beforehand in planning but not on the network where congestion would be the result.

Taking an example of time slot allocation, time from 8:00am to 9:00am is divided into four time slots with 15 minutes each. In each time slot there is certain traffic demand, but only one of them generates congestion on part of the network. Thus it is possible to shift some of the traffic demand from this given time slot to other slots, to reduce the predicted congestion. But how to shift and how much demand to be shifted are challenging questions.

Koolstra (2005) applies time-slot on all the transport modalities with theoretical analysis. Caramia (2005) uses time slot to freight delivery and offers am algorithm for switching the volume among time slots.

Koolstra (2005)
In this thesis, transport infrastructure slot allocation has been studied, focusing on selection slot allocation. It considers selection slot allocation as a separate slot allocation level. Separating selection and scheduling slot allocation enables the application to each level of different rules with respect to slot validity, valuation of alternative slot requests, etc. The selection problem may be analyzed using congestion theory, resulting in a generic specification of traffic supply and demand. Greedy approximation is the main solution algorithm in this paper.

Caramia, Olm, Gentilia and Mirchandani (2005)
This paper considers the bi-level problem in freight delivery issue: delivery/pick-up firms and transportation planner. Both viewpoints are addressed by solving the following problem: what delivery itineraries are

available so that parking loading/unloading capacities and associated time windows are respected and the itineraries are "balanced" in a way that costs and number of deliveries fall in given ranges. Branch-and-bound approach and a heuristic are used as the method. This paper more focuses on how to shift freight volume in each time slots. However, owing to unlimited capacity, the shifting method cannot be moved to my methodology directly.

2.2 Ramp Metering and Corridor Control

The theory of ramp metering has developed fast. Many researchers have proposed some classical theories. The concept of time slot allocation is promising with the same function and similar mechanism as ramp metering. Thus literature review in this aspect can help to give some inspiration to time slot allocation.

A ramp meter is a device, usually a basic traffic light or a two-phase (red and green, no yellow) light together with a signal control, that regulates the flow of traffic entering freeways according to current traffic conditions. Ramp metering is reclaimed to reduce congestion (increases speed and volume) on freeways by decreasing demand and breaking up platoons of cars. Here, ramp metering serves corridor control without any route choice. Therefore, the control is vital for the traffic state. Some papers introduce ramp metering into corridor control.

Taale and Middelham (2000)
This paper focuses on ramp-metering in the Netherlands to realize dynamic traffic management. Ramp metering is the control of a traffic stream from an on-ramp to the motorway. This is done using special traffic lights which allow vehicles to enter the motorway one by one. About the principles of ramp-metering, on two cross-sections of the motorway (upstream and downstream the on-ramp) traffic data is measured with induction loops. The flow and average speed measured is compared with certain threshold values. If these thresholds are exceeded, the metering system is activated. After applying for ramp-metering capacity utility can increase by 5%, and both speed and travel time decrease. In the Netherlands three ramp-metering algorithms are used: the RWS strategy, the ALINEA strategy and one based on fuzzy logic.

Zhang and Recker (1998)
This paper examines the conditions for which ramp metering can be beneficial to the overall system in terms of travel time savings for a simple traffic corridor that consists of a freeway and a set of parallel arterials connected by entrance ramps. The analysis is concerned with the general behavior of the system under ramp control and traffic diversion. It assumes that time-varying traffic demands which originate from various locations are destined for a single location and that the freeway is uniformly congested throughout the control period. When the freeway is uniformly congested ramp control is counter-productive unless diversion occurs. The underlying traffic dynamics are LWR (Lighthill and Whiteham, Richards) theory, where flow, speed and density are basic relationship.

The essential formulations of total travel time are:

$$TT = T_f + T_a + T_q \tag{2-1}$$

Where,

$$T_f = T\sum_{k=1}^{K} \Delta \cdot l_f \cdot 1^t \cdot \rho^k \tag{2-2}$$

is the total time spent on the freeway.

$$T_a = T\sum_{k=1}^{K} \Delta \cdot l_a \cdot 1^t \cdot \rho^k \tag{2-3}$$

is the total time spent on the freeway alternative.

$$T_a = T\sum_{k=1}^{K} \Delta \cdot l_a \cdot 1^t \cdot \zeta^k \tag{2-4}$$

is the total time spent in ramp queues.

Where,

T:	size of each time increment
k:	time step number
K:	time step horizon
Δ:	length of each road section
l_f:	number of lanes of the freeway
1_t=[1,1,…,1]:	unit vector of appropriate dimension
ρ_k:	density of the freeway during time interval k
l_a:	number of lanes of the freeway alternative
ζ:	number of vehicles waiting at ramp during time interval k

Wu and Chang (1999)

An integrated optimal control model and its solution algorithm have been developed for commuting corridor management. It is based on flow conservation model and density evolution. Three traffic control measures, including ramp metering, intersection signal timing and freeway flow diversion, have been incorporated and optimized simultaneously. This study is in macro-level to analysis corridor issue with density and trajectory. Total travel time (TTT) is regarded as the objective function.

$$TTT = \sum_k \left\{ \sum_l \sum_{m=1}^{N(l)} \left[d_m^l(k) \cdot L_m^l \cdot n_m^l \right] \right\} \cdot \Delta t \tag{2-5}$$

Where,

$d_m^l(k) \cdot L_m^l \cdot n_m^l$ represents the average number of vehicles on section m of link l during time interval k.

Zhou, Mahmassani and Zhang (2007)

This paper describes the development of a dynamic trip micro-assignment and (meso) simulation system that incorporates individual trip-maker choices of travel mode, departure time and route in multimodal urban transportation networks. These travel choice dimensions are integrated in a stochastic utility maximization framework that considers multiple user decision criteria such as travel cost, schedule delay, as well as travel time reliability. For a typical case that assumes the logit-based alternative choice model, this paper develops an equivalent gap function-based optimization formulation and a heuristic iterative solution procedure. A two-stage estimation procedure that can systematically utilize historical static demand information, time-dependent link counts, as well as empirically calibrated stochastic departure time choice models is proposed to infer commuters' preferred arrival time distribution, which is important in modeling departure time choice dynamics.

Yuan (2008)
New algorithm (HERO) for coordination control of the whole ramp metering system is applied in this report. He performs an ex-ante study using a microscopic simulation model assessing the new control algorithm by comparing coordinated ramp metering to individual control. The new control strategy turns out to provide less congestion, higher mean speed and lower travel time spent in the network, and thus poses potential positive effects over the targeted application area.

2.3 Travel Time

Generally speaking, travel time can be regarded as a criterion to assess traffic states. The shorter travel time implies the less congestion and the better traffic states. Lower travel time should be one of good criteria.

Akcelik (2000)
This paper presents a time-dependent form of the original Davidson function, derived using the coordinate transformation technique. The modified form of Davidson's function proposed by Tisato(1991) is shown to over predict travel times for flows near and above capacity compared with the time-dependent form. A new travel time function is proposed as an alternative to Davidson's function to overcome the conceptual and calibration problems.

The travel time function is:

$$TT_{link} = L_{link} \cdot t = L_{link} \left\{ t_0 + \frac{T(x-1)}{4} + \frac{T}{4}\sqrt{(x-1)^2 + \frac{8J_a x}{QT}} \right\} \qquad \text{2-6}$$

$$x = \frac{q}{Q}$$

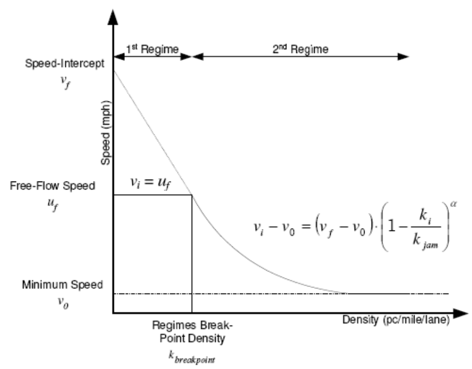
Where,

TT_{link}: travel time on link
L_{link}: link length
t: average travel time per unit distance (h/km)
t_0: free-flow travel time per unit distance (h/km)
T: flow period, i.e., the time interval in hours, during which an average arrival (demand) flow rate, v, persists
q: flow
Q: capacity
x: degree of saturation i.e., q/Q
J_a: delay parameter

GreenShield Model
In the User's guide of Dynasmart-P, two types of the modified Greenshields family models are available: one is a dual-regime model, the other a single-regime one. In dual-regime model, constant free-flow speed is specified for

the free-flow conditions (1st regime) and a modified Greenshields model is specified for congested-flow conditions (2nd regime) (Figure 2-1).

Figure 2-1 Type 1 modified Greenshields model



In mathematical terms, type 1 modified Greenshields is expressed as follows:

$$v_i = u_f \qquad 0 \le k_i \le k_{breakpoint}$$

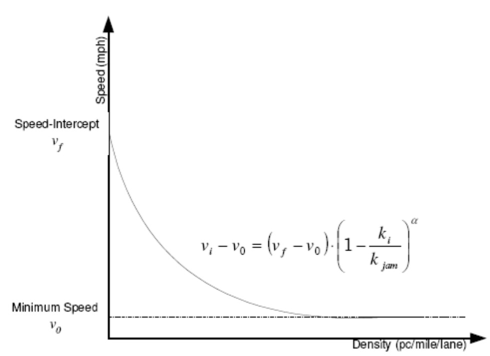
$$v_i - v_0 = (v_f - v_0)(1 - \frac{k_i}{k_{jsm}})^{\gamma} \qquad k_{breakpoint} \le k_i \le k_{jam} \qquad \text{2-7}$$

Where

v_i: speed on link i
v_f: speed-intercept
u_f: free-flow speed on link i
v_0: minimum speed on link i
k_i: density on link i
k_{jam}: jam density on link i

Type two uses a single-regime to model traffic relations for both free- and congested-flow conditions (Figure 2-2).

Figure 2-2 Type 2 modified Greenshields model



In mathematical terms, type 2 modified Greenshields is expressed as follows:

$$v_i - v_0 = (v_f - v_0)(1 - \frac{k_i}{k_{jsm}})^{\gamma} \qquad \text{2-8}$$

Dual-regime models are generally applicable to freeways, whereas single-regime models apply to arterials. The reason why a two-regime model is applicable for freeways in particular is that freeways have typically more capacity than arterials, and can accommodate dense traffic (up to 2300 pc/hr/lane) at near free-flow speeds

Li (2008)
This paper presents an analytical investigation of strategic departure time choice under stochastic capacities using Vickrey's bottleneck model. They study whether long term equilibrium may exist given day-to-day travel time variations. Based on the analytical analyses, consideration of random capacities and travel time reliability in the utility function results into significant shifts in the temporal demand pattern relative to the deterministic case.

2.4 Network Capacity Optimization

Network capacity is a complex concept. So far there is no acknowledged definition. The primary objective of a network capacity problem is to determine the maximum attainable flow that a network can carry. Anthony Chen's paper (2002) gives a draft idea about it. Then dynamic Capacity is a state-of-art concept, compared with the normal capacity idea, which changes according to different real station, taking changing weather and sudden accidents for instance. Capacity in Brilon's paper (2007) is defined as the maximum flow rate up to which acceptable traffic performance of the facility is achieved and beyond which – in case of greater demand – unacceptable traffic conditions arise. Instead of constant-value capacities, the capacity of a highway facility is regarded as a random variable.

Chen and Yang (2000)
This paper mentions one of the definitions of network capacity. Consider a transportation network modeled by a directed graph G (N, A) where N is a set of nodes and A is a set of arcs. W is a subset of N, which designates as origin/destination pairs where travel demands are originated from and attracted to. The arcs on the strongly connected graph are roadways that make up the transportation network. Each arc (roadway) has a certain capacity (ca) and the maximum capacity of the network is determined by the value of an output parameter (μ), which can be computed from the capacities of all the roadways.

$$\mu = g(c_1, c_2, ..., c_a) \qquad \text{2-9}$$

For the simple networks with arcs connected in series or in parallel, a closed functional form is available to compute the maximum network capacity. However, when the network contains complicated couplings among the use paths between each OD pair, the function g() may not exist analytically. Nevertheless, it can be determined by an optimization procedure. For example, the maximum flow problem, which is to find a feasible flow that leads to maximum flow capacity, can be formulated as a linear program. Additionally the capacity of a road network depends not only on the arc capacities, but also on demand level, congestion effect, and route choice.

Olszewski (2000)
The paper compares two methods of modeling the relationship between arterial travel speed and traffic flow. The Highway Capacity Manual method

relies on estimating delay at individual intersections and requires a lot of detailed input data. The model requires only two input parameters: intersection spacing and minimum signal delay. Both models show similar trends in travel speed but the HCM method generally predicts lower speeds for uncongested traffic. The Singapore survey data show that arterial running time per kilometer depends on flow rate as well as on intersection spacing. Suggestions are made on how to improve the existing models by using more precise definitions of arterial flow, capacity and running time. It seems that aggregate models such as the Singapore model are more appropriate for planning applications when detailed information on signal timing is not available.

Munoz and Daganzo (2001)

This paper describes the bottleneck mechanism and the behavior of multi-lane freeway traffic, upstream of an oversaturated off-ramp. The main findings are:

- FIFO blockage. Even on wide freeways, an off-ramp queue can grow across all lanes and entrap through vehicles in a fisrt-in-first-out (FIFO) system with similar speeds on all lanes and a well-defined kinematic wave (KW). This can hamper freeway flow much more than an on-ramp bottleneck.
- Variable capacity. Under FIFO, the freeway discharge flow can change significantly without a change in the off-ramp flow when the percent of exiting vehicles changes.

Daganzo and Laval (2004)

This paper shows how moving obstructions in (kinematic wave) traffic streams can be modeled with “off the shelf” computer programs. It shows that if a moving obstruction is replaced by a sequence of fixed obstructions at nearby locations with the same “capacity”, then the error in vehicle number converges uniformly to zero as the maximum separation between the moving and fixed bottlenecks is reduced. This result implies that average flows, densities, accumulations and delays can be predicted as accurately as desired with this method. Thus, any convergent finite difference scheme can be used to model moving bottlenecks. The approach can be used with non-concave fundamental diagrams and multiple bottlenecks, even if they pass each other. Examples are given. It is assumed that the bottleneck trajectories are exogenous to the model. However, by introducing suitable car-following laws and interaction rules, slow trucks and busses embedded in the traffic stream can be modeled endogenously.

Brilon and Geistefeldt (2005)

In this paper capacity is understood as the traffic volume below which traffic still flows and above which the flow breaks down into stop-and-go or even standing traffic. Weibull-distribution with a nearly constant shape parameter is used here. This was identified using the so-called Product Limit Method, which is based on the statistics of lifetime data analysis.

They use the likelihood function to calibrate the parameters. The function includes both breakdown and fluent parts.

$$L = \prod_{i=1}^{n} f_c(q_i)^{\delta_i} \cdot [1 - F_c(q_i)]^{1-\delta_i} \qquad \text{2-10}$$

where,
$f_c(q_i)$: statistical density function of capacity c
$F_c(q_i)$: cumulative distribution function of capacity c
n: number of intervals
δ_i=1, if uncensored
δ_i=0, elsewhere

Brilon, Geistefeldt and Zurlinden(2007)
In this paper, a stochastic concept for highway capacity analysis is presented. Instead of constant-value capacities, the capacity of a highway facility is regarded as a random variable. Weibull distribution is regarded as capacity distribution functions from the lifetime data analysis. Interestingly, they apply this concept to intersection. The same mathematical estimation technique based on the statistics of lifetime data analysis can be applied.

Geistefeldt (2008)
A new empirical method for estimating passenger car equivalents for heavy vehicles on freeways is presented. Capacity distribution functions are estimated in passenger car units. By determining the equivalency factor for which the coefficient of variation of the capacity distribution function becomes minimal, passenger car equivalents for heavy vehicles can be derived.

2.5 Conclusion

Time slot allocation, ramp metering, corridor control and network capacity optimization are all the present concepts that have been discussed by some researchers in quite an advanced perspective. Bur no evidence shows that anyone has combined them within a consistent system framework to solve the congestion problem.

These reviewed papers all give a state-of-art idea in each individual topic. Chen’s paper (2002) offers one of the definitions about network capacity. Daganzo analyzes the bottleneck mechanism in traffic streams. Interestingly, capacity in Brilon’s paper (2007) is regarded as a random variable, instead of constant-value capacity. With Weibull distribution, capacity distribution functions can be obtained based on the lifetime data analysis with the failure events. Considering capacity in time-slice is a step further to link dynamic demand to network traffic state.

Researchers have done a lot of work about corridor control with ramp metering. Taale (2000) gives an insight of Dutch ramp-metering. And Zhang (1998) considers the topic with the approach of system travel time. This concept is interesting to our topic as it proposes to consider ramp metering and corridor control with the network management perspective.

Time slot allocation is much used in the airport and railway scheduling. Seldom is it applied in the road traffic management. Koolstra (2005) gives a theoretical idea about how to allocate time-slot on the roads, but it does not get further with any network traffic state.

These reviewed papers offer much valuable theoretical supports from ramp metering, time slot allocation and network capacity optimization perspectives. Our understanding is that it is possible to combine some of the knowledge concepts and meanwhile rebuild a part of our own idea for considering time-slice demand to network traffic state, thus influencing network traffic behavior via the change of demand in time-slice. For instance, dynamic network capacity is a quite nice concept, but it is not easy to make it practical. Thus static capacity is still a dominated concept in the later methodology. And how to evaluate time slot allocation is almost the same as evaluating ramp metering. This method is transplantable.

Therefore it is an opportunity to see how to realize time slot allocation based on current theories in different aspects. Ramp metering can offer a similar theory to time slot allocation to some extent. Then travel time reducing and network capacity maximum utilization should be main criteria for assessing traffic state with time slot allocation. Later on, a real case analysis on A15 network will be carried out to see the feasibility of allocating time slots, and the methodology based on the analytical formulation and simulation will be presented.

3. Analysis of A15 Motorway Area and Monica Data

From pervious chapter, we have some ideas about time-slot allocation to network traffic state improvement. But still we have not obtained a clear picture about the exact formulation of the problem. Taking now A15 motorway as a real case, try to test the feasibility of allocating time slots. First we can take a part of A15 motorway as a no-route-choice network, testing time slot concept to see if it helps reducing the congestion, using both flow and travel time as indicators.

In this chapter, more information about A15 motorway study area is introduced. Monica data as real observation helps to analyze current traffic state. Our purpose is to analyze the problems and to see whether we could come up with an approach to time-slot allocation.

