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Driving behavior modeling and evaluation of merging control strategies - A microscopic simulation study on Sirat Expressway

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2018-02-28

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Abstract

Bangkok is a city where the congestion levels have been a major problem for many years. In 2017, Bangkok was rated the most congested city in Asia, and the second most congested in the world. According to The Expressway Authority of Thailand (EXAT), on-ramp merging is one of the most critical problem that causes congestion on the urban expressways. EXAT have evaluated several merging control strategies through microscopic traffic simulation to find suitable strategies for implementation in real life. However, their simulation studies were all based on the assumption that all motorists strictly follow the traffic rules. This is not the actual case in Bangkok, where the drivers ignore both solid lines and striped areas, as well as utilize the shoulder lane on a regular basis.

The aim of this thesis is to investigate if it is possible to include this complex driving behavior in existing microscopic simulation models. A second objective is to identify merging control strategies that can reduce the occurrence and the effects of this driving behavior in order to increase the throughput at an on-ramp area on Sirat Expressway.

A model was built in VISSIM and calibrated based on data collected from video recordings. In the study, parameters that are significant for the driving behavior modeling, as well as the difficulties that arise from performing a realistic calibration of the model using video observations and model-specific constraints, are identified.

From the video recordings it was discovered that the main problem causing the congestion was a result of the mainline traffic who traversed to the on-ramp. Two merging control strategies were suggested to address this problem: the installment of a center barrier, and successive merging areas. The results confirmed that both actions can improve the traffic situation in terms of reducing the individual travel time. Installing a center barrier was the most efficient option and reduced the travel time by 16.58 % on the mainline and 63.24 % at the on-ramp.

Keywords: microscopic, simulation, VISSIM, driving behavior, on-ramp, merging, control strategy, expressway, Bangkok

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1 Introduction

In this chapter, the background of the problem and the aim of this thesis are given. It also contains the research questions investigated to fulfil the aim, as well as the scope of work and a methodology section.

1.1 Background

Bangkok is a city where the traffic situation and the congestion levels have been a major problem for many years. In 2017, both TomTom (2017) and Cookson & Pishue (2017) rated Bangkok as the most congested city in Asia, and according to the former also the second most congested city in the world. In addition to the amount of vehicles on the roads, Carlisle (2017) states that the Thai traffic officials points out the accidents, floods and bad driving behavior of the Thai motorists as the main causes of the problems related to congestion.

According to Kritsadaniramit et.al (2016) at the Expressway Authority of Thailand (EXAT) there are three main problem areas in Bangkok that causes congestion on the expressways off-ramp areas, on-ramp merging and queues at the toll stations. Out of these, on-ramp merging is the most critical one and constitutes for 3 out of the 5 most critical congestion points of the expressway system in Bangkok. A map showing the expressway system in urban Bangkok, including the five critical congestion points identified by EXAT, can be seen in Figure 1.

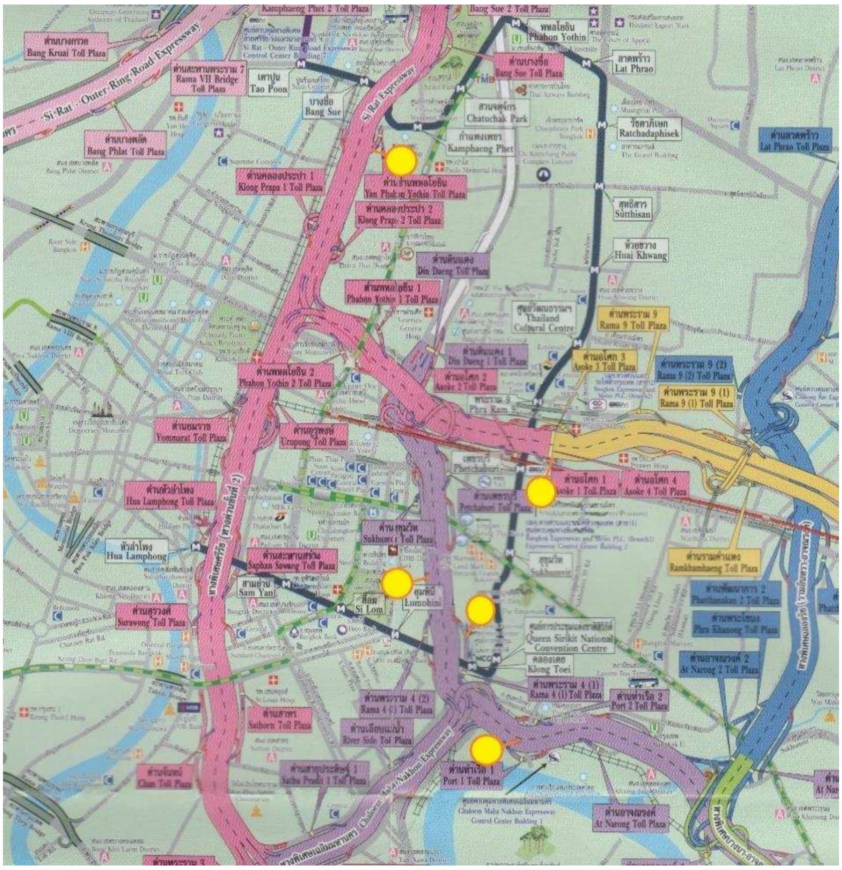


Figure 1: Expressway network in Bangkok including critical points of congestion identified by EXAT

Currently EXAT has investigated four types of strategies (by simulation) to deal with this problem: solid lines, the use of cones to move the merging point, reversible lanes and lastly ramp metering. Their studies, EXAT (2016a) and EXAT (2016b), showed that solid lines would have the greatest positive impact on the congestion in the former case and that ramp metering would have a positive effect in the latter. Both studies is however based on the assumption that the motorists strictly follows the traffic rules. At the present state however, Panyalimpanun, T. (2013), Fredrickson, T. (2016) and EXAT (2016c) state that the drivers are ignoring both solid lines as well as striped areas, and also that it is common that drivers utilize the shoulder lane at the expressway as regular lane to avoid the congestion. These observations are also confirmed by a video recorded by Min Thu (2017). The bad driving behavior greatly impacts the overall traffic operations and subsequently increases the problems of congestion at the on-ramp areas. At some on-ramp areas, the police have tried to ease the situation by acting as “ramp meters” and stopping the flow of vehicles for some arbitrary time and then letting them go again. This is a dangerous way to control the traffic, and since the issues with driver discipline and merging behavior of the motorists’ still remains, the efficiency of using this strategy can be questioned.

Traffic simulation models in the earlier studies made by EXAT typically describe traffic situations with stricter lane division and a higher level of driver discipline than what can be seen on the on-ramp merging areas in Bangkok. Since the behavior of the Bangkok drivers differs from the driver behavior commonly implemented in traffic simulation models, there is a need to create a model that considers a more realistic driver behavior.

1.2 Aim

The aim of this thesis is to investigate how the relatively complex driver behavior of the Bangkok drivers at on-ramp merging areas can be included in microscopic traffic simulation models. In addition, the objective is to investigate how this driver behavior in combination with different merging control strategies affects the congestion in the studied on-ramp area.

1.3 Research questions

The following research questions are going to be investigated in order to fulfil the aim of this thesis:

Part 1: Driving behavior modeling of the Bangkok traffic

- What driving behavior characteristics can be identified from the expressway traffic in Bangkok?
- How can existing driving behavior models in a microscopic traffic simulation tool be adapted to reflect a realistic behavior of the Bangkok drivers?
- What limitations in capturing the actual driving behavior at the studied site can be identified from the adapted driver behavior models?