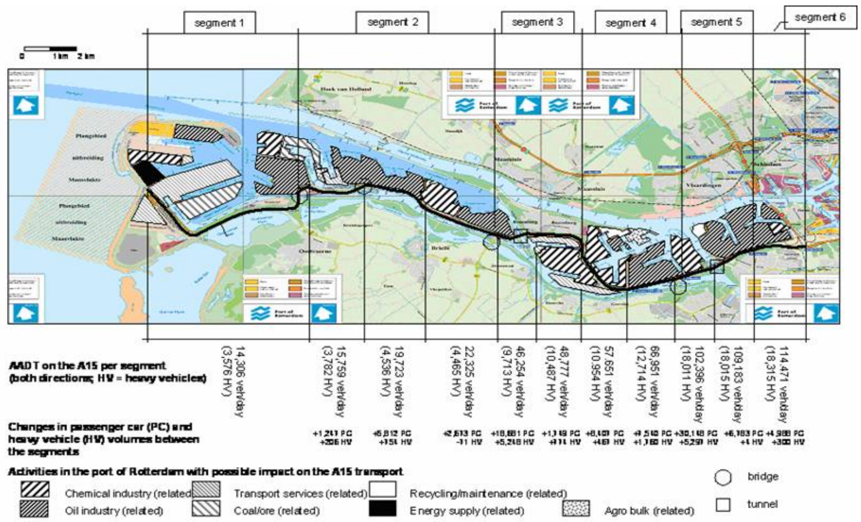
3.1 A15 Motorway Area

A15 motorway is the unique highway to Port of Rotterdam, which has to load the significantly increasing number of vehicles with the port business in the ascendant. Around this 40km motorway, different industry areas reside, taking chemical industry, oil industry, coal/ore, and cargo bulk for instance. And living areas are also located near A15. Therefore, every early morning, A15 is extremely busy loaded by cars and trucks. Serious congestion cannot be avoided, which impacts on the travel time, transport safety, environmental issues, etc. The layout of A15 Motorway is illustrated in Figure 3-1.

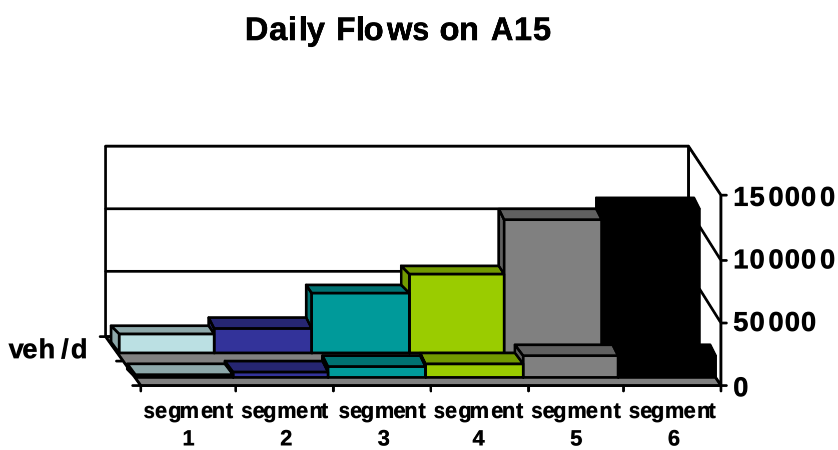
Figure 3-1:Layout of A15 Motorway
(source: Google map)

One part of A15 before A4 has been divided into 6 segments from west to east (Figure 3-2). From Figure 3-3 the daily traffic flow in eastbound is far more than the westbound, researching 120,000 in segment 6 with cars and trucks, compared with 20,000 in segment 1 only trucks left. Between segment 4 (Botlek) and segment 5 (Vondelingenplaat) there is a big traffic volume drop approximately 50,000. So normally the congestion happens in segment 5 and 6 near A4 motorway.

. . . .
Figure 3-2: Industry Area near A15 with 6 Segments (Van Zuylen, 2007)



. . . .
Figure 3-3: Daily flow of 6Segments (Van Zuylen, 2007)



3.2 Monica Data

DVS (Dienst Verkeer en Scheepvaart) of the Dutch Ministry of Transport, Public Works and Water Management (Ministrie van Verkeer en Waterstaat) uses Monica system to collect traffic data on Dutch motorway. A15 data is also collected with detectors at each distance of 500m and at every minute (Figure 3-4, Figure 3-5). It includes traffic flow, average speed (veh/h), location, and time. The data aggregation can be processed with MoniGraph Software, developed by Henk Taale with DVS. This software can help to aggregate the one minute data to the needed minute data in a specific location, time period and date, with density (veh./h), speed (km/h), calculated travel time (sec/veh) and calculated route speed (km/h) as output in both data and diagram forms.

Figure 3-4: Detectors Location of A15 Eastbound (Van Zuylen, 2007)

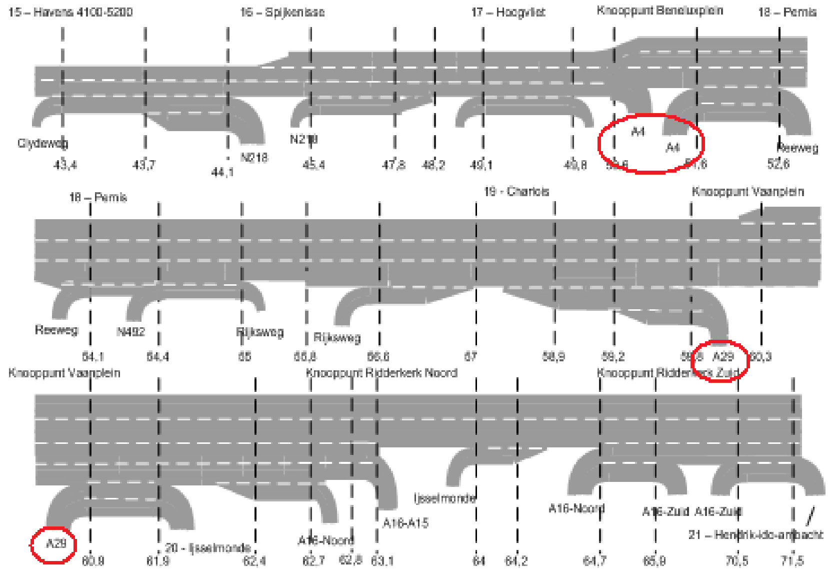
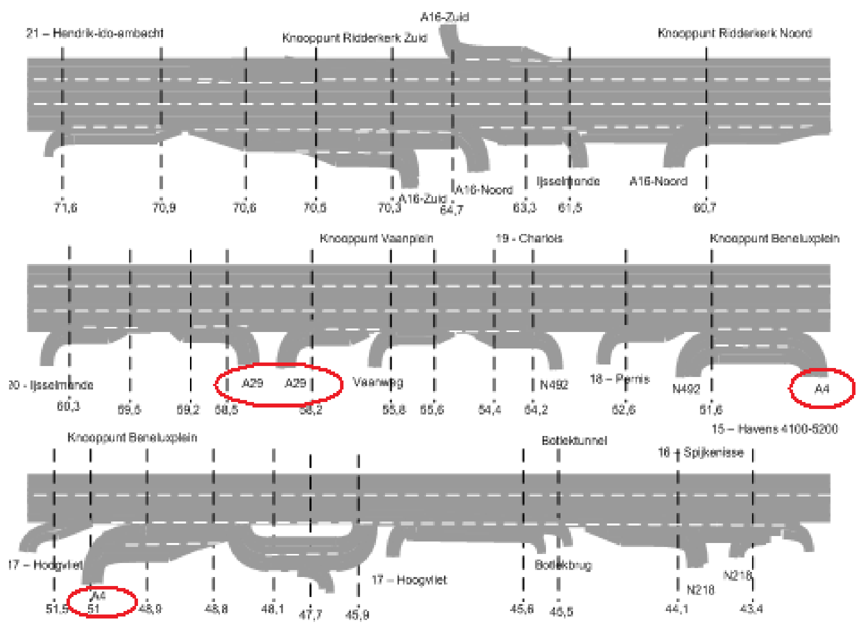


Figure 3-5: Detectors Location of A15 Westbound (Van Zuylen, 2007)



3.3 Analysis of traffic situations on A15

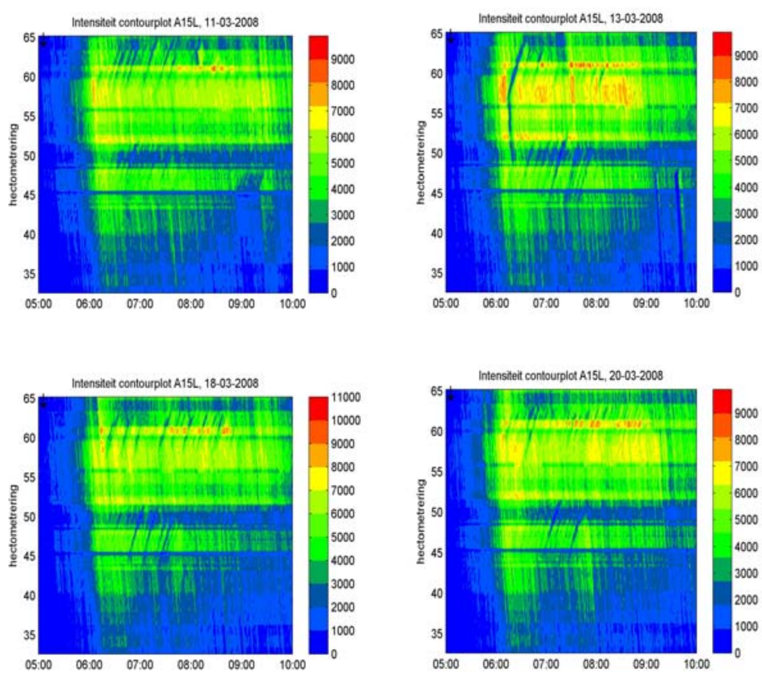
The data is on March 11th, 13th, 18th and 20th, 2008. They are all on Tuesday (11th and 18th) and Thursday (13th and 20th), when busy traffic situation exists in the Netherlands, and on A15 motorway as well (Taale, 2008). According to graphs plotted from MoniGraph[1] and the real geographical surroundings, traffic states on A15 are analyzed as follows.

Figure 3-6 and Figure 3-7 illustrate traffic states of Westbound (from Entrance 17 Hoogrleit to Exit 15 Havens) of A15 from 5:00am to 10:00am on Tuesday (March 11th and 18th,2008) and Thursday (March 13th and 20th, 2008). Obviously, serious congestion occurs near A29 area, around 60km of detector location in the whole morning peak and A4 area, around 50km of detector location (Figure 3-4 and Figure 3-5) in one hour (6:30am~7:30am) Due to the busy oil industry, there is increasing oil which has to be transported to Rotterdam Port in the early morning. Meanwhile they may have a fixed logistics schedule, which leads to generate congestion in the whole morning peak.

Additionally, travel time on A15 (Left(L)) is always greater than reference value nearly 20 minutes (Figure 3-8), even at 6:30am reaching slightly more than 35 minutes, except 18th March with 30 minutes, which lasts 15 minutes. Then a sharp decrease happens at 7:30am, but some day there is a small peak again, depicted in Figure 3-8.

For the traffic states of Eastbound (Right(R)) of A15 in the morning, plotted in Figure 3-9 and Figure 3-10, the congestion situation is much less compared with westbound (L). The reason is that not much traffic generating in the morning from Rotterdam port. Therefore the travel time is always near the reference line, except 18th March with roaring travel time line. There should be an accident at 9:15 at the beginning of A15.

Figure 3-6 Flow on A15 (Westboutd-L) in 11th, 13th, 18th, 20th March, 2008



[1] Source: Rijkswaterstaat – DVS, 2008, http://www.flexsyt.nl/monigraph.htm

Figure 3-7 Speed on A15 (Westboutd-L) in 11th, 13th, 18th, 20th March, 2008

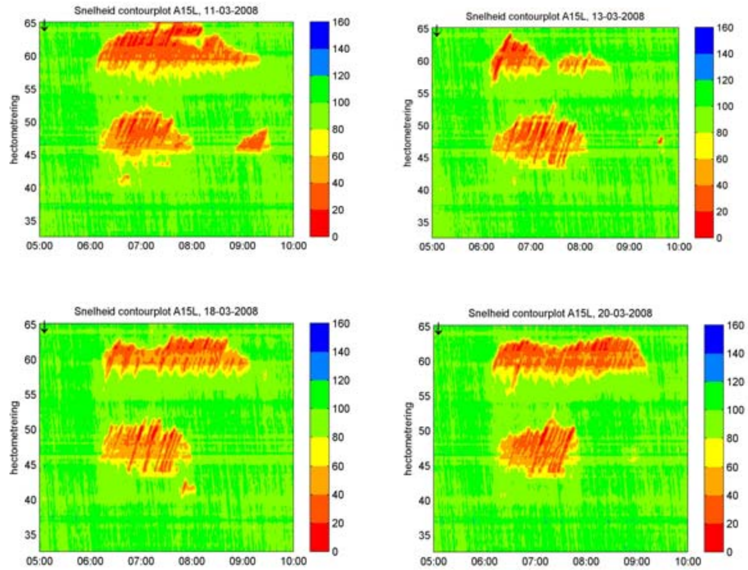


Figure 3-8 Travel time on A15 (Westboutd-L) in 11th, 13th, 18th, 20th March, 2008

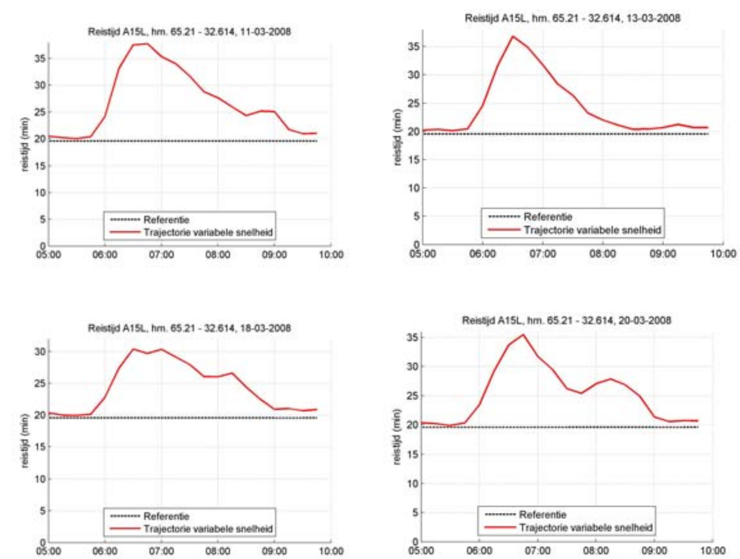
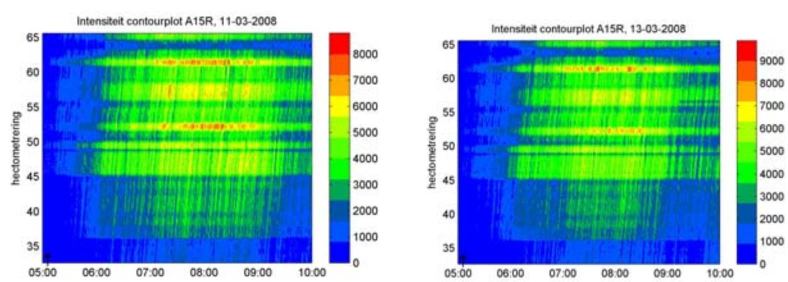
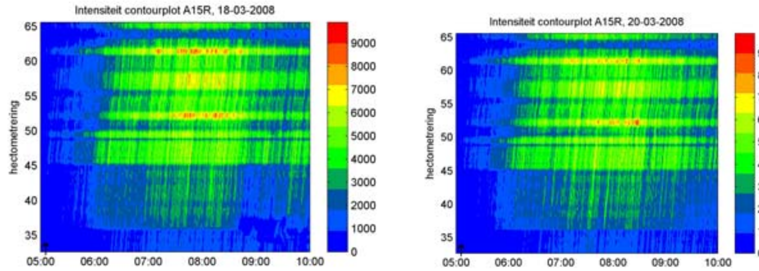
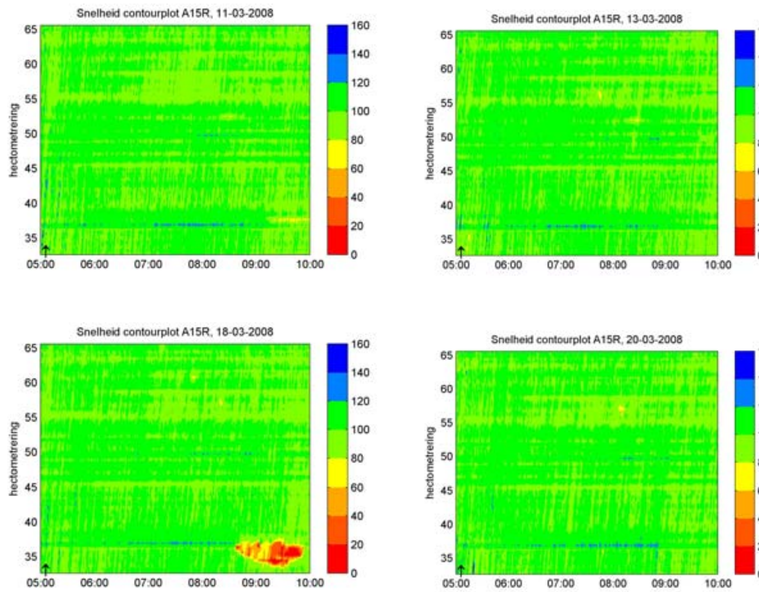