Part 2: Effects of merging control strategies

- What merging control strategies can be expected to reduce the congestion in the studied area?
- How do the studied merging control strategies affect the traffic performance of the vehicles in the studied on-ramp area?
- Which of the suggested merging control strategies is most efficient in terms of travel time reduction of the vehicles in the studied on-ramp area?

1.4 Scope of work

The delimitations and limitations of this thesis are:

- Only two travel modes, personal cars and buses, will be considered in the suggested model. Hence three wheeled vehicles will be categorized as personal cars and heavy vehicles as buses respectively.
- Motorcycles are forbidden to drive at the expressways in Bangkok and are hence not included in the model.
- The driving behavior modelled is based on the studied on-ramp area only and might not be valid for other on-ramp areas.
- Data collection is made during 3 weekdays between 9:00-12:00 at an on-ramp merging area at Sirat Expressway in Bangkok. Hence, the model only reflects the traffic conditions during this time and at the specified location.
- The microscopic simulation software PTV VISSIM will be used in this study and hence the sub-models that can be adapted are the ones available in the software package. This might lead to model specific delimitations.
- The collected data contains vehicle flows, travel times and number of lane changes in the studied area. All data is extracted manually from video recordings and no data is available on the actual demand. The lack of sufficient, high quality data might cause complications in obtaining a satisfying calibration result.

1.5 Methodology

The literature review of this thesis gives a brief introduction to microscopic simulation models and driver behavior models available in the microscopic simulation tool VISSIM. It also includes learnings from earlier studies on microscopic driver behavior modeling in areas with similar traffic and road conditions as Bangkok, as well as theory on relevant merging control strategies that can be used to alleviate congestion in on-ramp merging areas.

Field observations needed to perform the simulation study was made by the help of video recording at three occasions. At all occasions, 2-4 video cameras were mounted in high-rise buildings from where the studied on-ramp merging area could be observed. The recordings were made during three consecutive weekdays between 9:00 and 12:00 am. Next, the recordings were visually analyzed by manually stopping the video and noting the corresponding time stamp at different occasions. Data on traffic volumes, vehicle composition, speeds, and travel times were obtained as well as observations on number of lane changes and merging behavior characteristics. Data regarding road geometry and other features was obtained from EXAT.

A microscopic simulation model of the studied site was constructed using VISSIM. Within VISSIM, parameters of the available car-following and lane changing models were adjusted in order to mimic the driver behavior observed from the videos. In addition, lateral driving behavior parameters and parameters related to conflict areas were modified. The model was calibrated using flow and travel time data from the field observations. Data on lane changing occasions and their location were used to calibrate the merging behavior.

As one of the objective of this thesis is to suggest suitable merging control strategies that might reduce the congestion, a base scenario and two alternative scenarios were created in VISSIM. The alternative scenarios applies one merging control strategy each, and the efficiency was measured in terms of average individual travel time. The two merging control strategies were selected based on a combination of on-site observations of the traffic situation and the data from the video recordings. From the simulation results, the most efficient merging control strategy out of the two suggested could be identified.

2 Literature review

In this section, a review of literature relevant for this thesis is presented. In the first section an overview of microscopic driver behavior models is given, followed by a description of the driver behavior models available in VISSIM. The second section gives a brief summary of earlier studies on microscopic driver behavior modeling in Bangkok and sites with similar road and traffic conditions. In the last section, examples of merging strategies that can be used to handle congestion problems in on-ramp areas are presented.

2.1 Microscopic driver behavior models

Microscopic traffic simulation models consists of several sub-models that are used to describe driving behavior. These sub-models are referred to by Gao (2008) as the "underlying logic" of a traffic simulation model. In turn, this logic consists of a car-following logic, a lane-changing logic, and a gap-acceptance logic which are all highly relevant in driver behavior modeling. This theory is partly supported by Olstam (2005) who lists all the mentioned logics as the most important driver behavior models.

Furthermore, Gao (2008) and Panwai & Dia (2005) state that the ability, of a traffic simulation model, to create an accurate output depends greatly on the sub-models at its core. Among these, they claim that the car-following and lane changing models are the key components. Lateral movements are also important when modeling driving behavior, but is normally included in the lane changing models. Car-following models and lane changing models will hence be the main focus of this section, as modeling of interaction between vehicles are important for the performance at on-ramp areas on expressways.

Since merging behavior is similar but yet different from lane-changing behavior a description of how it can be modeled will be included as well.

2.1.1 Car following models

Among all microscopic traffic models, Treiber and Kesting (2013) claims that the car-following models are the most important. Their importance is further supported by Gao (2008), who states that the car-following model is the key component in a microscopic traffic simulation software. There are several ways to define what a car-following model actually is. However, the main idea is to model how the driver of a constrained vehicle responds to changes in relative position and speed of the leading vehicle in an uninterrupted flow.

A number of well-known car-following models have been developed since the 1950's. Among the first were the group of so called General Motors (GM) models, out of which two were used in a car-following behavior study performed in Bangkok by Paoprayoon (2004). His work will be further discussed in section 2.3 Relevant studies on microscopic driving behavior modeling and merging, and a description of the GM models will be given below. Other well-known car-following models are Greenshields' fundamental model, as well as Pipes, Gipps, Van Aerdes, and Wiedemanns models which are incorporated in CORSIM, AIMSUN, INTEGRATION and VISSIM respectively. They are all further explained below by the help of Figure 2.

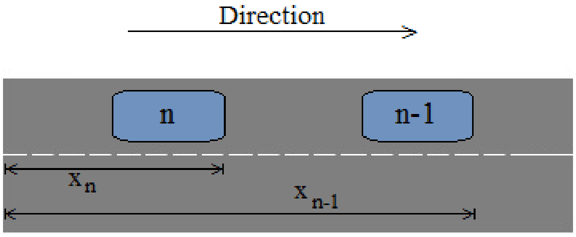


Figure 2: Basic car-following notation

Greenshields model

The Greenshields model is one of the fundamental car-following models, and assumes a linear relationship between speed and density while the traffic flow is continuous. The model also suggests a parabolic relationship between flow and density, as well as between speed and flow. According to Rakha & Crowther (2002), the car-following model derived from these assumptions and the relation between density and space headway can be expressed mathematically as:

$$h = \frac{\left({}^{u_f}/_{k_j}\right)}{u_f - u} \qquad (2.1)$$

where h is the space headway, u_f the free flow speed, and k_j the jam density.

This model however assumes that the speed at capacity is equivalent to half the free flow speed, which according to Kehoe (2011), can be a challenging task to validate via field observations.

Pipes model

One of the first car-following models was proposed by Pipes (1953) almost seventy years ago. In Pipes' model, which according to Rakha & Crowther (2002) constitutes the steady state car-following model in both CORSIM and VISSIM, the follower wants to keep a safety distance to the vehicle in front, a distance that should be kept proportional to the speed. The latter statement can, according to Treiber and Kesting (2013), also be formulated in terms of time as the time gap between the vehicles has to be larger than a fixed minimum safe time gap. However, the basic assumption of Pipes' model is generally quoted "A good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between your vehicle and the vehicle ahead for every ten miles per hour of speed at which you are traveling." (Dr. Tom V. Mathew, 2014a)

In the work presented by May (1990), the mathematical formulation of Pipes' model is given as:

$$d_{min} = [\dot{x}_n(t) - \dot{x}_{n+1}(t)]_{min} = 1.36[\dot{x}_{n+1}(t)] + 20 \qquad (2.2)$$

where d_{min} is the minimum distance headway and $\dot{x}_n(t)$ and $\dot{x}_{n+1}(t)$ are the speed values of the leading and following vehicles respectively. The model is based on the assumption that the vehicle length is 20 feet and the speeds between 0-88 ft/sec.

Kehoe (2011) argues that Pipes model, in comparison to Greenshields model, is easier to validate through field data. However, the model assumes that the speed at capacity is equal to the free flow speed.

Van Aerde model

The Van Aerde model is used to model car-following behavior in INTEGRATION, and consists of a combination between Greenshields and Pipes models. This is a non-linear model formulated as:

$$s_n(t) = c_1 + c_3 u_n(t + \Delta t) + \frac{c_2}{u_f - u_n(t+\Delta t)} \qquad (2.3)$$

where c_1, c_2 and c_3 are constants. u_n and u_f represents the speed and the free flow speed of vehicle n, and $s_n(t)$ is the front-to-front distance between the vehicles at time t.

A study made by Kehoe (2011) shows that both the speed-flow relationship and the flow-density relationship of the Van Aerde's model falls in between the corresponding curves for Pipes and Greenshields models. Hence, the Van Aerde model can be said to overcome the shortages of both the other models since the speed at capacity does not have to be equal to either the free flow speed (as in Pipes) or half of the free flow speed (as in Greenshields').

General Motors models

Around a decade after Pipes model was presented, the first General Motors model was brought forward by a group of researchers at General Motors. This model was successively further developed into an additional four models who all, as stated by Li and Sun (2012), rely on the theory that the driver of the following vehicle always accelerates or decelerates as a response of its surrounding stimulus. The definition of this stimuli-response function differs, but the general version also includes a sensitivity term and can be formulated as

response= f(sensitivity, stimuli).

The fifth and final model is commonly referred to as the generalized (GHR) model and is, according to May (1990), be formulated as

$$\ddot{x}_{n+1}(t + \Delta t) = \alpha_{l,m} \frac{[\dot{x}_{n+1}(t+\Delta t)]^m}{[x_{n+1}(t) - x_{n+1}(t)]^l} [\dot{x}_{n+1}(t) - \dot{x}_{n+1}(t)] \qquad (2.4)$$

where $\ddot{x}_{n+1}(t + \Delta t)$ represents the response of the following vehicle at time $t + \Delta t$, Δt the reaction time, $\dot{x}_n(t)$ and $\dot{x}_{n+1}(t)$ the speed of the lead and the following vehicle respectively, and α the sensitivity parameter. l and m are the speed and distance headway exponent.

All five GM models uses the relative change in speed and headway between the lead and following vehicle to derive the stimuli. What separates the models is hence how the values of l and m defined.

Gipps model

Gipps model is the fundamental theory behind the car-following model used in AIMSUN. The Gipps model was introduced in 1981 and assumes that the speed of the following vehicle can be classified as either restricted or unrestricted by the lead vehicle. The speed of the following vehicle is hence, according to Gao (2008), defined as the minimum out of the maximum possible speed under unrestricted conditions, and the maximum safe speed when restrictions are imposed by the vehicle ahead.

Wiedemann model

In VISSIM, the car-following behavior is based on a so called psycho-physical model suggested by Wiedemann in 1974. According to Gao (2008) and Higgs et al. (2011), the Wiedemann model assumes that a driver can be in four different driving regimes: following, free driving, closing in, or braking. These regimes are defined by thresholds (or action-points) that represents the points at which a driver changes his driving behavior. The thresholds and regimes for the Wiedemann 74 model are further explained below by the help of Figure 3, the work by Olstam (2004), and PTV AG (2011). A more detailed description of the Wiedemann model is given in 2.1.4 Driving behavior models in VISSIM.

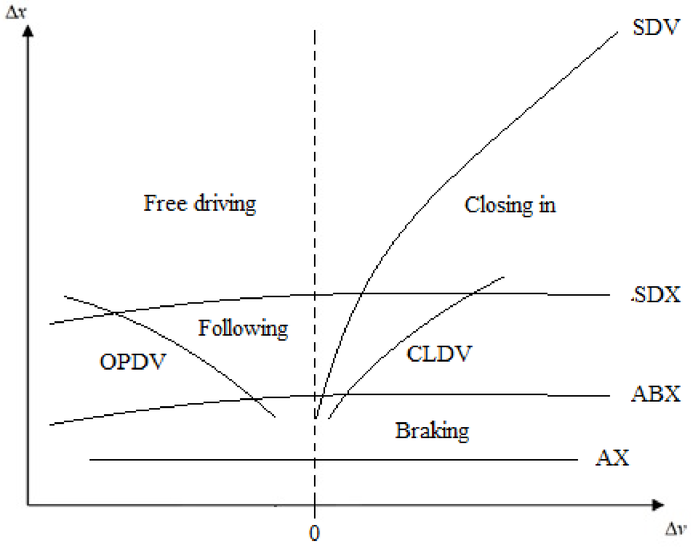


Figure 3: Graphical definition of Wiedemann model

Table 1: Threshold definitions for the Wiedemann model

Threshold	Description
AX	Represents the desired distance between two standstill vehicles.
ABX	The minimum following distance between two vehicles that travels in approximately equivalent speed.
SDX	Represents the maximum following distance during the same speed conditions as **ABX**.
SDV	The point at which a driver realizes that he is closing in on the vehicle in front.
CLDV	Defines the point at which a driver becomes aware of minor differences in speed at short, decreasing distances.
OPDV	The point when a driver realizes that he is traveling at a slower speed than the vehicle ahead.

The description of the regimes defined by the thresholds in Table 1 can be summarized as:

- **Following**

  A driver in this regime follows the vehicle ahead and is mostly concerned about keeping the safety distance relatively constant. When a vehicle enters the following regime by crossing either the OPDV or SDX threshold, it is assigned a positive acceleration rate. If the SDV or ABX is passed, the driver is assigned a negative acceleration rate instead.
- **Free driving**

  In the free driving regime, the driver is not restricted by any leading vehicle. Thus, the driver uses his maximum acceleration rate in order to reach in his desired speed.
- **Closing in**

  The closing in regime describes the scenario when a following vehicle has to decelerate in order to avoid collision with a slower vehicle ahead, that is, when the SDV threshold is passed. The deceleration of the following vehicle is adjusted to be equal to the speed of the leader at the time the desired safety distance is reached.
- **Braking**

  If the following vehicle is closer to the leading vehicle than the desire safety distance, the driver is said to be in the braking regime. Since the distance between the vehicles are too short, the driver of the following vehicle decelerates to avoid collision.

As mentioned earlier, Rakha & Crowther (2002) claims that the car-following model in VISSIM reverts to Pipe’s model under steady state conditions.

2.1.2 Lane Changing

Lane changing in practice refers to the act when a vehicle traverses to an adjacent lane from its present lane. To model a lane change in theory is, however, far more complex, but both Mathew (2014b) and Moridpour and Rose (2010) argue that lane changing is a significant component when modeling driver behavior using microscopic traffic simulation. What makes the lane changing descision difficult to model is the fact that it depends on multiple objectives that at times interfere with each other.

For example, Moridpour and Rose (2010) claims that lane changing maneuvers have a significant effect on traffic flow characteristics that might cause speed and traffic flow oscillations. Even though car-following behavior also can generate such oscillations, Moridpour and Rose (2010) claims that in the case of congestion, lane changes are more likely to be the main cause. In addition, frequent lane changing that occurs in for example merging areas might give rise to capacity drops on expressways. Bearing this in mind, the importance of modeling lane changing behavior in traffic simulation studies becomes clear.