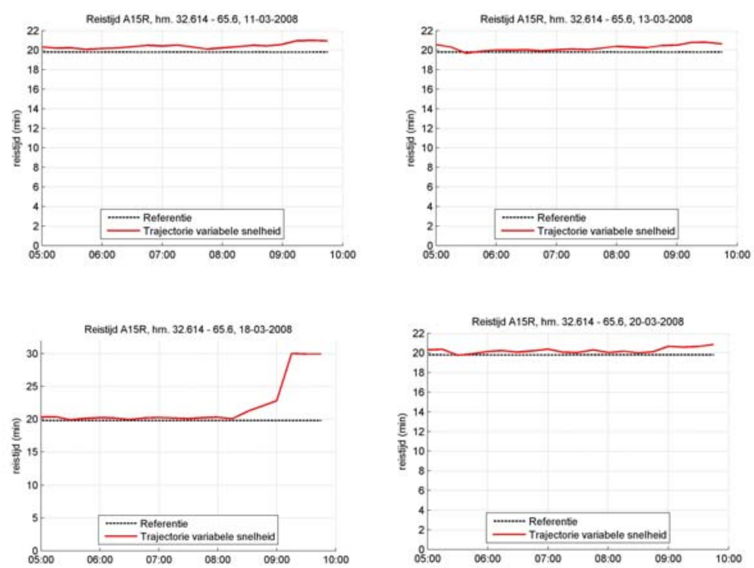
Figure 3-9 Flow on A15 (Eastbound-R) in 11th, 13th, 18th, 20th March, 2008







. . . .
Figure 3-10 Speed on A15 (Eastbound-R) in 11th, 13th, 18th, 20th March, 2008

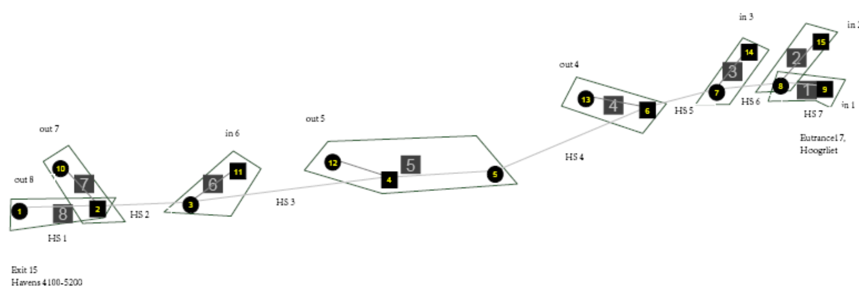


. . . .
Figure 3-11 Travel time on A15 (Eastbound-R) in11th, 13th, 18th, 20th March, 2008

3.3.1. Comparison between Observed Flow and Capacity

With the observed flow, comparison with capacity should be carried out to judge whether it is possible to judge congestion or not. Table 3-1 presents the relationship between observed flow and capacity with 7 highway sections (HS), which are on the westbound of A15 from location 43.1km (entrance 17) to 49.9km (exit 15), and 8 observed time (OT) from 6:00 am to 8:00am with 15 minutes for each time slot. One thing should be mentioned here that link capacity is the value of traffic flow when breakdown happens, around 75% of capacity from the flow-speed plots called applied capacity. If capacity from the flow-speed plot is used, no traffic flow can exceed capacity. Thus the values larger than value 1.0 mean the observed flow is greater than applied capacity, which is defined as congestion simply. When focusing on average percentages in time and space dimensions, front time slots (OT1-4) and downstream (HS1-4) parts have high traffic flow over capacity percentage. This is indicated in RED in the Table 3-1.

Figure 3-12 Part of A15 from Hoogliet to Havens(Eastbound)



However, generally speaking congestion should be defined from both capacity and speed. In Table 3-2 time-space pairs with speed less than 70km/h are considered as congestion. This is also the picture as given by previous speed (Figure 3-7) and flow plots (Figure 3-9).

Here we can see that congestion as identified by flow and speed is different. From traffic flow theory, it is logical, as at congestion location where speed drops hard, flow is mostly less than capacity, however it tails back in space and time. Taking both Table 3-1 and Table 3-2, congestion locations and spill-back can be identified jointly by both speed and capacity.

Table 3-1 Observed Flow/Capacity

	OT1	OT2	OT3	OT4	OT5	OT6	OT7	OT8	Average
HS1	1.04	1.18	1.14	1	0.85	0.92	1.06	0.79	100.0%
HS2	0.89	1	0.97	0.97	0.84	0.87	0.88	0.7	89.0%
HS3	0.9	1	0.94	0.85	0.74	0.76	0.83	0.68	83.7%
HS4	1	1.18	1.1	1.1	0.97	1	1.08	0.93	104.4%
HS5	0.85	1.05	1	1	0.92	0.85	0.91	0.76	91.7%
HS6	1	1.06	1.06	0.96	0.88	0.88	0.87	0.77	93.4%
HS7	0.66	0.69	0.68	0.61	0.51	0.46	0.45	0.37	55.3%
Average	90.6%	102.2%	98.2%	92.7%	81.5%	82.2%	86.9%	71.4%	

Table 3-2 Observed speed

	OT1	OT2	OT3	OT4	OT5	OT6	OT7	OT8	Average
HS1	99.6	96.12	97.3	92.85	93.77	89.05	92.76	102.36	95.5
HS2	99.08	94.56	93.11	65.24	57.15	59.24	90.35	100.22	82.4
HS3	98.54	90.46	83.38	73.45	60.91	53.02	85.9	99.89	80.7
HS4	99.47	66.36	55.62	51.57	46.17	48.43	52.29	96	64.5
HS5	98.65	78.13	48.77	43.91	44.11	39.13	72.86	99.39	65.6
HS6	95.94	92.65	67.65	53.02	55.42	62.03	81.54	98.62	75.9
HS7	108.11	106.97	87.07	79.33	103.27	100.88	108.26	114.75	101.1
Average	99.9	89.3	76.1	65.6	65.8	64.5	83.4	101.6	

The analysis, though simple, provides us with ***some very interesting concluding remarks***:

- Some time-space OD pairs have much left capacity, which can load extra traffic flow.
    - If we look at Table 3-1, we could discover that upstream (HS7) with 55.3% of flow over capacity percentage has much room to load traffic and also back time slot (OT8) with 71.4% is able to be assigned by traffic. At row "Average", it indicates how capacity is used for a given time-slice on the whole network; at column "Average", each figure shows average use of a given road section over whole time period. Both indicate that much room is available, from either time or space.
    - It is thus possible to use time-slot allocation concept to improve network traffic state and reduce congestion
- Capacity and speed should be taken as a combined criterion to judge congestion.
    - This implies also that only using traffic flow over capacity may not be enough to locate the congestion locations. However it is easier to identify congestion by using traffic flow over capacity as it can be calculated analytically. Travel time or speed does not correspond to one unique flow value, which is not easy to be computed analytically.

The challenge is ***how to judge congestion*** when performing analytical evaluation. We are thinking to combine both theoretical/analytical analysis and dynamic traffic simulation to help identify the congestion locations. In order to see if this is possible, a corresponding simulation model is built in the next section and to test how it works.

3.3.2. Simulation Model on A15 Highway

To work out the traffic engineering details, simulation is a suitable approach. Dynamic simulation can represent the traffic states of the network, combined with density, speeds, traffic flow and so on. Here dynamic simulation software—DYNASMART-P (Dynamic Netowrk Assignement Simulation Model for Advanced Road Telematics for Planning application) developed by Maryland University (Mamhassani, 2007) — is used. Dynasmart is mesoscopic software, which can address complex and dynamic transportation operations and planning issues, particularly in the intelligent traffic system (ITS) context. A mesoscopic model combines the features of both microscopic and macroscopic simulation models, which simulates individual traveler's decisions, particularly route, departure time & mode including traveler's response to pre-trip & en-route travel information; and also group travelers' decisions such as total travel time. It is an efficient hybrid traffic simulation, moving individual vehicles according to local prevailing speeds, consistent with macroscopic speed-density relations (Tolle, 2005).

As we can see, Dynasmart is quite suitable software to test time slot allocation. Time-dependent OD matrices in Dynasmart are similar to time slot concept to group travelers in a certain time period. Then with the outputs from the mesoscopic model, the trajectory of each vehicle can be checked to know who brings congestion and total traffic states can be presented.

Dynamic assignment module Dynasmart can be deployed to operate in three distinct modes. These modes differ mainly in the assignment component applied. In the first mode, vehicles are assigned to current-best-paths, random paths or any pre-determined paths (e.g., historical paths). In the second mode, a consistent iterative assignment procedure (user equilibrium (UE) and/or system optimum (SO)) is applied. The third mode is a day-to-day system evolution modeling framework (DHV, 2008).

Based on Monica observation data, simulation can be carried out to give a dynamic overview of traffic situation on A15 highway. Here A15 model is splitd up from the Netherland national model (LMS). After some steps, it changes to dynamic model. It is a traffic loading model with dynamic OD-matrices. The dynamic network loading (DNL) model addresses both the behavior of traffic at different roadway elements (sections, merges and diverges) as well as the propagation of flows along routes (Blumberg, 2007). Then with the output analysis can be done for the further research.

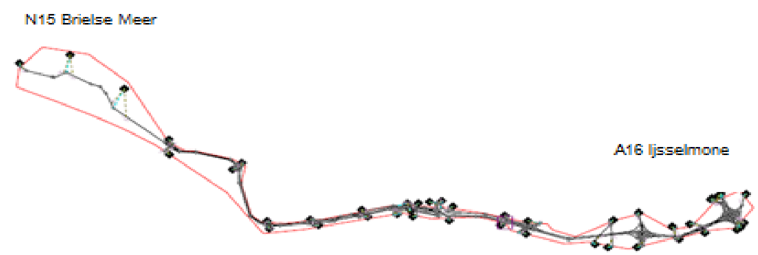
3.3.2.1 Dynamic Model for A15 is generated in several steps

There are two essential tasks to do: one is to generate A15 motorway model, getting useful dynamic OD matrices; and the other is to calibrate the dynamic model from observations. Here operational and theoretical explanations as follows:

Step1: Generate Submodel with one-hour static OD matrix

The sub-model of A15 Motorway (Figure 3-13) is subtracted from LMS model with the help of Questor software. (Questor is traffic assignment software, developed by DHV. It has the strong function to deal with static model.) The traffic demand is generated at each cutting point in centroid. For this model there are 44 zones totally. Automatically one-hour morning peak static OD-matrix is generated for A15 submode.

Figure 3-13 A15 Submodel in Questor with submodel area



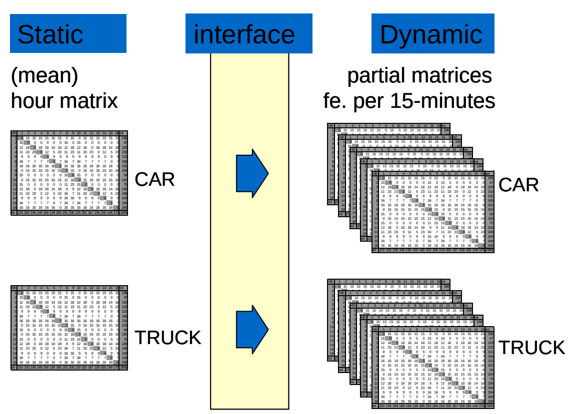
Step 2: Run the static model

Car is the unique type of vehicles for A15 submodel. In order to get the results in the fast way, All-or-Nothing assignment is carried out for the short running period. After checking the error information in "report", it is time to convert static model to dynamic one.

Step 3: Split static OD-matrix to dynamic one and Check Dynasmart generation link

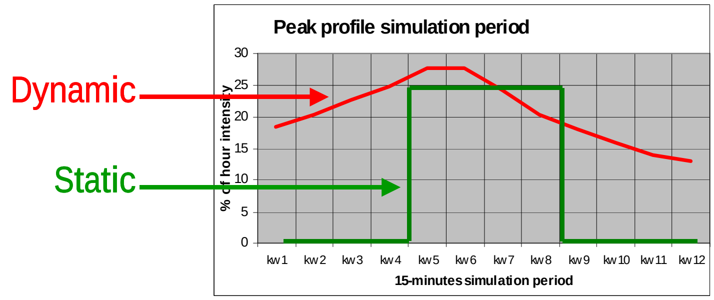
In the dynamic model traffic flows are generated by assignment of dynamic OD matrices to the road network. Starting point for dynamic OD estimation are the calibrated OD matrices per vehicle type from the static traffic model. These matrices contain mean departures, arrivals and relations of motorized vehicles within, from and to the A15 model in the morning peak between 7:00am and 8:00am. The dynamic traffic model requires separate OD matrices per time slice for a broader simulation period, 15-minute intervals in the peak period from 6:00am to 9:00am (Figure 3-14).

Figure 3-14 Procedure from static to dynamic O-D matrices (DHV, 2008)



On the basis of the percentages in the departure profile per area (group of traffic zones) the mean 1-hour matrix is separated into four 15-minute matrices. The plotting has been executed in such a way that the summation of the four dynamic matrices for all individual zones will be identical to the original 1-hour static OD matrix. Then the OD matrices of the 15-minute interval before and after the peak hour are also calculated by multiplication of the percentage in the departure profile and the static OD matrix, in the same way as the matrices in the peak hour itself. Figure 3-15 represents the relationship.

. . . .
Figure 3-15 Dynamic OD and Static OD (DHV, 2008)



Following these principle dynamic OD matrices of A15 motorway can be generated. One assumption is made that all zones follow the same departure distribution function, edited according to traffic flow in corresponding periods from Monica Data.

Step 4: Do dynamic assignment and read DTA results
After running DTA, the important results are represented in "VehTrajectory.dat" and "SummaryStat.dat". So it is better to check report information and do some rectification.

3.3.2.2 Dynamic OD Matrix and Estimation

The OD matrix in the current model is based on LMS model in 2006. The traffic demand may not suitable for the present traffic situation on A15. It seems that calibrating OD matrix by DVS real data is essential at this moment.

REMODE-Dynamic OD Estimator (Chen, 2007) is able to realize the calibration. The formula is as follows:

$$\min Z = \left\{ (1-w)\sum_{l,h}\left[\sum_{ijt} p_{(l,h),(t,i,j)} \cdot d_{(t,i,j)} / c_{(l,h)} - 1.0\right]^2 + w\sum_{i,j}\left[\sum_{t} d_{(t,i,j)} / g_{(i,j)} - 1.0\right]^2 \right\} \quad 3\text{-}1$$

where,

w: a positive weight between 0 and 1
p: link flow proportion, for departure time t, origin i and destination j at link l and observation interval h
d: estimated traffic demand
c: measured traffic flow
g: historical static demand

One thing should be mentioned here that if traffic flow is zero, because of serious congestion, "c" will be zero. Then the formulation will be meaningless. In this case, value of 1 or the other low value will be given to avoid the meaninglessness.

Through percentage difference between estimated/observed value and observed/estimated one as output of REMODE, the satisfaction of estimated results can be check: normally less than 10% is regarded as acceptable. Then mapping file can also be obtained with origin nodes, destination nodes, departure time, link ID, observed time and mapping. Moreover the new traffic demand (Demand.dat) from REMODE can be viewed as a new input file.

3.3.3. Concluding remarks

Before using simulation model as an analysis tool, calibration should be carried out to match the real situation. A15 model in Dynasmart is calibrated based on Monica data, replicating real traffic observation such as queue, speed and flow to make the model close to the real traffic state. A well-calibrated simulation model helps in identifying traffic congestion and provides with evaluation indicators. And the parameter-settings in Dynasmart should be consistent with analytical calculation about the relationship between traffic flow and capacity, taking saturation flow in Dynasmart equal to capacity for instance. In our test case, this is done by REMODE and DVS observation data, to make sure that the model replicates the reality.

Moreover dynamic OD matrix offers a platform to integrate time slot allocation. Discrete OD matrix is similar to discrete time slots and traffic demand in OD matrix in a specific time period is just like the number of travelers in each time slot needed to be assigned to the network. It is this kind of similarity that makes the time-slot-allocation test can be supported by dynamic OD matrix, which will carry out a dynamic assignment later on.

3.4 Conclusion

A15 as the unique motorway to Rotterdam Port is facing with the serious and recurrent congestion problem. The main possible reasons are that fixed logistics scheduling with port industry, residents who are using available on-ramps at peak hours and no major alternative route, resulting in tidal flow and over-saturation.

Based on Monica data, congestion in this case is defined as a phenomenon that traffic flow exceeds capacity and speed drops sharply. In A15 case, situation with traffic flow per lane larger than 2300veh/h/lane and traffic speed less than 70km/h is defined as congestion. Through analyzing this situation, some links have no congestion, thus with more capacity left in both time and space perspectives. They have more room to load traffic from the other congested areas. This suggests that time slot allocation to reduce congestion should be feasible.

In order to check traffic states after time slot allocation being implemented, traffic flow and speed are two criteria. Traffic flow can be judged analytically, but speed can only be represented in simulation. Here a mesoscopic software, Dynamart, is used, to present the trajectory of each vehicle and macroscopic speed-density relations and to obtain simulated speed.

Therefore, the challenging thing is to combine both analytical formulation and consistent simulation, in order to effectively represent traffic states. With such an approach, time-slot allocation can be implemented and further analyzed.

4. Methodology and Formulation

As we have discussed in previous chapters, we cannot overcome congestion problem in a short term but it is possible to migrate congestion from one location to another or/and from one time slot to another, and make the maximum use of the whole network with network traffic management. This requires understanding of whole traffic situation on the network. The problem can be viewed as a bi-level issue: user level—minimizing the difference between optimum demand and desired demand, and system level—reducing congestion by managing traffic flow with space and time dimensions.

4.1 Mechanism

The mechanism of time slot allocation follows First-In-First-Out (FIFO) principle at on-ramps, that is to say, travelers enter on-ramps first can leave it first. Meanwhile they are controlled by different time slot settings. They may wait in the queue at on-ramps to the next time slot or actively jump to the late time slot based on traffic information. That is late departure situation. On the other hand, travelers can enter on-ramps in the earlier time slot, or they would like to departure early to get the front time slot actively according to information. That is early departure. Thus travelers, who are divided as groups in each 15-minute period based on the current situation, are called desired demand. After the optimization, new demand is called optimum demand. In addition, the whole phenomenon is a demand-cumulative process. Only cumulative demand is able to reflect the mechanism, thus which is the research object, instead of the single demand.

The initial concept of this mechanism is from *Vickrey's discrete model of departure time*. This model assumes a single bottleneck with constant capacity with a given total demand larger than capacity during a limited period, the usual peak, and known preferred arrival times of the travelers (Li, 2008). And in this model, the dynamic user equilibrium for departure time choice results that no traveler can reduce its travel cost by unilaterally altering its departure time. In other word, it makes an assumption of user's departure time equilibrium, that is to say travelers' travel costs are all the same. In addition, a first-come first served queue discipline (FCFS) is applied at the bottleneck. There are n symmetric players who travel along a single road connecting a common origin O and a common destination D. Each player independently and anonymously chooses a departure time. It is assumed that service capacity per unit of time is s (>0). If $s \geq 1$, at most s players is served per unit of time. If $s<1$, say $s=1/d$, where d is an integer larger than 1, then only one player is served at a time, and it takes each player d units of time to pass through the bottleneck (Otsubo, 2007). As we can see, from the constant capacity aspect, FCFS and cumulative demand idea, Vickery's model can help to set up methodology to some extent, but formulation is from the other aspect.