Lane changes are, according to Mathew (2014b) and Ramanujam (2007), traditionally divided into two groups based on what triggers the urge of changing lane. The first is called Mandatory Lane Changes (MLC), which constitutes of lane changes that are imposed by a lane drop, incident or because the vehicle is approaching the exit of a junction. The second one is Discretionary Lane Changes (DLC) and describes lane changes that are performed due to a driver’s desire of traveling by higher speed or with more space. This division into two different types of lane changes are implemented in CORSIM and INTEGRATION, as well as in VISSIM and AIMSUN.

To understand the complexity of modeling a lane change, one has to start with the initial step: to model how the decision to change lane is reached. Among the first to do so was Gipps (1986), who suggested that the decision to perform a lane change is made by evaluating a set of three questions:

- Is a lane change possible?
- Is a lane change necessary?
- Is a lane change desirable?

Subsequently, the latter part of the lane changing process can be modeled.

Based on the structure presented by Gipps (1986), Hidas (2002) developed a different strategy to describe the lane changing process. In comparison to Gipps (1986), Hidas (2002) claims that it is unnecessary to perform a feasibility check before the necessity to change lane has been established. Hence, he suggests a swap of question one and two, in addition to a step concerned with the choice of target lane as well as the final execution.

Similarly to Hidas (2002), researchers like Ramanujam (2007) argues that lane changing models can be seen as two-step decision processes initiated by a lane selection step, and completed by a lane change execution step. The lane selection-step depends on the situation which called for the lane change, i.e. if it is MLC or DLC. Lane change execution, on the other hand, is modeled using so called gap acceptance models, which are summarized by Trejber and Kesting (2013) as models where a current gap are compared to a critical gap. The gaps can be defined in terms of time or available space, or as accepted speed difference and accepted deceleration as in Hidas (2002). Despite the gap definition, a lane change will be performed if the current gap surpasses the critical gap.

The DLC model is described by Mathew (2014b) as a three step process initiated with the decision whether to consider a lane change or nor. Subsequently, the vehicle have to check if the desired lane change is feasible, and lastly perform a gap acceptance control. Each step in the DLC process will be further explained below.

- **Decision to consider a lane change**

  There are several factors that might motivate a driver to perform a lane change, but one of the main thought of the driver should be to improve his driving conditions i.e. increase his speed. Mathew (2014b) states that the decision to change lane hence can be motivated by finding out if it is possible for a driver to reach his desired speed within the space gap available between his vehicle and the vehicle ahead. If the available gap is too short, the driver will decide to perform a lane change.

- **Check for the feasibility**

  According to Mathew (2014b), a lane change is said to be feasible if it can be performed without a risk of collision between the subject vehicle and the lead, or lag, vehicle in the target lane. In the first scenario, the lane change is considered feasible if the subject vehicle can reach his desired speed within the specific time and space available between him and the leading vehicles without applying the maximum deceleration allowed. Similarly, in the second scenario the lane change is said to be feasible if the lag vehicle in the target lane can reach the desired speed and the above deceleration criteria is met.

- **Gap acceptance**

  As stated earlier a gap, when it comes to lane changing models, can be measured in time, distance or speed difference between the lead and lag vehicles. According to Mathew (2014b), most models requires two sub-gaps to be acceptable before the total gap is accepted, namely the lead gap and the lag gap. The lead gap is the distance between a vehicle and the vehicle in front of it in the target lane. Similar, the lag gap constitutes of the distance between the own vehicle and the vehicle behind in the target lane. An illustration of the gap theory is presented in Figure 4.

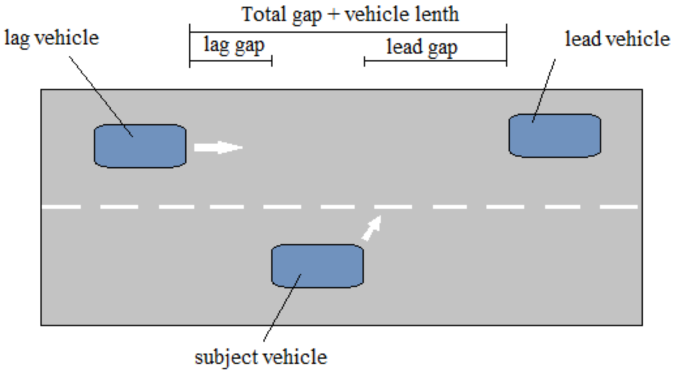


Figure 4: Gap definitions

In addition to the MLC and DLC models, Mathew (2014b) mentions Forced merging models and Cooperative models as commonly used lane changing models.

A Forced merging model describes a situation where the available gap between the subject vehicle and the lag vehicle on the target lane is not large enough to accommodate a lane change. Despite the lack of space, the subject vehicle decides to change lane and hence forces the lag vehicle to decelerate until the gap size is big enough to be accepted. This strategy assumes that the driver of the subject vehicle is continously (1) evaluating the traffic conditions in the target lane in order to decide if he should merge in front of the lag vehicle, and (2) trying to communicate with the lag vehicle to verify if his right of way is recognized. If the right of way is accepted the driver merge into the target lane. If not, the subject vehicle repeats step (1) and (2) until the right of way is accepted or until a specific stopping criteria is met.

What distinguished the so called Cooperative model from the models mentioned earlier is that it is not using gap acceptance as a tool to execute lane changes. This type of model is particularly useful in congested traffic conditions where acceptable gaps do not exist. Instead, a driver in the cooperative model changes lane by cooperating with other drivers. More specifically, the driver of the lag vehicle in the target lane will reduce his speed in order to facilitate the lane change of the subject vehicle.

2.1.3 Merging behavior models

Merging can be described as a special case of necessary lane changing, where the lane change is made due to the reduction of the number of lanes. In on-ramp areas, merging is inevitable since the traffic seeking to enter the expressway has to merge into the mainline traffic before the acceleration lane ends. As a consequence of this forced merging, Sun et al. (2015) argues that a competitive behavior between the mainline and the on-ramp drivers is born. The competitive driving behavior in combination with capacity restrictions of the merging area often results in recurrent congestion problems. As an increasing number of cities have to battle with severe cases of congestion, traffic flow characteristics at on-ramp areas has become an important field of study.

According to Marczak et al. (2013), most of the merging behavior models utilizes the gap acceptance theory presented in section 2.1.2 Lane Changing. The earliest merging models, as the one presented by Yang & Koutsopoulos (1996), simplifies the task of modeling the interaction between merging and mainline vehicles by assuming that the former one has no impact on the mainline traffic flow. Both AIMSUN and VISSIM uses rather simple gap acceptance models. In AIMSUN, the merging model is a modified version of the lane changing model presented by Gipps (1986). To ensure and control the urgency of changing lane towards the end of the acceleration lane some extra parameters are added. In VISSIM the gap acceptance model is not specified, but the merging behavior can instead be modeled by adjusting the aggressiveness of the driver.

Hidas (2005) presented a more complex merging model in which both forced and cooperative merge features were included. However, it could not account for the cooperative merging behavior of the subject vehicle. This problem was partly solved by Choudhury et al. (2007) who managed to include cooperative merging behavior of both vehicles.

A second, but less common approach to model merging behavior was, according to Marczak (2013), brought forward by Kita & Fukuyama in 1999. They suggested that the vehicle interaction could be model using game theory. The basic idea of this model is that every vehicle considers the other vehicles' alternative actions before making its own decision.

2.1.4 Driving behavior models in VISSIM

In this section, the driving behavior models available in VISSIM are presented. Initially, the car following models will be discussed, followed by the lane changing options and parameters for modeling lateral behavior.

2.1.4.1 Car following

There are two car-following models available in VISSIM: Wiedemann 74 and Wiedemann 99. The implemented models differs slightly from the Wiedemann model presented in 2.1.1. The main difference is that the models in VISSIM seeks to create a more diverse driver population, where for example the estimation of distance or desired speed varies among the individual drivers. In order to create a model that reflects such a heterogeneous behavior, Higgs (2011) explains that a driver's perception ability and risk behavior in VISSIM are modeled by adding random values to each of the thresholds presented in Table 1.

A mathematical definition of the Wiedemann 74 model in VISSIM is presented by Gao (2008) as

$$u_n(t+\Delta t) = min\left\{\begin{matrix} 3.6\cdot\left(\frac{s_n(t)-AX}{BX}\right)^2 \\ 3.6\cdot\left(\frac{s_n(t)-AX}{BX\cdot EX}\right)^2 \end{matrix}, u_f\right\} \tag{2.5}$$

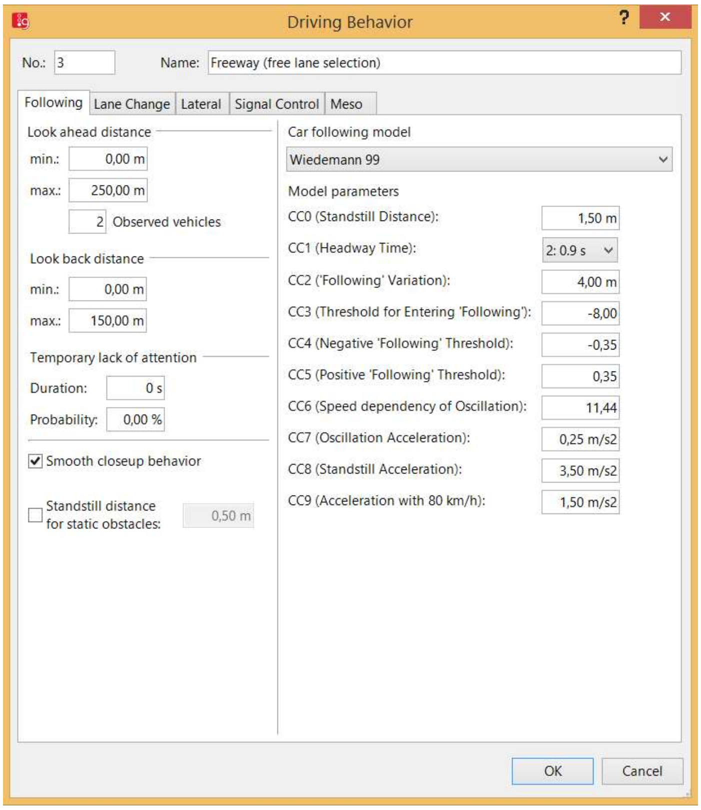
where BX and EX are random parameters.

The Wiedemann 99 model is a modified version of the Wiedemann 74 model with the difference that some thresholds are added and some redefined in order to simplify expressway traffic modeling. According to Gao (2008) the Wiedemann 99 model used in VISSIM is formulated as:

$$u_n(t+\Delta t) = min\left\{\begin{matrix} u_n(t) + 3.6\cdot\left(CC8 + \frac{CC8-CC9}{80}u_n(t)\right)\Delta t \\ 3.6\cdot\frac{s_n(t)-CC0-L_{n-1}}{u_n(t)} \end{matrix}, u_f\right\} \tag{2.6}$$

where $u_n(t+\Delta t)$ is equivalent to the minimum of two speeds. The first is based on vehicle acceleration restrictions imposed by CC8, the maximum vehicle acceleration at 0 km/h, and CC9, the maximum vehicle acceleration at 80 km/h. The second represents the model under steady-state conditions, where CC0 defines the distance between front-to-rear distance between the following and leading vehicles.

The parameters available for modeling car-following behavior in VISSIM can be seen in Figure 5 and are further explained in Table 2. All definitions are based on the information given in PTV AG (2011) and PTV AG (2017).



No.: 3

Name: Freeway (free lane selection)

Look ahead distance

min.: 0,00 m

max.: 250,00 m

2 Observed vehicles

Look back distance

min.: 0,00 m

max.: 150,00 m

Temporary lack of attention

Duration: 0 s

Probability: 0,00 %

☑ Smooth closeup behavior

☐ Standstill distance for static obstacles: 0,50 m

Car following model

Wiedemann 99

Model parameters

CC0 (Standstill Distance): 1,50 m

CC1 (Headway Time): 2: 0.9 s

CC2 ('Following' Variation): 4,00 m

CC3 (Threshold for Entering 'Following'): -8,00

CC4 (Negative 'Following' Threshold): -0,35

CC5 (Positive 'Following' Threshold): 0,35

CC6 (Speed dependency of Oscillation): 11,44

CC7 (Oscillation Acceleration): 0,25 m/s2

CC8 (Standstill Acceleration): 3,50 m/s2

CC9 (Acceleration with 80 km/h): 1,50 m/s2

Figure 5: A print screen of the driving behavior parameters for car-following models in VISSIM

Table 2: Definition of car-following parameters in VISSIM

Element	Description
Look ahead distance	The distance that a driver can see ahead of his own vehicle and still be able to react to actions made by surrounding drivers. **Observed vehicles**: Controls a driver's ability to predict other vehicle's actions and respond to them. The higher the value the more vehicles can be observed.
Look back distance	Equivalent to the **Look ahead distance**, but refers to the distance a driver can see behind his vehicle.
Temporary lack of attention	Refers to the period of time during which a driver are not able to respond to changes in the preceding vehicles driving behavior. **Duration** and **Probability** defines how long respectively how often the lack of attention occurs.
Smooth closeup behavior	If active, a driver will reduce his speed more evenly when approaching a static obstacle.
Standstill distance for static obstacles	Only applicable when **Smooth closeup behavior** is active. Determines at wat distance from a static obstacle a driver should stop. Concerned with AX in Table 1.
Car following model	Defines what car following model that should be implemented. **No Interaction**: The drivers will not be able to perceive each other's behavior.

What parameters that are possible to adjust differs between the car following models. The model with corresponding model parameters are presented in Table 3 and 4.

Wiedemann 74

Table 3: Adjustable parameters for Wiedemann 74

Element	Description
Average standstill distance	(ax) The desired distance between two stationary vehicles. Corresponds to AX in Table 1.
Additive part of safety distance	(bx_{add}) Included in the calculation of desired safety distance d. Concerned with time requirement adjustments.
Multiplicative part of safety distance	(bx_{mult}) Included in the calculation of desired safety distance d. Concerned with time requirement adjustments. A high value corresponds to a greater standard deviation.

The desired safety distance d is computed as:

$$d = ax + bx \tag{2.7}$$

where

$$bx = (bx_{add} + bx_{mult} * z) * \sqrt{v} \tag{2.8}$$

v is the vehicle speed [m/s], and z is a value of range [0,1] which is normal distributed around 0.5 with a standard deviation of 0.15.