Moreover, we should respect travelers' initial departure pattern. They would not like to change their departure schedule much. Thus respecting travelers' current desire as much as possible is vital in the optimized process, that is to say, it is better if the cumulative optimum demand is close enough to the cumulative desired demand. Meanwhile congestion should be reduced to some extent, keeping flow under capacity.

As we can see, slot allocation is such a measure that capacity constraints and simulated speed limitation need to be satisfied. It is a type of traffic planning in time-space dimension. However as formulation it is difficult to include both of factors in one objective function, since capacity is an absolute value while speed is vector. In the following sections formulation only covers capacity perspective, and then in the framework how to present speed and combine with capacity constraints are explained.

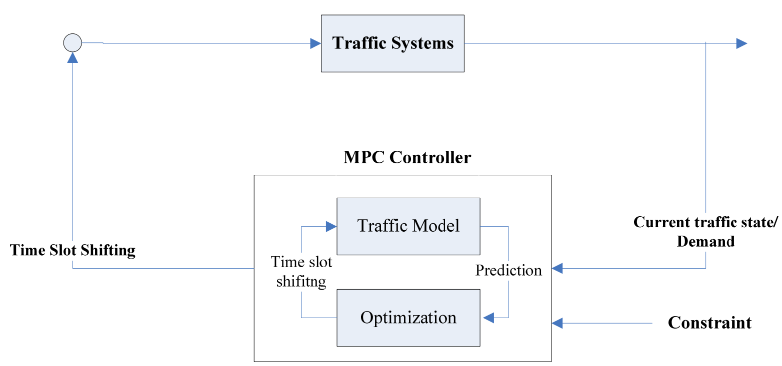
Combined with calculation, simulation should be executed synchronously. Close loop is a represented method to harmonize these two aspects. In the system control perspective in Figure 4-1, current traffic demand can be regarded as initial input. After dynamic loading of the traffic demand into network by Dynamic Traffic Assignment (DTA), current traffic state is simulated. The relationship between traffic demand and traffic states (flow, travel time, etc.) is thus established.

What is more, about Model Predictive Control (MPC, SC4060) controller in Figure 4-1, the general concept of MPC is: based on the current traffic conditions and demands, the MPC controller generates the best time slot allocation (shifting). This is done with the optimization and traffic models in the MPC controller. It first predicts the future evolution of the traffic and selects the best time slot shift which can improve the traffic flow. The selected time slot shifting is applied to the system (traffic system). This changes the flow in the system. Again the MPC controller takes the measurement of the traffic condition and performs the optimization. This gets on repeating continuously.

For the methodology, optimization in MPC controller is the principal step to be realized at this moment. The whole loop requires on-line system to support, which will be taken into account in the further research.

. . . .

Figure 4-1: Control Process



To start with, just consider late departure. Taking the example of A15 without any route choices, it allows late departure concept to be implemented with on-ramp metering with time slots independently. Of course early and late departure should be both designed, but this will be tried out in a later stage.

Our approach will consist of following main components:

- Analytical approach with flow and speed constraints
- Simulation helps verifying traffic states
- Iterations to make both analytical formulation and simulation converge

In terms of specific formulation, we take the following:

- Late departure only
- Both late and early departure with costs
- Both late and early departure with costs using genetic algorithm

These will be dressed in next sections.

4.2 Late Departure Only

Following the idea by Prof. Henk van Zuylen (2008), late departure means cumulative desired demand should be always larger than or equal to cumulative optimum demand in the specific time slot. In order to respect travelers' initial departure profile, minimizing the difference between cumulative desired demand and cumulative optimum demand is regarded as the objective "Z".

The objective function for late departure can be expressed as follows:

$$\min Z = \sum_{ij}\left[\sum_{T=1}^{N}\left(\sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o}\right)\right] \tag{4-1}$$

s.t

$$Q^{kh} < C^{k}$$

$$Q^{kh} = \sum_{i}\sum_{j}\sum_{t}\left(D_{tij}^{o} \cdot p_{ijt}^{kh}\right) \tag{4-2}$$

$$\sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o} \geq 0 \quad (T \in 1,2,3\ldots N-1) \tag{4-3}$$

$$\sum_{t=1}^{N} D_{tij}^{d} - \sum_{t=1}^{N} D_{tij}^{o} = 0 \tag{4-4}$$

$$0 \leq D_{tij}^{0} \leq \max_{t} D_{ijt}^{d} \tag{4-5}$$

where,

Z:	difference between desired demand and optimum demand
i:	origin
j:	destination
T:	cumulated time slots
N:	number of cumulated time slots
t:	time slot
D_{tij}^{d}:	desired demand on certain time slot t from i to j

D^o_{tij} :	optimum demand on certain time slot t from i to j
p:	mapping
k:	link
h:	observed time
Q:	flow,
C:	capacity

The desired demand D^d_{tij} is the current demand and the optimum demand D^o_{tij} is a variable to solve and to obtain.

Constraints are explained as follows:
4-2 means that traffic flow on link k in observed time h should be smaller than its corresponding link capacity.

4-3 limits that the cumulative desired demand should be larger than or equal to the cumulative optimum demand for each time slot except last time slot, which can ensure the late departure situation. It takes the assumption that at each on-ramp vehicles follow the first-in-first-out rule.

4-4 is for the total number of vehicles, which should be the same after shifting, for each OD pair over all time slots.

4-5 gives the up-bound and low-bound of optimum demand, which should be larger than 0 and less than the maximum desired demand in the corresponding time slot.

Following this, a very simple example of one OD pair with 10 time slots (TS) will give the idea about the definition of late departure and early departure.

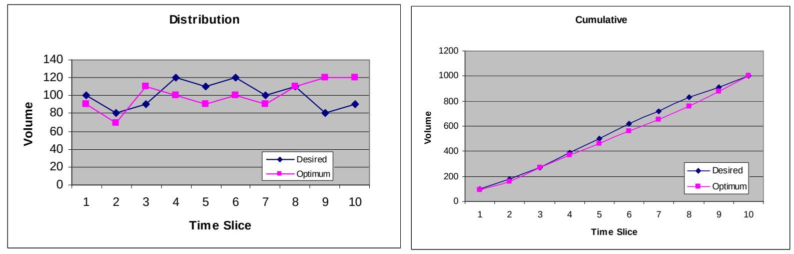
An example of late departure is given:

Table 4-1 Late departure for one OD pairs

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9	TS10	SUM
Desired Demand	100	80	90	120	110	120	100	110	80	90	1000
Optimum Demand	90	70	110	100	90	100	90	110	120	120	1000
Difference	10	10	-20	20	20	20	10	0	-40	-30	0
Cumulative Desired Demand	100	180	270	390	500	620	720	830	910	1000	
Cumulative Optimum Demand	90	160	270	370	460	560	650	760	880	1000	
Leftover	10	20	0	20	40	60	70	70	30	0	

In Figure 4-2, the desired demand is input, representing current traffic situation with congestion. The optimum demand is the output which can help reducing congestion problems. Then the leftover is the difference between the cumulative desired demand and the cumulative optimum demand. Here for late departure all leftovers are larger than or equal to 0.

Figure 4-2 Distribution graph and Cumulative graph of Late departure



In detail, if data satisfies $\sum_{t} D_{ij}^{d} - \sum_{t-1} D_{ij}^{o} \geq D_{tij}^{o}$, that is late departure in time slot t. For instance, cumulative desired demand in time slot 6 is 620 and cumulative optimum demand in time slot 5 is 460. The difference between them is 160 which is larger than 100, the optimum demand in time slot 6.

4.3 Late Departure and Early Departure

According to LP calculation with only late departure, congestion on the motorway can be reduced by re-allocation timeslots. According to Prof. Henk van Zuylen’s idea, if we take both late departure and early departure into account as a general case, what kind of situation will be? In addition, real time slot allocation should include value of time, which is the cost of time that a traveler spends on their journey. Here are values of early departure and late departure. Travelers have to get the penalty if they departure late and they can get award if they departure early. Thus the total cost difference from early and late departure is minimized as an objective.

Objective function

$$\min Z = \sum_{i,j} \sum_{t=1}^{T} \{[\alpha_2 + (\alpha_1 - \alpha_2) \cdot \frac{1}{2}(1+\gamma)] \cdot (\sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o})\} \qquad 4\text{-}6$$

$$\gamma = sign(\sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o}) = \begin{cases} 1, \sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o} > 0 \\ 0, \sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o} = 0 \\ -1, \sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o} < 0 \end{cases} \qquad 4\text{-}7$$

s.t.

$$Q^{kh} < C^{k}$$

$$Q^{kh} = \sum_{i} \sum_{j} \sum_{t} \left(D_{tij}^{o} \cdot p_{ijt}^{kh} \right) \qquad 4\text{-}8$$

$$\sum_{t=1}^{N} D_{tij}^{d} - \sum_{t=1}^{N} D_{tij}^{o} = 0 \qquad 4\text{-}9$$

$$0 \leq D_{tij}^{0} \leq \sum_{t} D_{tij}^{d} \qquad 4\text{-}10$$

$$\alpha_1 \geq 0 \qquad 4\text{-}11$$

$$\alpha_2 \leq 0 \qquad\qquad 4\text{-}12$$

where,

Z:	difference between desired demand and optimum demand
i:	origin
j:	destination
T:	cumulated time slots
N:	number of cumulated time slots
t:	time slot
D^{d}_{tij} :	desired demand on certain time slot t from i to j
D^{o}_{tij} :	optimum demand on certain time slot t from i to j
sign:	in mathematics, the sign of a number tells whether it is positive or negative.
p:	mapping
k:	link
h:	observed time
Q:	flow,
C:	capacity
α_1 :	value of late departure
α_2 :	value of early departure

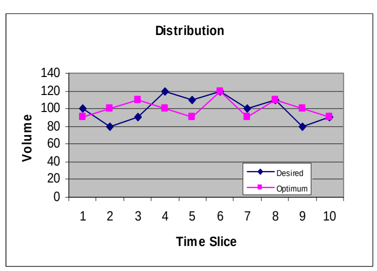
Table 4-2 example of early/late departure

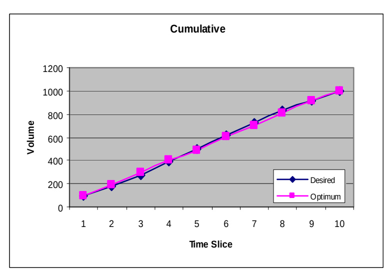
An example of early/late departure given:

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9	TS10	SUM
Desired Demand	100	80	90	120	110	120	100	110	80	90	1000
Optimum Demand	90	100	110	100	90	120	90	110	100	90	1000
Difference	10	-20	-20	20	20	0	10	0	-20	0	0
Cumulative Desired Demand	100	180	270	390	500	620	720	830	910	1000	
Cumulative Optimum Demand	90	190	300	400	490	610	700	810	910	1000	
Leftover	10	-10	-30	-10	10	10	20	20	0	0	

Negative values show up in the leftover in Table 4-2, indicate an early departure part.

Figure 4-3 Distribution graph and Cumulative graph of Early/Late departure





The detailed explanation of late departure is the same as in sanction 4.2. Here early departure has the similar mechanism, but follows $\sum_{t} D_{ij}^{d} - \sum_{t-1} D_{ij}^{o} \leq D_{tij}^{o}$. That is to say, the difference between cumulative desired demand in time slot t and cumulative desired demand in time slot t-1, should be less than optimum demand in time slot t. For instance, in Table 4-2 the difference cumulative demand between the cumulative desired demand in time slot 4 ($\sum_{t=4} D_{ij}^{d} = 390$) and the cumulative optimum demand in time slot 3 ($\sum_{t=3} D_{ij}^{o} = 300$) is 90, which is less than optimum demand in time slot 4 ($D_{4ij}^{o} = 100$).

Value of late departure (α_1) and value of early departure (α_2)

About value of late departure (α_1) and value of early departure (α_2), they have the similar meaning with value of time as usual. From Wikipedia, in transport economics, the value of time is the opportunity cost of the time that a traveler spends on their journey. In essence, this makes it the amount that a traveler would be willing to pay in order to save time, or the amount they would accept as compensation for lost time. Value of late departure is the money that travelers are willing to pay for this penalty. And value of early departure is the money that travelers can save from this award. Both of them are non-monetary costs, but as weights for the cumulative demand differences.

According to AVV report a time of day model in the Dutch National Model System (LMS) predicts car drivers' responses to changing travel time (e.g. from congestion or to the imposition of time-dependent road user charging (AVV, 2001). It takes account of the degree of (in)flexibility of starting and departure times and the possible link between a change in time-of-day of the outward and inward leg of the same tour. Here value of time is defined as coefficient of travel time divided by coefficient of travel cost. So both early and late schedule penalty are schedule penalty coefficient divided by travel time coefficient.

An example of value of late departure and early departure:

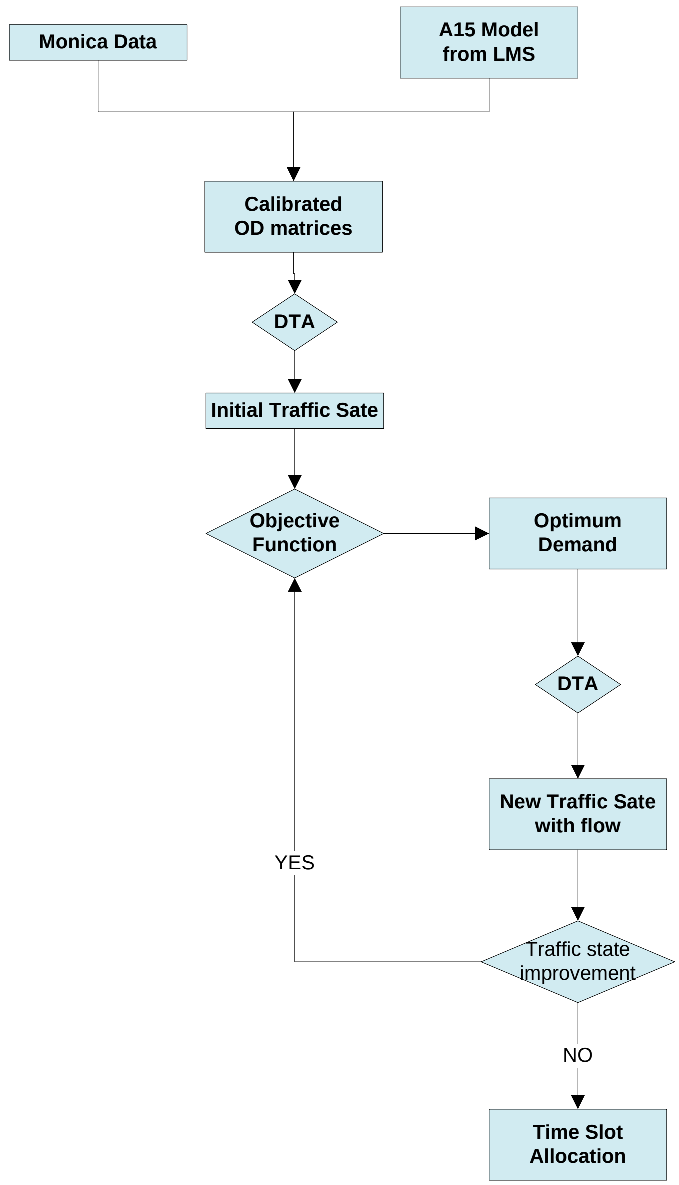
Table 4-3 value of late and early departure (AVV, 2001)

	schedule penalty coefficient divided by travel time coefficient		
	All business	Only car users	Only train users
Early schedule penalty—outward leg	1.83	1.13	1.15
Late schedule penalty—outward leg	0.89	0.304	1.36
Early schedule penalty—Return leg	1.69	1.19	0.675
Late schedule penalty—Return leg	0.46	0.37	/

4.4 Implementation Framework

As mentioned in the beginning of this chapter, congestion should be judged both from capacity-maximum-utilization perspective and travel-time-reduction perspective. Based on the formulation, optimum demand can satisfy the capacity constraint, but only with the help of simulation travel time can be obtained. So here implementation framework represents how to integrate both aspects as a whole.

Figure 4-4 Implementation Framework



Step 1: Calibrate Dynamic OD matrix

Based on Monica Data from DVS and OD matrix in A15 Model cut from LMS model in DHV, calibration of dynamic OD matrix can be carried out in REMODE.

Step 2: Get Initial Traffic State

Taking calibrated OD matrix as an input to dynamic traffic assignment (DTA) software, the output can help to get current traffic states on A15 motorway.

Step 3: Calculate Optimum Demand with objective function
With calibrated OD matrix and other input files such as mapping, optimum demand can be calculated in the objective function.

Step 4: Get New Traffic State
New traffic state with flow can be obtained after DTA simulation. If all flow is less than capacity and travel time reduces to some extent, it means traffic states improve.

Step 5: Time Slot Allocation
The concept of time slot allocation is set up with improved traffic states. If there is an improvement in computed traffic state, the objective function will continue to iterate from step 3; otherwise it stops.

4.5 Conclusion

Based on Prof. Henk van Zuylen's idea, this chapter sets up a new methodology for time slot allocation. Vickrey's discrete model of departure time is used as reference to form the initial model idea. The model assumes a single bottleneck with constant capacity, with a given total demand larger than capacity during usual peaks and known preferred arrival times of the travelers with the same travel cost (Li, 2008). Additionally system control concept with MPC controller is applied to make the whole concept integrated.

In order to get the optimum demand, the model is abstracted as LP for late departure only and NLP for both late and early departure with costs. Congestion is defined with both speed and traffic flow. Since speed cannot be formulated analytically, merely capacity constraint limits the computation. Fortunately with the help of dynamic traffic simulation, speed can be represented with corresponding computed flow. Therefore in the framework, formulation and simulation are carried out synchronously for several iterations.

As we can see, time slot allocation is a quite new concept in road transport, but there still exit some related concepts that can be taken as references to help formulate its own methodology. The objective function is non-continuous and non-convex, which may result in multi-solutions. Further discussions will take place in next sections.