Wiedemann 99

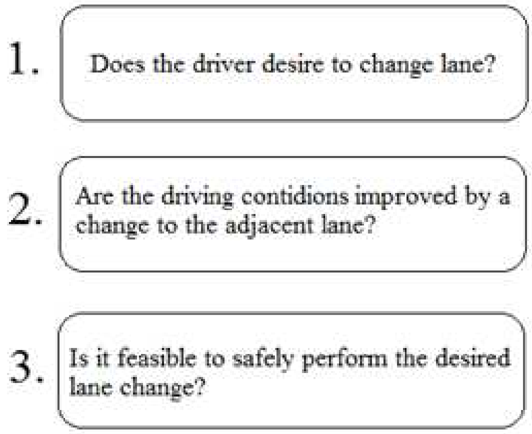
Table 4 Adjustable parameters for Wiedemann 99

Element	Description
CC0 (Standstill distance)	The desired distance between two stationary vehicles. Correspond to AX in Table 1.
CC1 (Headway time)	Refers to the time the driver wants to maintain to the preceding vehicle. A high value yields a more cautious driver.
CC2 *('Following' variation)*	Restrains the longitudinal oscillation of a vehicle in relation to the vehicle in front.
CC3 *(Threshold for entering 'Following')*	Defines at what time the deceleration process will begin in terms of seconds before reaching the safety distance.
CC4 and **CC5** *('Following' thresholds)*	Regulates the speed differences during the 'Following' state. Lower values corresponds to a more careful driver e.g. vehicles will be allowed to be more close to each other.
CC6 (Speed dependency of oscillation)	Refers to the impact of distance on speed oscillation within the following regime.
CC7 (Oscillation acceleration)	Defines the actual acceleration during the oscillation process.
CC8 (Standstill acceleration)	Desired acceleration when starting from a stationary state.
CC9 (Acceleration at 80 km/h)	Desired acceleration at a speed of 80 km/h.

Among the car following parameters, CC0, CC1 and CC8 are believed to have the greatest impact on the merging behavior during the calibration process. This guess is made based on the definitions presented in Table 4, from which it can be assumed the distance between vehicles and their aggressiveness can be controlled.

2.1.4.2 Lane changing in VISSIM

The lane changing model in VISSIM is based on the so called Sparmann model which was originally developed by Willmann and Sparmann in 1978. Sparmann's model is, according to PTV AG (2011) and Gao (2008), a rule-based model where lane changing behavior is categorized as lane change to a faster or a slower lane respectively. In order to model the lane change-decision in VISSIM, Gao (2008) as well as Fellendorf & Vortisch (2001) argues that the set of three hierarchical questions presented in Figure 6 have to be evaluated:



1. Does the driver desire to change lane?
2. Are the driving contidions improved by a change to the adjacent lane?
3. Is it feasible to safely perform the desired lane change?

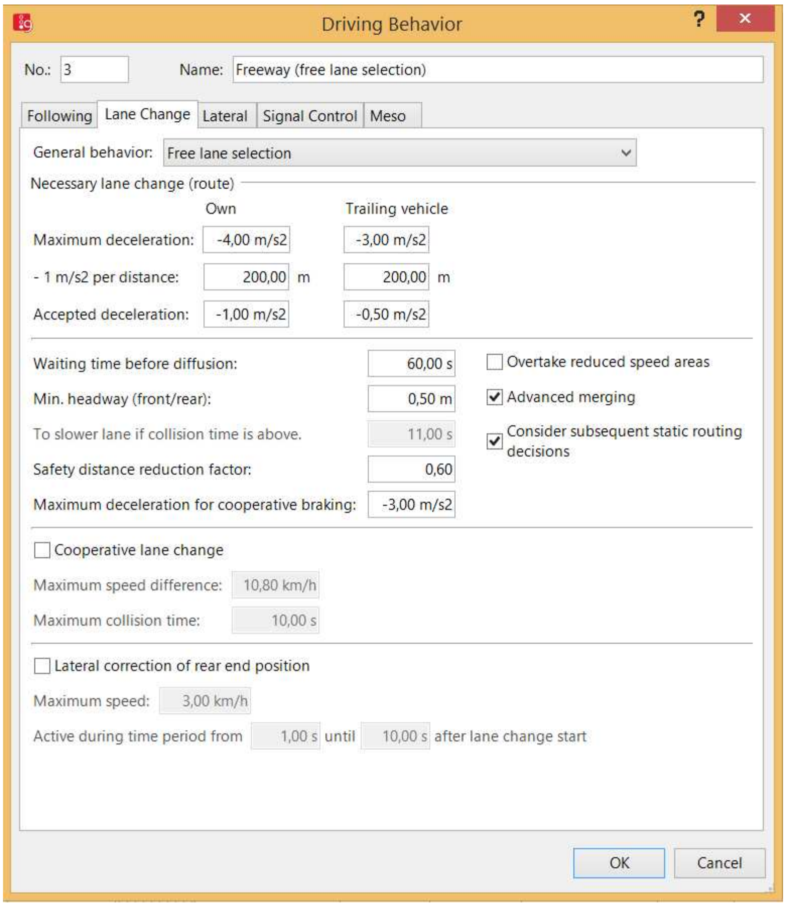
Figure 6: Questions to be evaluated before a lane change

Moreover, there are two types of lane changes in VISSIM, namely Necessary lane change and Free lane change. These corresponds to the MLC and DLC presented in section 2.1.2 Lane Changing respectively. Both are dependent on the distance to the emergency stop position of the next connector of the route.

For the Free lane change, the adjustable parameters are related to the desired safety distance of the trailing vehicle. The safety distance itself depends on the speed differences between the trailing vehicle and the vehicle that wishes to change lane. Currently, it is not possible for the VISSIM user to adjust the “aggressiveness” of the free lane change. However, this aggressiveness can be modified by varying the values for the desired safety distance related to the car-following behavior.

Also, PTV AG (2011) points out that no matter which type of lane change that is being performed, the initial step when a vehicle wish to change lane in VISSIM is to find a “suitable time gap” (headway) in the destination flow. The size of this time gap depends on the speed of the own vehicle and the trailing vehicle in the targeted lane. For the necessary lane change scenario the gap size also depends on the deceleration values of the “aggressiveness”.

The full set of parameters available for modeling lane changing behavior in VISSIM can be seen in Figure 7 and are further explained below in Table 5. All definitions are based on the information given in PTV AG (2011) and PTV AG (2017).



No.: 3
Name: Freeway (free lane selection)

General behavior: Free lane selection

Necessary lane change (route)

	Own		Trailing vehicle	
Maximum deceleration:	-4,00 m/s2		-3,00 m/s2	
- 1 m/s2 per distance:	200,00	m	200,00	m
Accepted deceleration:	-1,00 m/s2		-0,50 m/s2	

Waiting time before diffusion: 60,00 s
Min. headway (front/rear): 0,50 m
To slower lane if collision time is above. 11,00 s
Safety distance reduction factor: 0,60
Maximum deceleration for cooperative braking: -3,00 m/s2

☐ Overtake reduced speed areas
☑ Advanced merging
☑ Consider subsequent static routing decisions

☐ Cooperative lane change
Maximum speed difference: 10,80 km/h
Maximum collision time: 10,00 s

☐ Lateral correction of rear end position
Maximum speed: 3,00 km/h
Active during time period from 1,00 s until 10,00 s after lane change start

Figure 7: A print screen of the driving behavior parameters for lane changing in VISSIM