5. Application and Results

This chapter implements the theoretical framework as presented in the previous chapter and uses a test case of a part of A15. The key issue is to translate the objective function into traffic state. To achieve this, the analytical formulation is first computed and its outcome feeds the corresponding simulation. The main challenge here is to see whether we could reach a balance and consistency between the analytical formulation and simulation. Should this be possible, we would check whether time slot allocation does improve the traffic states and reduces congestion.

We start with building and calibrating a test simulation model, which will feed the objective function and allows us to compute the optimum demand. In the objective function, different forms of optimization will be tested and tried out to see which one performs better. A few common indicators will be used for evaluation. Further result analysis, remarks and conclusions will follow.

5.1 Test case

In the test case, we will analyze the traffic situation, in order to get insight into the traffic state in this area. We then build and calibrate a dynamic model, using a part of A15 motorway. Following the procedures as such: (a) defining the test network; (b) obtaining on-ramp flow, performing a dynamic OD estimation and building a dynamic simulation model and (c) calibrating the model.

All this will serve as the input to the objective function in next sections.

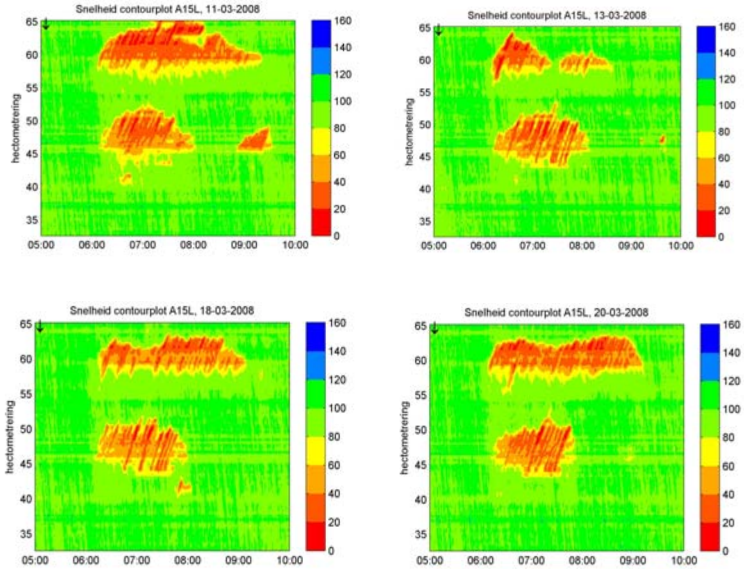
5.1.1. Network for the test model

The test case is a small part of A15 Motorway between entry 17 and exit 15 from east to west. A part of the detectors in the Monica data from locations 43.1km to 49.9km at 6:00-8:00 am on June 4th 2007 with 15-minute intervals is used for the small test model, depicted in Figure 3-12.

5.1.2. Observations

The flow and speed can be obtained from Monica data on 4th June, 2007. With the plotted graphs below, congestion happens when speed is less than 70km/h. Based on data, flow-speed relationship can be plotted to get capacity. Interesting thing is that in some highway sections, taking HS2 for instance, even if speed reduces a lot, flow still does not increase. The same situation occurs in HS3 and HS4, implying that congested traffic spilling back from downstream (HS1) to upstream (HS7).

Figure 5-1 Speed on A15 (L) in 11th, 13th, 18th, 20th March, 2008



Measured flow is represented in Table 5-1. As we can see, flow is always less than capacity from flow-speed diagram. Normally traffic state is assessed by flow and speed. When speed reduces to some extent, congestion will show up. The red word is the flow that is larger than applied capacity in "[]" (it will be explained later on) and yellow parts are congestion based on the speed.

Table 5-1 Monica Data of A15 on 4th June, 2007

	Time Slot	Capacity	Flow(>CC)	Speed(<60)
HS1	1) 6:00-6:15	4000	3228	99.6
	2) 6:15-6:30	[3092]	3664	96.12
	3) 6:30-6:45		3512	97.3
	4) 6:45-7:00		3092	92.85
	5) 7:00-7:15		2636	93.77
	6) 7:15-7:30		2852	89.05
	7) 7:30-7:45		3288	92.76
	8) 7:45-8:00		2452	102.36
HS2	1) 6:00-6:15	6000	4240	99.08
	2) 6:15-6:30	[4764]	4764	94.56
	3) 6:30-6:45		4624	93.11
	4) 6:45-7:00		4620	65.24
	5) 7:00-7:15		3984	57.15
	6) 7:15-7:30		4164	59.24
	7) 7:30-7:45		4184	90.35
	8) 7:45-8:00		3348	100.22
HS3	1) 6:00-6:15	4400	3792	98.54
	2) 6:15-6:30	[4212]	4212	90.46
	3) 6:30-6:45		3952	83.38
	4) 6:45-7:00		3584	73.45

	5) 7:00-7:15		3116	60.91
	6) 7:15-7:30		3200	53.02
	7) 7:30-7:45		3488	85.9
	8) 7:45-8:00		2852	99.89
HS4	1) 6:00-6:15	6000	4476	99.47
	2) 6:15-6:30	[4476]	5264	66.36
	3) 6:30-6:45		4920	55.62
	4) 6:45-7:00		4916	51.57
	5) 7:00-7:15		4344	46.17
	6) 7:15-7:30		4460	48.43
	7) 7:30-7:45		4824	52.29
	8) 7:45-8:00		4176	96
HS5	1) 6:00-6:15	7400	4648	98.65
	2) 6:15-6:30	[5492]	5740	78.13
	3) 6:30-6:45		5492	48.77
	4) 6:45-7:00		5500	43.91
	5) 7:00-7:15		5052	44.11
	6) 7:15-7:30		4692	39.13
	7) 7:30-7:45		4996	72.86
	8) 7:45-8:00		4164	99.39
HS6	1) 6:00-6:15	6000	4580	95.94
	2) 6:15-6:30	[4580]	4832	92.65
	3) 6:30-6:45		4832	67.65
	4) 6:45-7:00		4392	53.02
	5) 7:00-7:15		4028	55.42
	6) 7:15-7:30		4052	62.03
	7) 7:30-7:45		3996	81.54
	8) 7:45-8:00		3508	98.62
HS7	1) 6:00-6:15	2800	1844	108.11
	2) 6:15-6:30	[2800]	1936	106.97
	3) 6:30-6:45		1892	87.07
	4) 6:45-7:00		1708	79.33
	5) 7:00-7:15		1416	103.27
	6) 7:15-7:30		1292	100.88
	7) 7:30-7:45		1268	108.26
	8) 7:45-8:00		1028	114.75

Based on Monica Data, calibration is carried out for Dynasmart model running. With the output, total network travel time is 2466.3 minutes with 19.6% congestion left (number of congestion location in RED in Table 5-2 divided by the total time-space pairs). And the average percentages of difference between estimated flow and observed flow are between -6% and 0.3% in special perspective. In HS4, the average percentage is the lowest, which means this highway section can load more traffic in some time slots. In HS1 with highest average percentage, more congestion happens there.

Similarly, for time aspect, TS2 can load more traffic with -10.1% of average parentage; and TS6 has saturated with 5.6%. Additionally, still 27.9% of cars stay in the network after simulation.

5.1.3. Simulation model

Based on the Monica data, simulation in this small model (Figure 3-12) can be carried out. All the steps have been represented in section 3.3.2. After calibration between the model and real detected data, mapping flow can be obtained (Table 5-2). Compared with Table 5-1, red words in Table 5-2 mean also flow larger than capacity (cap), which is consistent in both tables and thus shows that calibration is good. Thus later on, mapping flow from the simulation will be used for analysis.

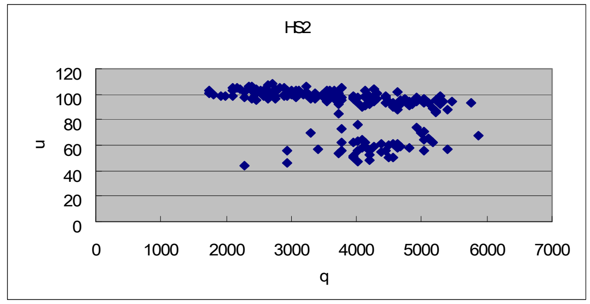
Table 5-2 Initial Mapped Flow (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	699	753	918	840	783	832	799	536	773	
	807	916	878	773	659	713	822	613		
	-13%	-18%	5%	9%	19%	17%	-3%	-13%		0.3%
HS2	1060	1124	1184	1068	1152	1076	1001	811	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	0%	-6%	2%	-8%	16%	3%	-4%	-3%		0.1%
HS3	814	821	869	773	888	872	807	726	1053	
	948	1053	988	896	779	800	872	713		
	-14%	-22%	-12%	-14%	14%	9%	-7%	2%		-5.6%
HS4	1124	1091	1041	1030	1083	1162	1287	954	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	1%	-17%	-15%	-16%	0%	4%	7%	-9%		-5.8%
HS5	1387	1317	1075	1083	1106	1190	1298	1096	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	19%	-8%	-22%	-21%	-13%	1%	4%	5%		-4.2%
HS6	1295	1134	897	1030	851	1112	1327	839	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	13%	-6%	-26%	-6%	-16%	10%	33%	-4%		-0.3%
HS7	450	514	533	474	286	305	306	256	700	
	461	484	473	427	354	323	317	257		
	-3%	6%	13%	11%	-19%	-5%	-4%	0%		-0.2%
Average%	0.4%	-10.1%	-7.9%	-6.5%	0.1%	5.6%	3.6%	-3.1%		

Challenging questions:

As we can see, even if a quantity of congestion show up, flow do not exceed the capacity obtained from the flow-speed diagram based on Monica data. Therefore the first constraint of the objective function – flow should be less than capacity — is not always valid in this case.

Figure 5-2 relationship graph of flow and speed in HS2



The question now is what we should do to satisfy the objective function in this situation?

Capacity definition:
Facing this problem, the original capacity definition from the fundamental diagram is not suitable in this case. Congestion may happen before speed-reduction emerges. Thus Prof. van Zuylen suggests that value of capacity be the corresponding flow that appears two time slots ahead of the speed reduction. This capacity is marked. In other words, speed is regarded as an extra criterion to judge operational capacity.

However, this capacity reduction cannot match with congestion representation based on the speed dropping. In some highway sections, speed has reduced a lot, but flow is not as high as we expect. Thus we cannot obtain its operational capacities. See the results in Table 5-1 where HS7 has only the maximum capacity of 2800 while it has 2 lanes!

Discussion:
1) Capacity from the fundamental diagram in Table 5-1, without "[]", is always larger than observed traffic flow. So if this constraint is used, the resulting optimum demand always equals to the desired demand.
2) With respect to this situation, capacity is defined as traffic flow before speed drops off, value in "[]". Then the first constraint can find a solution. However, speed depends on different situations; so capacity as function of speed change should be a dynamic one, instead of a static one.

5.2 Implementation with Late Departure

Here the late departure only will be implemented to check the feasibility of time slot allocation, which is based on linear programming (LP).

5.2.1. Linear Programming in Matlab

Time slot allocation could be abstracted as a linear programming (LP), taking the assumption that at each on-ramp vehicles follow the first-in-first-out rule.

By "linprog" in Matlab, it can be solved. The general function is as follows:

$$\min_x f^T x$$

such that

$$Ax \le b$$

$$Aeq \cdot x = beq$$

$$lb \le x \le ub$$

where,

x: variable

f: coefficient of x in objective function

A: coefficient of x in inequality

b: constant of inequality

Aeq: coefficient of equation

beq: constant of equation

lb: low bound

ub: up bound

In the objective function, D^o_{tij} is Matlab variable x. Equations 4-2 follow $Aeq \cdot x = beq$ and equation 4-3 follows $Ax \le b$. A is DTA mapping, which is obtained by REMODE.

5.2.2. Input for LP

Following van Zuylen's suggestion, the input capacity is the traffic flow before speed drops down, which is almost 75% of the original capacity. Based on this, the objective function can be implemented. The challenge now is to try out and to analyze the results.

5.2.3. Output from LP

With Matlab, optimum demand can be obtained. Four of plotted graphs represent the cumulative demand of desired demand (blue line) and optimum one (red line).

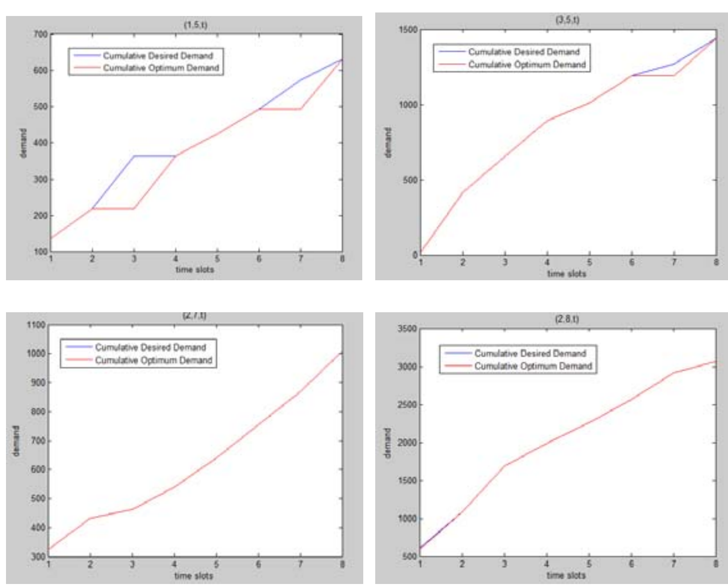


Figure 5-3 desired demand and optimum demand in LP

In order to check up the new traffic state, new traffic flow is calculated with computed optimum demand and DTA mapping. There still have 19.6% congestion left, but travel time has slightly decreased to 2462.8 minutes, by 0.2%. LP does not solve much congestion on network.

Table 5-3 Mapping Flow from LP (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	685	766	825	943	830	792	757	583	773	
	807	916	878	773	659	713	822	613		
	-15%	-16%	-6%	22%	26%	11%	-8%	-5%		1.1%
HS2	1060	1130	1106	1201	1164	1023	953	877	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	0%	-5%	-4%	4%	17%	-2%	-9%	5%		0.7%
HS3	814	820	802	932	858	829	758	795	1053	
	948	1053	988	896	779	800	872	713		
	-14%	-22%	-19%	4%	10%	4%	-13%	12%		-4.9%
HS4	1121	1080	1040	1047	1097	1145	1263	985	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	0%	-18%	-15%	-15%	1%	3%	5%	-6%		-5.6%
HS5	1378	1308	1095	1104	1099	1221	1256	1117	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	19%	-9%	-20%	-20%	-13%	4%	1%	7%		-3.9%
HS6	1274	1079	891	933	1083	927	1373	925	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	11%	-11%	-26%	-15%	8%	-8%	37%	6%		0.2%
HS7	442	276	433	643	440	189	364	337	700	
	461	484	473	427	354	323	317	257		
	-4%	-43%	-8%	51%	24%	-42%	15%	31%		3.0%
Average%	-0.5%	-17.7%	-14.2%	4.4%	10.4%	-4.3%	3.9%	7.1%		

As we can see, HS4 still can load some traffic in some time slots with -5.6% average percentages. Compared with current situation, congestion on HS1 increases to 1.1% which means more traffic move to HS1. The highest average percentage goes to HS7, where fortunately have no congestion at all.

After one LP run, traffic state does not improve as expected. And it does not get into convergence. There may be two reasons:

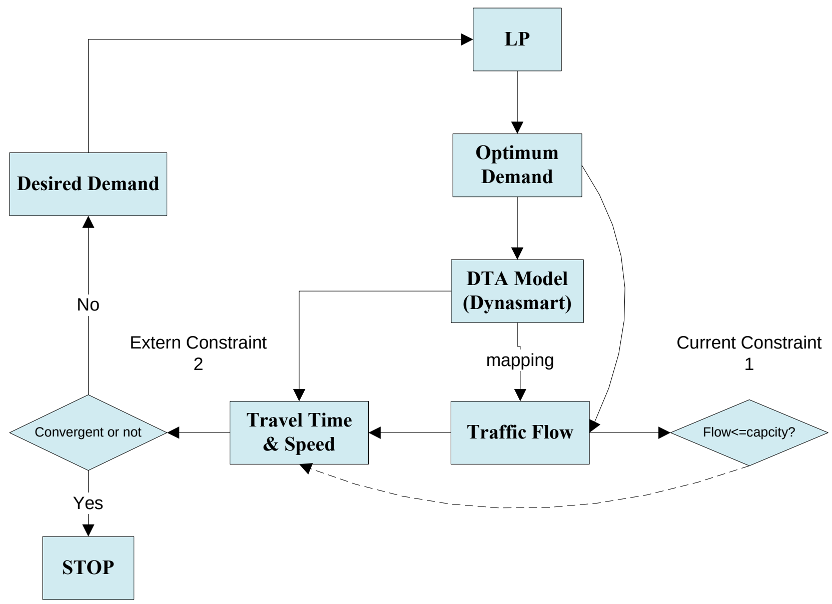
- The one is the applied capacity which is about 75% of original capacity. Probably it is too low to load expected traffic. But if capacity increases, saturation flow in Dynasmart should also be changed, which may lead to other parameters inconsistent.
- And the other one is related to algorithm. Normally linear programming is not suitable to handle large scale problem, with 512 variables in this case. LP cannot find the optimum output one by one when facing with a large quantity of searching points. So it cannot get the real optimum demand. Therefore LP iterations will be carried out.

5.2.4. DTA with iterations of LP

First we would test LP and check whether it delivers convergent results. For this, Ir. Solomon Kidane Zegeye's suggestion with control is useful, which is depicted in Figure 5-4.

By linear programming in Matlab, optimum demand can be calculated taking the initial desired demand as input. It is time to do iterations to get the converged situation: all flow smaller than capacity and total travel time reduced.

Figure 5-4 iteration process



As the congestion persists, iterations are carried out to try to get the converged optimum demand. Congestion is decreasing, though still there, but travel time gets the lowest value when LP executes at iteration 3.