Table 5: Definition of lane changing parameters in VISSIM

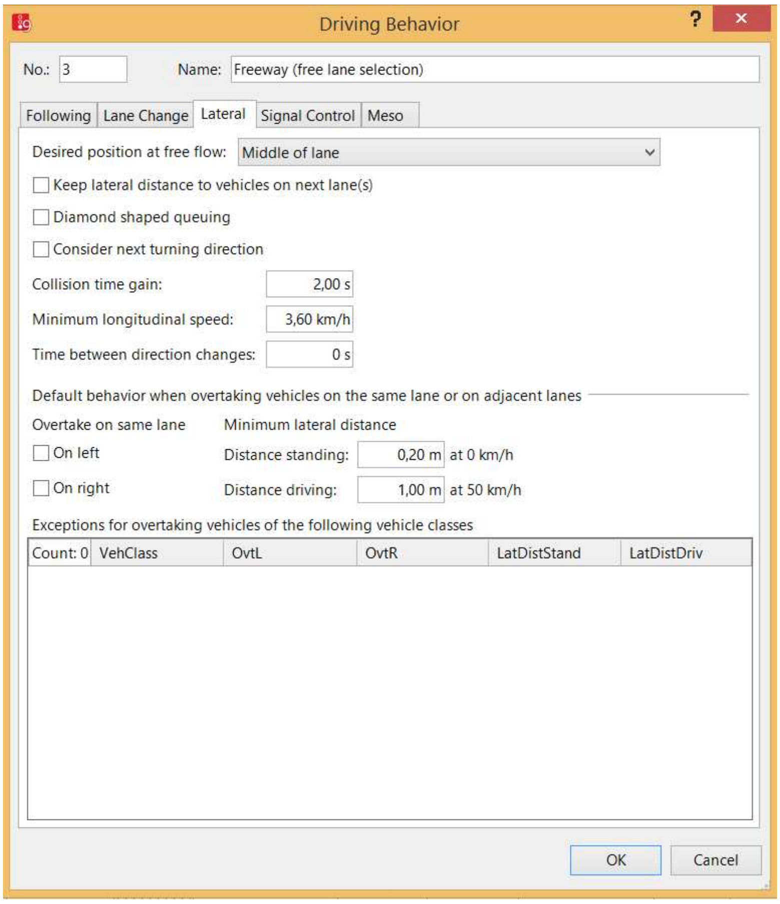
Element	Description
General behavior	Determines which type of overtaking that should be allowed. The options are either Free lane selection, where overtaking is allowed in any lane, or Right Side Rule respectively Left Side Rule.
Necessary lane change (route)	By defining deceleration thresholds for the own vehicle and the trailing vehicle the aggressiveness of the necessary lane change can be adjusted. The **Maximum** and **Accepted deceleration** defines the range of deceleration allowed to perform a lane change. The reduction rate **1 m/s^2 per distance** determines the pace at which the **Maximum deceleration** will change in relation to the emergency stop distance.
Waiting time before diffusion	The maximum time a vehicle will stay at the emergency stop position waiting to perform a necessary lane change. If the waiting time

	exceeds the specified value the vehicle will be removed from the network.
Min. Headway (front/rear)	The minimum remaining distance required between two vehicles after a lane change.
To slower lane if collision time	The minimum time headway that has to be available on the slower lane in order to make a faster vehicle traverse to it.
Safety distance reduction factor	Determines how much the safety distance between vehicles should be reduced during lane change. The value 0.6 means that the safety distance is reduced by 40% compare to the standard value.
Maximum deceleration for cooperative braking	Decides if a trailing vehicle will start cooperative braking, i.e. let a leading vehicle change from to its own lane, or not by reducing his speed. The higher the value of this parameter is, the higher is the probability of a lane change to take place.
Overtake reduced speed areas	Determines if lane-dependent speed restrictions will be considered. If this parameter is not included, vehicles will not perform a lane change upstream a reduced speed area, and any reduced speed restrictions in the target lane will be ignored.
Advanced merging	If active, this option allows more vehicles to change lane at an earlier point, and by doing so also decrease the risk of vehicles stopping to wait for a merging possibility. This is done by taking the speed of the adjacent vehicles into account in addition to the emergency stop distance. If not active, a vehicle will not break or cooperate with another vehicle within 50 m ahead.
Consider subsequent static routing decisions	Determines whether a vehicle leaving a static route will consider other routing decisions ahead when choosing lane.
Cooperative lane change	This option makes it possible for a vehicle to observe if a vehicle on an adjacent lane intends to change to its own lane, and hence will try to change lane itself to accommodate the lane change.
Lateral correction of rear end position	Ensures that the lateral position of a vehicle is in line with the middle of the lane after a lane change. **Maximum speed**: lateral correction will be performed by vehicles traveling in a pace below the defined value. **Active during time period from**: Defines how long after the initiation of the lane change that the correction should start.

The hypothesis on which lane changing parameters that will have the greatest impact on the merging behavior includes minimum headway, safety distance reduction factor, advanced merging, and cooperative lane changing. This guess is partly based on the definitions presented in Table 5 and partly on a study presented by Whaley (2016).

2.1.4.3 Lateral Behavior

The lateral behavior settings in VISSIM controls the lateral orientation of a vehicle within its current lane as well as during overtaking. By default, all vehicles are programmed to occupy the entire lane width. However, it is possible to assign a vehicle to position itself to the left, right, or in the middle of the lane. The set of parameters concerned with the lateral driving behavior in VISSIM are listed in Table 6 and based on the information given in PTV AG (2017). The default parameter values are shown in Figure 8.



No.: 3
Name: Freeway (free lane selection)

Desired position at free flow: Middle of lane

☐ Keep lateral distance to vehicles on next lane(s)

☐ Diamond shaped queuing

☐ Consider next turning direction

Collision time gain: 2,00 s

Minimum longitudinal speed: 3,60 km/h

Time between direction changes: 0 s

Default behavior when overtaking vehicles on the same lane or on adjacent lanes

Overtake on same lane
☐ On left
☐ On right

Minimum lateral distance
Distance standing: 0,20 m at 0 km/h
Distance driving: 1,00 m at 50 km/h

Exceptions for overtaking vehicles of the following vehicle classes

Count: 0	VehClass	OvtL	OvtR	LatDistStand	LatDistDriv

Figure 8: A print screen of the driving behavior parameters for lateral behavior in VISSIM

Table 6: Definition of lateral behavior parameters in VISSIM

Element	Description
Desired position at free flow	The vehicle’s lateral position within its lane during free flow
Keep lateral distance to vehicles on next lane(s)	If **Observe adjacent lanes** is active, vehicles adapt their lateral position to the vehicles in the adjacent lane by keeping the **Lateral min. distance**.

Diamond shape queue	Vehicles will be represented as rhombuses instead of rectangles, yielding a more realistic shape of a built up queue.
Consider next turning direction	If selected, a vehicles will not pass a vehicle on the same lane if there is a risk for collision at the subsequent turning connector.
Collision time gain	The minimum time gain to be met between a vehicle and an obstacle ahead in order to justify a change in lateral movement.
Minimum longitudinal speed	The minimum longitudinal speed required for a vehicle to move laterally.
Time between direction changes	The minimum simulation time between two lateral movements in opposite directions. Not applicable for lateral movements during lane change.
Default behavior when overtaking vehicles on the same lane or adjacent lanes	**Overtake on same lane**: Allow or prevent vehicles in non-lane bound traffic to overtake on the same lane, either to the left, right or both. **Minimum lateral distance**: The distance that has to be available between vehicles while overtaking on the same lane.
Exceptions for overtaking vehicles of the following vehicles classes	With this option, vehicle classes with a driver behavior that differs from the default one can be defined.

2.2 Merging control strategies

On-ramp merging areas are well-known freeway bottlenecks and several studies, i.e. Zhang & Levinson (2004), and Chung et al. (2007) presents empirical evidence of a relationship between ramp merging and capacity drop. In line with the findings presented by the two former studies, Srivasrava & Geroliminis (2013) show that the capacity drop is inflicted by not only the mainline and ramp flows, but also the ration between them. Hence, studying the merging behavior and how it affects the traffic conditions at these sites are highly significant in order to tackle congestion problems.