Table 5-4 Travel time comparisons among 4 iterations

	Dd	LP	LP1	LP2	LP3
Total Travel Time	2466.3	2462.8	2403.5	2396.3	2381.1
Congestion Left	19.6%	19.6%	17.9%	12.5%	12.5%

Table 5-5 Flow for iteration 1: Computed Flow, Observed Flow, Difference percentage

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	710	812	771	848	699	816	851	524	773	
	807	916	878	773	659	713	822	613		
	-12%	-11%	-12%	10%	6%	14%	4%	-15%		-2.0%
HS2	1076	1155	1111	1170	998	1053	1035	831	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	2%	-3%	-4%	1%	0%	1%	-1%	-1%		-0.6%
HS3	844	824	801	878	776	812	840	741	1053	
	948	1053	988	896	779	800	872	713		

	-11%	-22%	-19%	-2%	0%	2%	-4%	4%		-6.5%
HS4	1128	1079	1043	1047	1045	1200	1189	1052	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	1%	-18%	-15%	-15%	-4%	8%	-1%	1%		-5.5%
HS5	1392	1298	1109	1112	1103	1225	1184	1173	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	20%	-10%	-19%	-19%	-13%	5%	-5%	13%		-3.6%
HS6	1210	1123	909	935	1106	874	1156	1171	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	6%	-7%	-25%	-15%	10%	-14%	16%	34%		0.5%
HS7	379	332	441	644	422	133	208	561	700	
	461	484	473	427	354	323	317	257		
	-18%	-31%	-7%	51%	19%	-59%	-34%	118%		4.9%
Average%	-1.9%	-14.6%	-14.4%	1.6%	2.7%	-6.2%	-3.7%	22.0%		

Table 5-6 Flow for iteration 2: Computed Flow, Observed Flow, Difference percentage

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	646	826	759	674	793	685	785	527	773	
	807	916	878	773	659	713	822	613		
	-20%	-10%	-14%	-13%	20%	-4%	-5%	-14%		-7.3%
HS2	905	1124	1014	894	1078	1045	1097	847	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-15%	-6%	-12%	-23%	8%	0%	5%	1%		-5.1%
HS3	711	837	848	742	799	859	808	722	1053	
	948	1053	988	896	779	800	872	713		
	-25%	-21%	-14%	-17%	3%	7%	-7%	1%		-9.2%
HS4	828	1062	1138	1081	1049	1079	1301	1051	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	-26%	-19%	-8%	-12%	-3%	-3%	8%	1%		-7.9%
HS5	870	1149	1371	1367	1175	1114	1273	1176	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	-25%	-20%	0%	-1%	-7%	-5%	2%	13%		-5.4%
HS6	829	980	1239	1151	1055	998	1178	1171	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	-28%	-19%	3%	5%	5%	-2%	18%	34%		1.9%
HS7	169	230	535	561	646	279	215	556	700	
	461	484	473	427	354	323	317	257		
	-63%	-52%	13%	31%	82%	-14%	-32%	116%		10.2%
Average%	-28.8%	-20.9%	-4.6%	-4.2%	15.4%	-2.8%	-1.6%	21.7%		

Table 5-7 Flow for iteration 3: Computed Flow, Observed Flow, Difference percentage

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	701	757	765	733	733	736	761	622	773	
	807	916	878	773	659	713	822	613		
	-13%	-17%	-13%	-5%	11%	3%	-8%	1%		-5.0%
HS2	942	1049	991	959	1091	1096	1105	886	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-11%	-12%	-14%	-17%	10%	5%	6%	6%		-3.5%
HS3	773	825	816	732	845	840	804	780	1053	
	948	1053	988	896	779	800	872	713		
	-19%	-22%	-17%	-18%	8%	5%	-8%	9%		-7.6%
HS4	899	1089	1139	1070	1041	1047	1340	1052	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	-20%	-17%	-7%	-13%	-4%	-6%	11%	1%		-7.0%
HS5	946	1233	1412	1334	1122	1129	1313	1220	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	-19%	-14%	3%	-3%	-11%	-4%	5%	17%		-3.2%
HS6	848	1060	1211	1125	985	1189	1242	1153	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	-26%	-12%	0%	2%	-2%	17%	24%	32%		4.4%
HS7	181	278	463	582	693	340	198	577	700	
	461	484	473	427	354	323	317	257		
	-61%	-43%	-2%	36%	96%	5%	-38%	125%		14.9%
Average%	-24.0%	-19.6%	-7.3%	-2.5%	15.3%	3.7%	-1.0%	27.2%		

In the second iteration, travel time drops with less congestion. In the third iteration traffic state does not improve much. So it stops here. More highway sections can load more traffic with negative average percentages. The lowest one is HS3 with -7.6%. Then from the time aspect, most travelers would like to departure late (this is also our assumption!), so in TS1 average percentage is -24.0% and TS8 27.2%.

Discussions

1) Congestion does not disappear fully with the optimum demand. What should we do next? It seems that only capacity constraint without speed constraint does not fully represent real traffic situation. Both capacity and speed should be taken into account in constraints, but speed is not measurable/computable during the LP computation while flow can be mapped with demand and assignment map.
2) In LP, the first constraint limits traffic flow less than capacity. But in reality, flow larger than capacity seldom happens. At congestion situation, flow is even lower than capacity. This suggests that constraints should be amended with other terms, for instance taking speed into account.
3) Value of capacity is defined as the traffic flow before speed drops off. While in speed-flow relationship, one flow has two corresponding speed values. How to define capacity based on speed is still a problem.

4) For the traffic problem, traffic states can be simulated with a DTA program. LP offers the first step solution. Then for the rest, DTA helps identifying congestion links. The control concept suggests to further update new demand based on congestion links, check objective function, get new demand and perform iterations till convergence.

5.2.5. Conclusion

The late departure implementation proves that the formulation can represent no congestion situation, based on the definition/constraint of traffic flow less than capacity, but traffic flow less than capacity does not mean no congestion exists, as it also depends on speed. Thus traffic flow less than capacity is a necessary but insufficient condition of no congestion.

According to the output of one LP run and simulation, travel time does not reduce much and congestion locations have the same number of time-space pairs. But after LP iterations with simulation, total travel time decreases by 3.5% and congestion remaining at 12.5% from original 19.6%. The main reason is that LP is one-time optimization which cannot get the large number of variables solved at once. After some iterations, the result becomes better. In space aspect, more room is left in downstream; and in time aspect, more room is available to accommodate extra traffic in front time slots.

5.3 Implementation with Early and Late Departure

We try now the objective function with non-linear problem (NLP), instead of linear problem (LP) with only late departure. Two algorithms in Matlab could be used: “fmincon” and genetic algorithm (GA). The former one is to find minimum of constrained nonlinear multivariable function, and the latter one is a search technique used in computing to find exact or approximate solution to optimization and search problems

Discussion about “sign()” and “Heaviside()”:

In Matlab “sign()” and “Heaviside()” have similar purpose. The expressions are as follows:

$$sign(x) = \begin{cases} -1, x < 0 \\ 1, x > 0 \\ 0, x = 0 \end{cases} \quad \text{and} \quad heaviside(x) = \begin{cases} 0, x < 0 \\ 1, x > 0 \\ NaN, x == 0 \end{cases}$$

For this case, sign(x) should be more suitable than Heaviside(x), because if x=0, it returns NaN (not-a-number) for Heaviside(x). But there are many situations that $\sum_{t=1}^{T} D_{tij}^{d} - \sum_{t=1}^{T} D_{tij}^{o} = 0$ applied. Comparing with this, sign(x) gives normal value.

In Matlab, “fmincon” can find the minimum of a problem specified by

$$\min_{x} f(x)$$

s.t

$$c(x) \le 0$$
$$ceq(x) = 0$$
$$A \cdot x \le b$$
$$Aeq \cdot x = beq$$
$$lb \le x \le ub$$

Where,
x,b,beq,lb and ub are vectors. A and Aeq are matrices. c(x) and ceq(x) are functions that return vectors. f(x) is a function that returns a scalar. f(x), c(x) and ceq(x) can be nonlinear functions.

For this objective function, there is no nonlinear constraint, so c(x) and ceq(x) are both empty matrices. “A” is mapping p_{tij}^{kh}, “b” is link capacity C^k, “Aeq” is a matrix with “1”, “beq” is $\sum_{t=1}^{N} D_{tij}^{d}$, low bound is a zero matrix and up bound is $\sum_{t} D_{tij}^{d}$.

5.3.1. Input for NLP

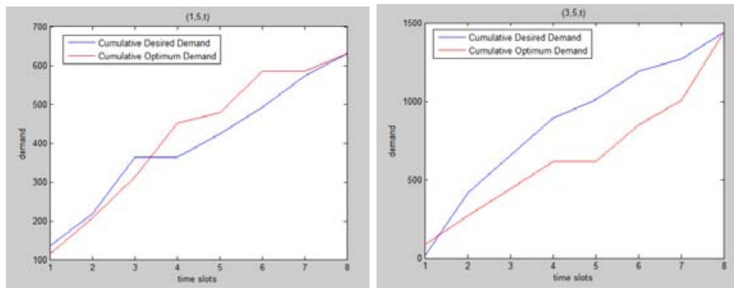
Input of NLP is almost the same as LP, such as desired demand, mapping and capacity. But here initial values of variables are required. The output of iterations from LP can be regarded as initial values of NLP.

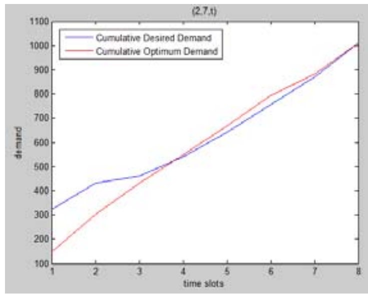
Here value of late departure (α_1) is 1.67, and value of early departure (α_2) is -1.32, which are late schedule penalty and early schedule penalty from AVV report (AVV, 2001). Both values are calculated by schedule penalty coefficient divided by travel time coefficient, thus they are relative values rather than absolute ones. It is suitable for this case, because minimum optimization do not care the scaling.

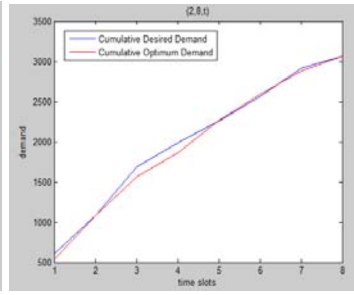
5.3.2. Output from NLP

With Matlab, Z is calculated as 131241.3, and optimum demand can be computed. Take four OD pairs (3, 5), (1, 5), (2, 7) and (2, 8) and plot them as the cumulative demand of desired demand and optimum one in Figure 5-5. Obviously, none of OD pairs get both late and early departure. They still present the late departure as the optimum demand.

Figure 5-5 desired demand and optimum demand from non-linear problem







Based on the output of NLP, traffic state should be checked, using both flow mapping and dynamic simulation.

Table 5-8 Flow Mapping for NLP (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	693	814	660	834	727	616	696	586	773	
	807	916	878	773	659	713	822	613		
	-14%	-11%	-25%	8%	10%	-14%	-15%	-5%		-8.2%
HS2	985	1110	935	1078	1042	1009	1030	836	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-7%	-7%	-19%	-7%	5%	-3%	-2%	0%		-5.0%
HS3	796	870	749	836	767	861	774	758	1053	
	948	1053	988	896	779	800	872	713		
	-16%	-17%	-24%	-7%	-2%	8%	-11%	6%		-7.9%
HS4	1109	1130	1034	1053	1050	1131	1344	987	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	-1%	-14%	-16%	-14%	-3%	2%	11%	-5%		-5.1%
HS5	1387	1374	1250	1100	1116	1098	1304	1132	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	19.30%	-4.20%	-9.00%	-20.00%	-11.60%	-6.40%	4.40%	8.80%		-2.30%
HS6	1195	1258	1001	957	1066	1101	996	909	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	4%	4%	-17%	-13%	6%	9%	0%	4%		-0.5%
HS7	501	509.9	554.9	565	415.7	198.9	0	378.3	700	
	461	484	473	427	354	323	317	257		
	9%	5%	17%	32%	17%	-38%	-100%	47%		-1.3%
Average%	-0.8%	-6.3%	-13.3%	-2.9%	3.1%	-6.2%	-16.1%	8.0%		

Table 5-9 Network Travel Time

	Dd	D0(NLP)
Total Travel Time	2466.3	2322.0

5.3.3. Conclusion

As we can see, late departure still dominates the results, although both early and late departures are allowed. 16.7% of congestion left and travel time reduces by 5.9%. For the mapping flow, all average percentages in space perspectives are negative values, which means congestion reduces compared with current situation. And traffic move from downstream to upstream, since downstream has lower average percentage. For the time dimension, more travelers would like to departure late, so TS8 has the highest average percentage.

5.4 Late and Early Departure with Costs using Genetic Algorithm

Genetic Algorithm (GA) is categorized as global search heuristics, which is a particular class of evolutionary algorithm that uses techniques inspired by evaluating biology such as inheritance, mutation, selection and crossover. The advantage of GA approach is the ease with which it can handle arbitrary kinds of constraints and objectives; all such things can be handled as weighted components of the objective function, making it easy to adapt GA scheduler to the particular requirements of a very wide range of possible overall objectives.

Several values of early and late departure in Table 5-10 will be tried to test the sensitivity of optimum demand. α_1 is value of late departure and α_2 is value of early departure.

Table 5-10 Costs of late and early departure for GA

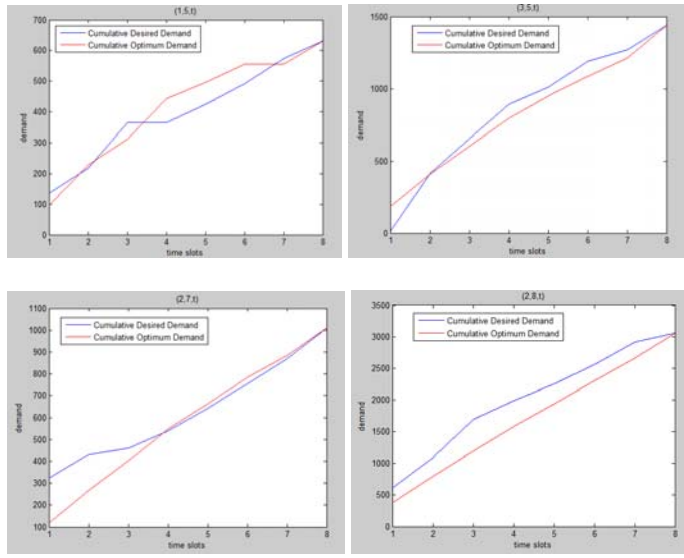
	α_1	α_2
Scenario 1	1.67	-1.32
Scenario 2	0.3	-1.13
Scenario 3	3	-1
Scenario 4	1	-3
Scenario 5	1	-5
Scenario 6	5	-1
Scenario 7	10	-1
Scenario 8	1	-10
Scenario 9	50	-1

The values in scenarios 1 and 2 are from AVV report (AVV, 2001). They are late and early schedule penalty divided by travel time coefficient respectively. Thus they are relative values. Then the other scenarios are the test scenarios. We would like to see how large the difference between values of early and late departure can influence the optimum demand. In scenario 9, enlarging the difference significantly may lead to demand change greatly. Following this all the scenarios are calculated to see the results. But some of them have the same results. All the situations are represented below.

1) Scenario 1 with $\alpha_1 = 1.67$ and $\alpha_2 = -1.32$

After calculation, Z is 131241.3. Four of plotted graphs are represented with both early and late departure. Some of optimum demand is closed to desired demand, and others are not.

Figure 5-6 Cumulative demand



In this scenario, total travel time is 2311.9 minutes, with 8.9% congestion remaining. Obviously, genetic algorithm offers the best solution, compared with LP and NLP. Traffic move from downstream (HS1) with -5.9%, and to upstream (HS7) with 1.4%, and from front time slot to TS8 with 15.2%. In other words, traffic flow in congestion spreads to the non-congestion areas and available time slots. So based on this pair of value of late/early departure, traffic state has improved a lot.

Table 5-11 Mapping Flow of GA scenario 1 (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	692	711	778	795	723	724	721	606	773	
	807	916	878	773	659	713	822	613		
	-14%	-22%	-11%	3%	10%	2%	-12%	-1%		-5.9%
HS2	957	983	1088	1104	1046	1026	1005	907	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-10%	-17%	-6%	-4%	5%	-1%	-4%	8%		-3.7%
HS3	711	709	801	824	789	809	823	826	1053	
	948	1053	988	896	779	800	872	713		
	-25%	-33%	-19%	-8%	1%	1%	-6%	16%		-9.0%
HS4	1105	1078	1039	1059	1052	1203	1219	1015	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	-1%	-18%	-16%	-14%	-3%	8%	1%	-3%		-5.7%
HS5	1339	1344	1157	1115	1101	1230	1213	1099	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	15%	-6%	-16%	-19%	-13%	5%	-3%	6%		-3.9%
HS6	1084	1245	973	953	925	1021	1170	1114	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	-5%	3%	-20%	-13%	-8%	1%	17%	27%		0.2%
HS7	460	588	431	471	278	318	184	395	700	

	461	484	473	427	354	323	317	257		
	0%	22%	-9%	10%	-22%	-2%	-42%	54%		1.4%
Average%	-5.8%	-10.3%	-13.7%	-6.5%	-4.2%	1.9%	-6.9%	15.2%		

2) Scenario 2 with $\alpha_1 = 0.304$ and $\alpha_2 = -1.13$

In this scenario, values of early/late departures are also from AVV report. After calculation, all the outputs are the same as scenario 1.

3) Scenario 4 with $\alpha_1 = 1$ and $\alpha_2 = -3$

With this pair of value of late/early departure time, optimum demands do not have many changes. But the travel time reduces to 2310.7 minutes by 6.3% and 10.7% congestion remaining, which is larger than scenario 1. And traffic still moves to upstream with 1.4% and late time slot with 15.5%.

Table 5-12 Mapping Flow of GA scenario 4 (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	701	707	779	807	737	717	727	620	773	
	807	916	878	773	659	713	822	613		
	-13%	-23%	-11%	4%	12%	1%	-12%	1%		-5.1%
HS2	961	999	1075	1108	1044	1052	1025	892	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-9%	-16%	-7%	-4%	5%	1%	-2%	7%		-3.3%
HS3	715	717	790	837	789	829	826	822	1053	
	948	1053	988	896	779	800	872	713		
	-25%	-32%	-20%	-7%	1%	4%	-5%	15%		-8.5%
HS4	1107	1088	1049	1059	1059	1214	1259	989	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	-1%	-17%	-15%	-14%	-3%	9%	4%	-5%		-5.2%
HS5	1337	1347	1171	1116	1122	1217	1215	1142	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	15%	-6%	-15%	-19%	-11%	4%	-3%	10%		-3.1%
HS6	1084	1240	987	983	892	949	1243	1108	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	-5%	3%	-18%	-11%	-11%	-6%	24%	26%		0.2%
HS7	460	588	429	472	277	315	187	397	700	
	461	484	473	427	354	323	317	257		
	0%	22%	-9%	10%	-22%	-3%	-41%	55%		1.4%
Average%	-5.5%	-10.0%	-13.6%	-5.6%	-4.1%	1.3%	-4.9%	15.5%		

4) Scenario 6 with $\alpha_1 = 5$ and $\alpha_2 = -1$

With this pair of value of late/early departure time, optimum demands do not have many changes. But the travel time reduces to 2305.7 minutes by 6.5% and 8.9% congestion remaining.

Table 5-13 Mapping Flow of GA scenario 6 (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	692	732	772	791	727	720	701	616	773	
	807	916	878	773	659	713	822	613		
	-14%	-20%	-12%	2%	10%	1%	-15%	0%		-5.9%
HS2	967	1002	1078	1096	1037	1030	1013	884	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-9%	-16%	-7%	-5%	4%	-1%	-3%	6%		-3.9%
HS3	712	716	808	815	784	813	818	812	1053	
	948	1053	988	896	779	800	872	713		
	-25%	-32%	-18%	-9%	1%	2%	-6%	14%		-9.3%
HS4	1106	1088	1049	1049	1043	1200	1212	1009	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	-1%	-17%	-15%	-15%	-4%	8%	1%	-3%		-5.9%
HS5	1340	1353.5	1155	1107.1	1107.2	1222	1212.7	1099.5	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	15%	-6%	-16%	-20%	-12%	4%	-3%	6%		-3.9%
HS6	1080	1233	975	947	903	1079	1152	1114	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	-6%	2%	-19%	-14%	-10%	7%	15%	27%		0.2%
HS7	459	588	429	471	280	315	186	397	700	
	461	484	473	427	354	323	317	257		
	0%	21%	-9%	10%	-21%	-3%	-41%	55%		1.5%
Average%	-5.7%	-9.7%	-13.8%	-7.1%	-4.6%	2.5%	-7.5%	14.8%		

5) Scenario 7 with $\alpha_1 = 10$ and $\alpha_2 = -1$

With this pair of value of late/early departure time, optimum demands do not have many changes. But the travel time reduces to 2292.8 minutes by 7.0% and 8.9% congestion remaining. This is the best situation so far, although it does not improve a lot. Based on the average percentages, more traffic move to upstream in the late time slots.

Table 5-14 Mapping Flow of GA scenario 7 (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	719	720	750	794	727	727	713	640	773	
	807	916	878	773	659	713	822	613		
	-11%	-21%	-15%	3%	10%	2%	-13%	4%		-5.10%
HS2	981	995	1072	1087	1046	1053	1022	884	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-7%	-17%	-7%	-6%	5%	1%	-2%	6%		-3.50%
HS3	727	718	800	805	789	827	836	810	1053	
	948	1053	988	896	779	800	872	713		
	-23%	-32%	-19%	-10%	1%	3%	-4%	14%		-8.80%
HS4	1116	1089	1050	1046	1042	1210	1226	1008	1119	

	1119	1316	1230	1229	1086	1115	1206	1044		
	0%	-17%	-15%	-15%	-4%	9%	2%	-4%		-5.60%
HS5	1339	1358	1167	1109	1098	1218	1224	1097	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	15%	-5%	-15%	-19%	-13%	4%	-2%	5%		-3.80%
HS6	1078	1255	979	952	906	1009	1189	1118	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	-6%	4%	-19%	-13%	-10%	0%	19%	27%		0.20%
HS7	460	588	428	470	277	315	187	398	700	
	461	484	473	427	354	323	317	257		
	0%	22%	-10%	10%	-22%	-2%	-41%	55%		1.50%
Average%	-4.70%	-9.60%	-14.20%	-7.30%	-4.60%	2.3	-6.00%	15.40%		

6) Scenario 8 with $\alpha_1 = 1$ and $\alpha_2 = -10$

With this pair of value of late/early departure time, optimum demands do not have many changes. But the travel time reduces to 2299.2 minutes by 6.8% and 10.7% congestion remaining.

Table 5-15 Mapping Flow of GA scenario 8 (Estimated Flow/Observed Flow)

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	Cap	Average%
HS1	704	731	771	791	763	711	685	636	773	
	807	916	878	773	659	713	822	613		
	-13%	-20%	-12%	2%	16%	0%	-17%	4%		-5.00%
HS2	967	1026	1078	1098	1048	1031	1011	899	1191	
	1060	1191	1156	1155	996	1041	1046	837		
	-9%	-14%	-7%	-5%	5%	-1%	-3%	7%		-3.30%
HS3	720	735	802	820	802	809	817	826	1053	
	948	1053	988	896	779	800	872	713		
	-24%	-30%	-19%	-9%	3%	1%	-6%	16%		-8.50%
HS4	1120	1096	1062	1053	1057	1202	1230	1006	1119	
	1119	1316	1230	1229	1086	1115	1206	1044		
	0%	-17%	-14%	-14%	-3%	8%	2%	-4%		-5.10%
HS5	1344	1369	1188	1115	1108	1206	1210	1134	1373	
	1162	1435	1373	1375	1263	1173	1249	1041		
	16%	-5%	-14%	-19%	-12%	3%	-3%	9%		-3.10%
HS6	1084	1260	983	966	880	1004	1194	1114	1145	
	1145	1208	1208	1098	1007	1013	999	877		
	-5%	4%	-19%	-12%	-13%	-1%	20%	27%		0.20%
HS7	462	588	428	471	279	316	186	395	700	
	461	484	473	427	354	323	317	257		
	0%	22%	-10%	10%	-21%	-2%	-41%	54%		1.40%
Average%	-5.00%	-8.50%	-13.30%	-6.60%	-3.60%	1.10%	-7.00%	16.10%		

Conclusion:
Compared with purely late departure, both late and early departure can solve more congestion. With respect to the best solution from scenario 7 (value of late departure is 10 and value of early departure is -1), it has the lowest total travel time and congestion remaining, and downstream part offers more room to load traffic (with negative average percentages). Then in the time dimension, front time slots have the low average percentages, which suggest that more people will be guided to late departure. Additionally, only if the difference between values of late and early departure reaches a certain gap, then optimum demand can produce better traffic states. In a nutshell, optimum demand from GA does give a better traffic state in the network.

5.5 Algorithm Comparison

Now it is high time to do the comparison among these three algorithms — LP, NLP and GA.

Table 5-16 Algorithm comparison

			Search Method	**Running Time** (minutes)	**Network Travel Time**		**Congestion Left**
					Total Travel Time	**TTT Indexing**	
Current Situation			--	--	2466.3	100%	19.6%
LP			local	1	2462.8	99.8%	19.6%
LP (iteration)			local	1	2381.1	96.5%	12.5%
NLP			local	25	2322.0	94.1%	16.7%
GA, with α_1 **and** α_2	1.67	-1.32	global	30	2311.9	93.7%	8.9%
	0.3	-1.13	global	30	2311.9	93.7%	8.9%
	3	-1	global	30	2311.9	93.7%	8.9%
	1	-3	global	30	2310.7	93.7%	10.7%
	5	-1	global	30	2305.8	93.5%	8.9%
	1	-5	global	30	2310.7	93.7%	10.7%
	10	-1	global	30	2292.8	93.0%	8.9%
	1	-10	global	30	2292.2	93.2%	10.7%
	50	-1	global	30	2308.9	93.6%	8.9%

Theoretically, both LP and NLP are local search methods, and GA is global one. It means the optimum value from LP and NLP may not be a real minimum for the objective function, especially NLP ("fmincon" in Matlab) that does depend on given initial value of variables. The bad initial value of variables can result in local optimum value. Compared with them, GA is an advanced algorithm with global search, which can do the optimization by searching among each value between low bound and up bound. So the optimum output from GA is more convictive. It is because of this, running time of GA is much longer than the other two.

However, focusing on GA, it seems that the higher value of early departure, the more congestion remaining will be: when values of early departure are -3, -5, -10, congestion remaining will reach 10.7%. But total time travel does not change a lot with different values of early/late departure. Optimum demands are almost the same. The main reason is due to the mechanism of GA. GA is a stochastic generator. The solution from GA follows uniform or normal distribution. They will not offer too many changes of output.

5.6 Conclusion

In this chapter, A15 model calculation in Matlab and simulation in Dynasmart are carried out. After synchronization between Matlab and Dynasmart, where saturation flow in Dynasmart is made equal to capacity in Matlab for instance, LP with only late departure as a test calculation is used. Optimum demand from LP cannot solve much congestion and total travel time does not reduce much. But optimum demand with LP iteration calculation reduces congestion to some extent. The main reason is that LP is an algorithm to get the optimum demand at one run, which is unable to handle large scale problem. LP cannot search for the optimum point one by one. If the iteration is carried out, more searching will be carried out, so the optimum demand can be optimized better. For the traffic state with a better solution, more traffic move to upstream and in late departure time.

Following this, “fmincon” in Matlab as one of NLP is called to solve both early and late departure with costs. The results are much better than output from LP. “fmincon” can handle the large scale problem, although it is still a local searching algorithm. Then the total travel time reduces by 5.9% and congestion decreases to 16.7% from initial 19.6%. The traffic state has been improved to some extent. In Dynasmart interface, in some time periods, congestion reduces a little bit. Thus some travelers taking early departure do offer more room to load the congested traffic on A15. And all highway sections give more room to load traffic (with negative average percentage of estimated and observed traffic flow).

Moreover, genetic algorithm as a global-searching algorithm offers almost average distribution of optimum demand, although values of early and late departure time change a lot. GA can offer the best solution compared with the other two local algorithms. Focusing on values of early and late departure, the larger value of late departure is, the less congestion left will be. And total travel time reduces by 7.0% and congestion decreases from 19.6% to 8.9%. Similarly, traffic moves to upstream and in late time slots. Obviously the traffic states represented in Dyansmart interface are the best among all the outputs of the algorithms, less queuing, less congestion and lowest travel time.

In conclusion, the concept of time slot allocation does help to solve congestion problem to some extent, migrating traffic to low utilized capacity time slots, which means congested traffic flow has spread to non-congested areas and time slots. With the global-researching algorithm, total travel time can reduce by 7.0% and congestion remains only 8.9% from DTA.

6. Conclusions and Recommendations

This chapter summarizes the work done about analyzing feasibility of time slot allocation to optimize network capacity and reports the findings from different optimization algorithms. The conclusion related to research questions is presented. Recommendations for further research are given as well.

6.1 Summary of Research Process

First of all, a brief introduction of this thesis is presented. Congestion as we know is a big issue for road transport. But few have done much with regard to departure time to optimize network capacity under the context of dynamic modeling. Here time slot is a group time slot, which influences or limits a cluster of travelers to enter the network. This kind of limitation is based on the discrete time periods, 15-minute each. So it has a different mechanism from ramp metering that is a continuous control. Meanwhile time slot has a wilder application range than ramp metering. Time slots can be allocated at on-ramps and at the boundaries of a city network. With respect of no route choice on A15 highway study area, it is chosen to be an application network to test the concept of time slot allocation.

As this concept is quite new in dynamic traffic management, field study and literature review have been performed to see how to set up a methodology for time slot allocation. Relevant topics—ramp metering and corridor control, travel time, network capacity optimization—are chosen to get fresh ideas and combined for the methodology of time-sliced demands.

Obtaining good results need reliable data in a proper network. Analysis of A15 motorway based on Monica data in the morning peak has been carried out. Because of fixed logistics scheduling with port industry, and residents using available on-ramps at peak hours without alternative route, congestion with over-saturation happens. Here congestion is defined as a phenomenon that traffic flow exceeds capacity and speed drops sharply. In A15 case, situation with traffic flow larger than 2300veh/h/lane and traffic speed less than 70km/h is defined as congestion.

We cannot overcome congestion problem in a short term but it is possible to migrate congestion from one location to another or/and from one time slot to another, and make the maximum use of the whole network with network traffic management. Travel time cannot be formulated so far in an analytical approach, so traffic flow less than capacity is the main constraint for the methodology. Based on the Vickrey's model and system control concept, the new methodology is to minimize the difference between cumulative desire demand and cumulative optimum demand with capacity constraints.

Then linear programming has been used in Matlab to test the late departure only. Output is not satisfying as expected. Travel time does not reduce much and still there is the same congestion. The main reason is that LP is one-time optimization, which can handle only a few variables. Facing with 512 variables in optimization model, LP cannot handle this large-scale problem. LP iterations are carried out, which does improve, to some extent, with less travel time and less congestion, but limited number of iterations cannot get real optimum demand. On the other hand, merely late departure cannot solve the traffic congestion, most of traffic move to late departure and upstream.

Then methodology is extended to both late and early departure with given values. "fmincon" in Matlab as one algorithm of the non-linear problems has been used to offer optimum demand. Traffic state is much better than LP, with less travel time and less congestion. Two main reasons can explain this phenomenon. One is "fmincon" is a self-iteration algorithm. The output is calculated after several iterations to get the optimum solution, although it searches still locally. Thus it is more advanced than LP. In addition, as a general case, both late and early departures are taken into account including value of late and early departure time. Travelers can choose to departure early or late. Of course it can alleviate congestion better.

Finally, more advanced algorithm—genetic algorithm -- is used, which is a soft algorithm and can handle a large quantity of variables with global searching. As expected, it offers the best optimum demand with lowest total travel time and least congestion left. Since GA is a stochastic generator, the output follows a uniform or normal distribution. So even if values of early and late departure time change a lot, optimum demand does not change much.

6.2 Implementation Consideration

As we can see, time slot allocation is capable of reducing congestion problem in the network. Thus in order to make this concept practicable, actor/stakeholder analysis -- Rotterdam Port Authority, motorway operator and urban planner -- is carried out to see what kinds of measures they can take to promote time slot allocation. Three of them belong to different levels to consider these issues. Rotterdam Port Authority is in the measures level (effects of a specific measure on a specific location); motorway operator in the program level (effects of ITS on a regional or national scale); and urban planner in the national level (socio-economic evaluation).

1) Rotterdam Port Authority

Getting profit is the main purpose of Rotterdam Port. Thus a better service quality to attract more industry companies is their strategy, of which highly accessibility is a vital service.

With the time-slot-allocation concept, Rotterdam Port should take some measures to promote companies to follow the optimum demand with certain time slot fees. According to different transported products, they rank the priority to encourage them. For instance, for fresh food companies, Rotterdam Port could encourage them departure early to get more award. And for oil industry as the main transport on A15 motorway, Rotterdam Port can offer some subsidies to the companies who need to pay high late departure fees.

In addition, based on on-line navigation system, Rotterdam Port can give real-time time slot pricing to the companies. If there is a large quantity of flowers needed to transport, the flower company may get the priority. For the delayed companies, Rotterdam Port reduces fees for them. All this processes are dynamic to solve congestion.

2) Motorway Operator

Motorway operator is located in the program level for both regional and national scales. The concept of time slot allocation can be extended to a large scale, such as the boundary of a city or even for the whole country. Motorway operator is interested in measurements to alleviate congestion problem. For the city, especially the mega polis like Amsterdam, time slot allocation can be applied at the boundary of the city to control the traffic to enter the city center in different time periods. On-line navigation system collects real-time traffic data and sends these data to the control center, letting them know what the current traffic state is in the city network and how much room left for extra traffic. Then after decision-making, through increasing prices of time slots, less traffic will enter the city network in these time slots. This concept can be applied in some specific festivals such as the Koninginsdag, when a large quantity of travelers would like to drive to Amsterdam. How many travelers can drive into Amsterdam and when they can are controlled by motorway operator based on time slots.

For the national scale, it is a more complex situation. Normally time of day is divided by three parts: 7:00 to 9:00, 16:00 to 18:00 and the rest. Different time slots in distinct areas interact each other to control traffic flow in the network to reduce congestion. Motorway operators may close one peak-hour time slot in one area, forcing travelers to enter in the other time slots in rest of day, or set the high fee for a certain time slot to limit traffic flow. But the problem is how to predict the traffic situation in the next time slot to realize real-time control and if the quantity of the sold time slots is not suitable for the next time slot as predicted how to reduce the impact? National data warehouse can support traffic information, sending time-slot information to travelers, letting them buy certain time slots and sending back to control centers. According to the data, control centers will do some adjustment.

3) Urban Planner

As urban planner in regional level, they take accessibility, safety and quality of the environment into account. In order to safeguard and improve the accessibility, they can do separately for each time period. They can aggregate the travelers in a certain area as a work-zone or distinguish between specific parts of the city accessibility for work zones, such as housing areas, and shopping areas. In peak hour, they may close the road entry of the shopping and work-zone or give a high fee (red card) for shopping zone and low fee (green card) for travelers who would like to go home from companies working-zones. In this way, the specific time slots can be given to the right people to the right destinations. In other words, urban planner may choose to give priority in specific time slots to residential and office areas during the rush hours. Outside the rush hours, priority can be given to economic centers, whereas during the weekends a shopping precinct or theme park might be given priority (Rijkswaterstaat, 2003). That is an approach for urban planner to use time slot to realize DTM.

Then urban planner in national level is interested in social, economic and environmental issues of each new measure. They would like to know whether time slot allocation with costs can make social welfare maximized. If not, they will suggest motorway operators changing prices. As non-profit authority, urban planner hopes time slots can promote economy to increase, more trades with a better traffic situation. What is more, time slot allocation decreases waiting time, which helps reducing emission sharply, protecting environment and saving energy. In this point, urban planner will suggest making the policy to carry out time slot allocation and offer more subsidies to travelers.

Evaluation Criteria

The measures are taken by actors in different levels. There should be some criteria to evaluate them. Four classes of criteria are taken into account: accessibility, processing on network parts, safety and quality of the living environment. In each class, detailed criteria are given in Table 6-1.

Table 6-1 frame of reference criteria (Rijkswaterstaat, 2003)

Theme	Criterion
Accessibility	travel time
	time lost per kilometer
	reliability (e.g. travel time variation)
Processing on the network	section (speed or journey speed)
	length, queue length, obstructions, tailback severity
	vehicle hours (lost)
	continuity (e.g. no. of stops at traffic lights)
	Availability (e.g. “no traffic jam outsides peak hours on 80% of all workdays)”
	Volume (no. of vehicles per hour)
	Vehicle kilometers
Safety	Accidents, deaths, injuries
	Road use (volume, speed, relationships) relative to the road function (flow, access, private)
Quality of the living environment	Noise (emission)
	Air pollution (emission)
	Crossability, barrier action
	Road use (volume, speed, relationships) relative to the road function (flow, access, private)

6.3 Conclusions

Four research questions posed in the beginning of this report are answered here.

1) *Is it feasible to allocate discrete time-slots on-ramps to solve congestion problem on motorway?*

Discrete time slots are feasible to solve congestion problem, as now we can say. As we can see from flow mapping based on the best optimum demand (Table 5-14), average percentages of estimated/observed flow in space aspects are almost negative, which means more room is left for loading traffic, and in time dimension traffic move to late time slot, more room left in the front time slots.

2) *Does shifting traffic demand in time slots improve traffic state?*

Optimum demand as output of Matlab is taken as an input to Dynasmart. In the interface of Dynasmart, pink queues still show up to represent the congestion. But in some highway sections in certain time slots, congestion does reduce much. With the output, total travel time reduces by 7.0% and congestion from 19.6% to 8.9%. It implies the improvement of traffic states on A15 already. Therefore shifting traffic demand in time slots can improve traffic state to some extent.

3) *Which algorithm is most suitable for this case?*

With respect to the objective function with 512 variables, genetic algorithm is the most suitable one. It is a global searching algorithm to handle a large quantity of variables. And with travel time and congestion left as two criteria, outputs based GA are the best solution with 7.0% reduction of total travel time and congestion left from 19.6% to 8.9%.

4) *Will time slots selling influence travelers' departure time?*

Whether time sots selling influences travelers' departure time, depends on the practicability and rationality of policy. In the short term, some travelers may complain about this pricing system, who have to spend opportunity cost on affordable time slot, such as getting up early or waiting at home. And the others may care less about the money, willing to pay for the certain time slot. However in the long term, travelers may get the benefit from being influenced by time slot, travel time reducing, waiting time shortening on the congestion, and less gas consuming. They will shift their own departure time to the new one, forming a new cluster of travelers to network in a certain time slot. At that moment, social welfare can be improved. Therefore time slot selling will influence traveler's departure time.

6.4 Recommendations for Further Research

In this section recommendations for further research are presented from three aspects.

6.4.1 Methodology Updating

In the current methodology, the objective function includes “sign()” to separate early and late departures, which is a good idea. But it makes objective function as non-convex and non-linear. Sometimes the outputs are strange. If using square, the objective function will be a convex problem, which has a unique solution definitely. It can offer likely better optimum demand for traffic state.

As a general congestion definition, speed and flow are two essential elements. In order to get more reliable solutions, speed constraint should be added in methodology. Also the applied capacity is still static with almost 75% of capacity. The problem will be that this applied capacity may lead to low infrastructure utilization. Additionally when congestion happens, the traffic flows will spillback. No flow means no capacity at all. Generally speaking, roadway capacities are continuous quantities subject to routine degradation due to physical and operational factors (Li, 2008). Even in the simulation assignment, capacity is calculated instantaneously with different outputs according to different situations. It is dynamic capacity. Some of literature have proposed dynamic capacity concept. It should be a nice direction to update methodology to see the results.

Moreover, synchronization between Matlab and Dynamsmart should be carried out further to get more reliable parameter settings.

6.4.2 Relevant Research Topics

The research on time slot allocation is not limited on the demand calculation. There are many research topics related to it.

First of all the application model should be extent to the whole A15 model with $44 \times 44 \times 12$ (44 origins, 44 destinations and 12 time slots) 3-dimenstion matrices. Then the model can be enlarged to more complex network with route choices or the other elements to see how time slot allocation influences or interacts with the others.

And with time slot allocation waiting time at on-ramps and in the congestion queue reduces, which means emission decrease. But to what extent time slot allocation can influence this emission reduction is a nice topic.

Additionally, owing to time slot allocation, unrealizable elements of travel time prediction are dropping. More accurate data can be captured. The target that “for trips longer than 50km over freeway 95% of the trips arrive within the time interval of the median travel time plus or minus 20%. For shorter trips the target is that 95% of the trips will be between the median travel time plus and minus 10 minutes (VW, 2005).” can be better realized.

Moreover time slot allocation on the road transport can be combined with time slot on railway and airport. The transit time can be more reliable for the multi-mode transport.

The last but not least, in the control loop (Figure 4-1), only optimization in MPC controller is tested. There is still a lot of research in this loop. It is a good concept to implemented time slot allocation to real network, which includes much technology such as data fusion, optimization, and information feedback. It is a promising topic for the further research.

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8 Appendices

Appendix 1: Matlab Codes

Linear Programming

```
clear all
close all
clc
%% Desired Demand (Dd)
DEMAND=zeros(16,6,8);
for i=1:8
D= importdata('demand0.dat',' ', 17*(i-1)+3);
DEMAND(:,:,i)=D.data;
end

Dd=zeros(8,8,8);
for i=1:8
    E=DEMAND(:,:,i);
    for j=1:8
        F=reshape(E(2*(j-1)+1:2*j,:)',1,12);
        Dd(j,:,i)=F(1:end-4)';
    end
end
Dd=Dd/4;
save demand.mat Dd

%% Mapping (p)
p=importdata('LinkMapIJTKD.dat',' ', 1);
p=p.data;
p=sortrows(p,[4 5]);
map = xlsread('map.xlsx');
for i=1: length(p)
    for k=1:7
        if p(i,4)==map(k,2);
          p(i,4)=map(k,1);
        end
    end
end
save mapping.mat p

%% Capacity
load capacity1.mat
C=C(:,1);
Cap=zeros(56,1);
for c=1:7
    Cap((c-1)*8+1:8*c,1)=C(c);
end
Cap=Cap/4;

%% O.F. :a0
N=8;
```

```
a0=0;
for k=1:8
   a0=a0+(N-k+1)*sum(sum(Dd(:,:,k)));
end

a=zeros(8,8,8);
for g=1:N
a(:,:,g)=-(N-g+1);
end

f=zeros(1,512);
k=1;
for i=1:8
   for j=1:8
      for t=1:8
         f(k)=a(i,j,t);
         k=k+1;
      end
   end
end
%% Do*p<Cap
B=zeros(56,512);
for ii=1:length(p)
   i=p(ii,1);
   j=p(ii,2);
   t=p(ii,3);
   col=(j-1)*8+t+(i-1)*8*8;
   row=(p(ii,4)-1)*8+p(ii,5);
   B(row,col)=p(ii,6);
end

%% N=1  Dd>=Do
N1=zeros(64,512);
for i=1:64
   for j=(i-1)*8+1
    N1(i,j)=1;
    end
end

D1=Dd(:,:,1);
D11=zeros(64,1);
k=1;
   for i=1:8
      for j=1:8
         D11(k)=D1(i,j);
         k=k+1;
      end
   end
%% N=2
N2=zeros(64,512);
for i=1:64
   for k=1:2
       for j=(i-1)*8+k
       N2(i,j)=1;
       end
   end
end

D2=Dd(:,:,1)+Dd(:,:,2);
```

```
D22=zeros(64,1);
k=1;
    for i=1:8
        for j=1:8
            D22(k)=D2(i,j);
            k=k+1;
        end
    end
%% N=3
N3=zeros(64,512);
for i=1:64
    for k=1:3
        for j=(i-1)*8+k
         N3(i,j)=1;
         end
    end
end

D3=Dd(:,:,1)+Dd(:,:,2)+Dd(:,:,3);
D33=zeros(64,1);
k=1;
    for i=1:8
        for j=1:8
            D33(k)=D3(i,j);
            k=k+1;
        end
    end
%% N=4
N4=zeros(64,512);
for i=1:64
    for k=1:4
        for j=(i-1)*8+k
         N4(i,j)=1;
        end
    end
end

D4=Dd(:,:,1)+Dd(:,:,2)+Dd(:,:,3)+Dd(:,:,4);
D44=zeros(64,1);
k=1;
    for i=1:8
        for j=1:8
            D44(k)=D4(i,j);
            k=k+1;
        end
    end

%% N=5
N5=zeros(64,512);
for i=1:64
    for k=1:5
        for j=(i-1)*8+k
         N5(i,j)=1;
         end
    end
end

D5=Dd(:,:,1)+Dd(:,:,2)+Dd(:,:,3)+Dd(:,:,4)+Dd(:,:,5);
D55=zeros(64,1);
```

```
k=1;
    for i=1:8
        for j=1:8
            D55(k)=D5(i,j);
            k=k+1;
        end
    end

%% N=6
N6=zeros(64,512);
for i=1:64
    for k=1:6
        for j=(i-1)*8+k
         N6(i,j)=1;
        end
    end
end

D6=Dd(:,:,1)+Dd(:,:,2)+Dd(:,:,3)+Dd(:,:,4)+Dd(:,:,5)+Dd(:,:,6);
D66=zeros(64,1);
k=1;
    for i=1:8
        for j=1:8
            D66(k)=D6(i,j);
            k=k+1;
        end
    end

%% N=7
N7=zeros(64,512);
for i=1:64
    for k=1:7
        for j=(i-1)*8+k
         N7(i,j)=1;
        end
    end
end

D7=Dd(:,:,1)+Dd(:,:,2)+Dd(:,:,3)+Dd(:,:,4)+Dd(:,:,5)+Dd(:,:,6)+Dd(:,:,7);
D77=zeros(64,1);
k=1;
    for i=1:8
        for j=1:8
            D77(k)=D7(i,j);
            k=k+1;
        end
    end

%% N=8
N8=zeros(64,512);
for i=1:64
    for k=1:8
         j=(i-1)*8+k;
          N8(i,j)=1;

    end
end
```

```
D8=Dd(:,:,1)+Dd(:,:,2)+Dd(:,:,3)+Dd(:,:,4)+Dd(:,:,5)+Dd(:,:,6)+Dd(:,:,7)+Dd(:,:,
8);
D88=zeros(64,1);
k=1;
   for i=1:8
      for j=1:8
         D88(k)=D8(i,j);
         k=k+1;
      end
   end

%%
AA=[B;N1;N2;N3;N4;N5;N6;N7];
b=[Cap;D11;D22;D33;D44;D55;D66;D77];
Ddd=zeros(512,1);
k=1;
for i=1:8
   for j=1:8
      for t=1:8
         Ddd(k)=Dd(i,j,t);
         k=k+1;
      end
   end
end
%% upbound
MAX=max(Dd,[],3);
W=zeros(64,1);
k=1;
for i=1:8
   for j=1:8
      W(k)=MAX(i,j);
      k=k+1;
   end
end
WW=zeros(512,1);
for i=1:length(W)
   WW((i-1)*8+1:(i-1)*8+8,1)=W(i,1);
end
%%
f = f;
A = AA;
b = b;
Aeq = N8;
beq = D88;
lb = zeros(512,1);
ub = WW;
ff=optimset;
ff.TolX=1e-15;
ff.TolFun=1e-20;
TolCon=1e-20;
ff.Display='iter';
 [x,fval,exitflag,output,lambda] = linprog(f,A,b,Aeq,beq,lb,ub);

D0=zeros(8,8,8);
k=1;
for i=1:8
   for j=1:8
      for t=1:8
         D0(i,j,t)=x(k);
```

```
            k=k+1;
        end
    end
end

% calculate Z
Z=f*x+a0;
save optimumdemand.mat D0
```

Genetic Algorithm

```
function x=costga()

clear all
clc
load demand.mat
%Dd=Dd/4;
load mapping.mat
load capacity1.mat

B=zeros(56,512);
for ii=1:length(p)
    i=p(ii,1);
    j=p(ii,2);
    t=p(ii,3);
    col=(j-1)*8+t+(i-1)*8*8;
    row=(p(ii,4)-1)*8+p(ii,5);
    B(row,col)=p(ii,6);
end

C=C(:,1);
Cap=zeros(56,1);
for c=1:7
    Cap((c-1)*8+1:8*c,1)=C(c);
end
Cap=Cap/4;

N8=zeros(64,512);
for i=1:64
    for k=1:8
        for j=(i-1)*8+k
          N8(i,j)=1;
        end
    end
end

D8=Dd(:,:,1)+Dd(:,:,2)+Dd(:,:,3)+Dd(:,:,4)+Dd(:,:,5)+Dd(:,:,6)+Dd(:,:,7)+Dd(:,:,
8);
D88=zeros(64,1);
k=1;
    for i=1:8
        for j=1:8
            D88(k)=D8(i,j);
            k=k+1;
        end
    end

%%
```

```
A=B;
b=Cap;
Aeq = N8;
beq = D88;
LB=zeros(512,1);

uub=zeros(8,8);
for i=1:8
    for j=1:8
        for t=1:8
            uub(i,j)=uub(i,j)+Dd(i,j,t);
        end
    end
end
uuub=zeros(8,8,8);
for s=1:8
    uuub(:,:,s)=uub(:,:);
end

uubb=zeros(512,1);
k=1;
for i=1:8
    for j=1:8
        for t=1:8
            uubb(k)=uuub(i,j,t);
            k=k+1;
        end
    end
end
UB=uubb;

ff=gaoptimset;
ff.StallGenLimit=100;
ff.Generations=2;
ff.PopulationSize=25;
ff.StallTimeLimit=99999;
ff.CrossoverFcn=@crossoverheuristic;

% ga
[x,fval,exitflag,output,lamba] =
ga(@cost_ga_fun4,512,A,b,Aeq,beq,LB,UB,@cost_ga_con4,ff);

v1=[];
v1=x(1,1:512);
x_3=zeros(8,8,8);
k=1;
for i=1:8
    for j=1:8
        for t=1:8
            x_3(i,j,t)=v1(k);
            k=k+1;
        end
    end
end
save x.mat x x_3 fval;
%%
function [c,ceq]=cost_ga_con4(x)
c=[];
ceq =[];
```

```
return;
%%
function z=cost_ga_fun4(x)
load demand.mat
N=8;
x=ones(512,1);

D00=zeros(8,8,8);
k=1;
for i=1:8
    for j=1:8
        for t=1:8
           x(k)=D00(i,j,t);
            k=k+1;
        end
    end
end

s1=zeros(8,8,8);
s2=zeros(8,8,8);
s1(:,:,1) = D00(:,:,1);
s2(:,:,1) = Dd(:,:,1);
for i = 2:1:8
  s1(:,:,i) = s1(:,:,i-1)+ D00(:,:,i);
  s2(:,:,i) = s2(:,:,i-1)+Dd(:,:,i);
end
   alpha1=1;
   alpha2=-3;
z1=( alpha2+ (alpha1-alpha2)*(1/2)*(1+sign(s2-s1)) ).*(s2-s1);
    z=sum(sum(sum(z1(:,:,:))));
   return
```

Realizing $Q^{kh} = \sum_i \sum_j \sum_t \left(D^o_{tij} \cdot p^{kh}_{ijt} \right)$

```
clear all
close all
clc
%% Demand (T-Dd)
DEMAND=zeros(352,6,12);
for i=1:12
D= importdata('Demand.dat',' ', 353*(i-1)+3);
DEMAND(:,:,i)=D.data;
end

T=zeros(44,44,12);
for i=1:12
    E=DEMAND(:,:,i);
    for j=1:44
        F=reshape(E(8*(j-1)+1:8*j,:)',1,48);
        T(j,:,i)=F(1:end-4)';
    end
end
```

```
save demand.mat T

%% Mapping (p)
p=importdata('LinkMapIJTKD.dat',' ', 1);
p=p.data;
save mapping.mat p

%% Flow (Q)
clear all
close all
clc

load demand.mat
load mapping.mat
p=sortrows(p,[4 5]);
save mapping45sort.mat p

% T*p=Q
Q=zeros(length(p),1);
for i=1:length(p)
    a=p(i,1:3);
    Q(i)=T(a(1),a(2),a(3))*p(i,6);
end

H=[p(:,4:5) Q];

G=[sum(H(:,1:2),2) H(:,3)];

J=[];
for i=1:length(p)
   if i~=length(p) & G(i,1)~=G(i+1,1)
        J=[J i];
   elseif i==length(p)
       J=[J i]
    end
end

U=zeros(length(J),1);
for i=1:length(U)
    if i==1
       U(i)=J(i);
    else
        U(i)=J(i)-J(i-1);
    end
end

%[khQ][khQ][khQ][khQ]...
K=zeros(max(U),3*length(U));
 for i=1:length(U)
    if i==1
         K(1:U(1),1:3)=H(1:J(1),:);
    else
         K(1:U(i),3*(i-1)+1:3*i)=H(J(i-1)+1:J(i),:);
    end
end

L=zeros(1,length(K));
for i=1:length(U)
```

```
    L( 3*(i-1)+1:3*(i-1)+2 )=K( 1,3*(i-1)+1:3*(i-1)+2 );
    L(3*i)=sum(K(:,3*i));
end

%[khQ]in columes
M=zeros(length(U),3);
for i=1:length(M)
    M(i,:)=L(3*(i-1)+1:3*i);
end
figure
plot(M)

%find the missing data
S=zeros(length(M),1)
S=M(:,2)
figure
plot(S)

% owing to lack of 2 flowdata. add 0 there
N=[M(1:10,:);[17 11 0];M(11:370,:);[112 12 0];M(371:381,:);[114 12
0];M(382:452,:);[130 12 0];M(453:462,:);[150 11 0];[150 12
0];M(463:486,:);[165 1 0];[165 2 0];[165 3 0];M(487:495,:);[173 1 0];[173 2
0];M(496:552,:);[224 12 0];M(553:863,:);[270 12 0];[280 1
0];M(864:1005,:);[332 12 0];M(1006:1016,:);[334 12 0];M(1017:end,:)];

% 3-dimentional matrices with link, obseved time,flow
FLOW=zeros(88,12,3);
FLOW(:,:,1)=reshape(N(:,1),12,88)';
FLOW(:,:,2)=reshape(N(:,2),12,88)';
FLOW(:,:,3)=reshape(N(:,3),12,88)'*4;

plot3(FLOW(:,:,1),FLOW(:,:,2),FLOW(:,:,3))


bar(FLOW(4,:,3));
title('link 57');
save flow.mat FLOW

%% Flow/Capacity
C = xlsread('linkcapacity.xls');
O=C(:,2);
K=[O O O O O O O O O O O O ];

FC=FLOW;
S=zeros(88,12);
for i=1:88
  for j=1:12
S(i,j)=FC(i,j,3)./K(i,j);
  end
end
```