Merging can be done in a number of ways, but what strategy that is more efficient varies between sites. However, Zhang & Levinson (2004), Chung et al. (2007), and Srivasrava & Geroliminis (2013) all agree that applying measures to control the merging behavior at on-ramps can be helpful to alleviate the congestion. In this chapter, the merging control strategies applied in two simulation studies by EXAT, EXAT (2016b) and EXAT (2016c), on the expressways in Bangkok will be presented. The first strategy presented, driving on the shoulder lane, offers drivers the possibility of utilizing the shoulder lane to avoid queue buildups in the merging area. The remaining strategies; solid lines, moving the merging point, and ramp metering are, in comparison, measurements that can be applied to control the vehicle flow itself.

2.2.1 Driving on the shoulder lane

As mentioned in the section above, driving on the shoulder lane is a strategy where drivers are permitted to utilize the hard shoulder. The shoulder lane is in general narrower than a standard lane, and is not designed to accommodate vehicles. However, by treating this lane as an ordinary one, the capacity of the road can be increased.

Allowing shoulder lane driving on a temporary basis, i.e. during rush hours, is an effective measure to increase the capacity of expressway sections facing problems with recurrent congestion. For example, Geistefeldt (2012) concludes that temporary shoulder lane driving could increase the capacity of a three lane expressway in Germany by 20%-25%, and reduce the total duration of congestion per year by approximately 90%.

In Bangkok, the congestion on some of the urban expressways are however so severe that the temporary use of shoulder lanes has transformed into a permanent solution. Since shoulder lane driving is accepted on a daily basis, regardless of the current traffic conditions, even EXAT (2016b) has chosen to include the hard shoulder as an ordinary lane in their simulation study. Despite the capacity increased imposed by the permanent shoulder lane driving, some of the on-ramp areas in Bangkok's metropolitan areas are still heavily congested. One example is the merging area at Sirat Expressway shown in Figure 9 and 10, which is the site being analyzed in this study.

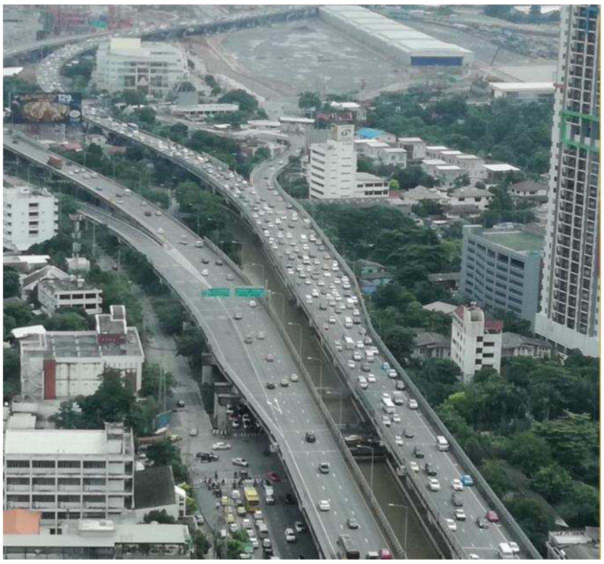


Figure 10: Shoulder lane driving on Sirat Expressway

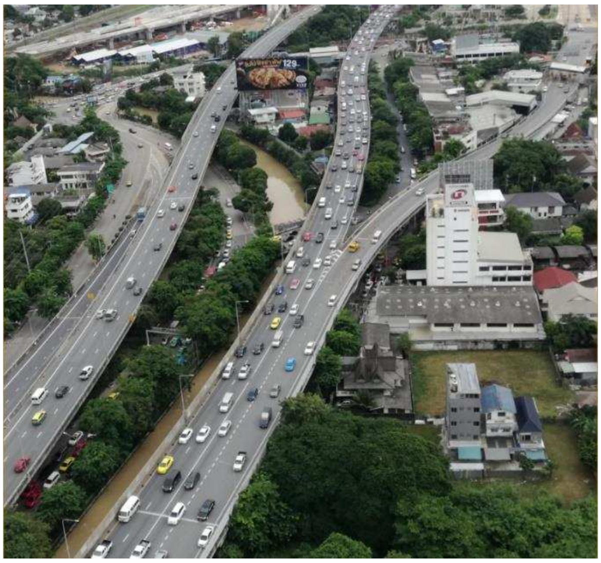


Figure 9: Shoulder lane driving on Sirat Expressway

In conflict with the drivers' intention of avoiding congestion by using the shoulder lane, and possibly an explanation to why the congestion still remains, is given by Chung et al. (2007). They found that shoulder lane driving itself caused queue buildups in merging areas, and as a result triggered a capacity drop due to the increased number of lane changes.

2.2.2 Solid line

The solid line method suggests applying solid white lines to the road surface, or extending already existing ones, in order to make drivers stay in their allocated lanes until the designated point of merging. The variations and impacts of this strategy can be similar to the ones mentioned in 2.3.3. However, this strategy is only found effective under the assumption that all drivers obey the traffic rules, as in the simulation study performed by EXAT (2016b). Their study revealed that, for the studied on-ramp area in Bangkok, solid lines were more efficient than moving the merging point or using ramp metering as described in section 2.3 Relevant studies on microscopic driving behavior modeling and merging. As stressed earlier, this is based on the assumption that all motorists drive according to the traffic laws, which is not the case in metropolitan Bangkok.

2.2.3 Moving the merging point

To move the merging point can, according to FHWA (2012), be a way of alleviate congestion if it is done in a proper way. For example closing one lane, and hence forcing the vehicles on the on-ramp to change lane, can have a positive effect on the traffic flow in terms of reduced delays and increased road safety. However, closing a lane might also have negative effects such as increasing the competitive driving behavior. Some drivers will see the unoccupied lane as a possibility to pass the built up queue, and as they reach the beginning of the queue force themselves back into the open lane just before the merging point. Three merging control strategies that deals with these issues are early merging, late merging, and dynamic merging, all built around the concept of moving the merging point. This is in general done by closing one or several lanes, and in some cases dynamic or fixed traffic signs are used to guide the vehicles in the desired direction.

Early merging

As can be concluded by the name, the early merging strategy has the purpose to force the vehicles to merge at an earlier point. This is usually done by placing obstacles in the closed lane, which direct the drivers to change lane in good time before they reach the new, forced merging point. This strategy is according to FHWA (2012) more efficient when the average on-ramp speeds are high and the traffic volume low. The concept of early merging is illustrated in Figure 11.

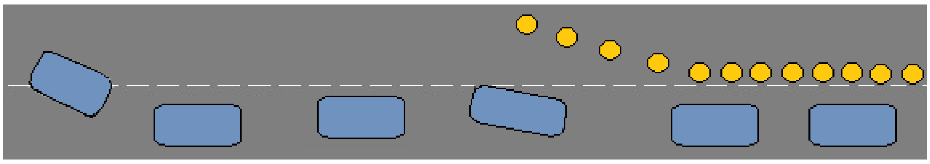


Figure 11: The concept of early merging

Late merging

When the traffic volume increases and the traveling speed falls, late merging is a more appropriate strategy. In comparison to early merging, this strategy aims to keep the drivers in to closed lane until just before the merging point. The reason behind this tactic is to prevent unnecessary lane changes and hence fully utilize the full capacity of both the open and the closed lane. In order to smoothen the transit from the closed lane at the merging point, zippered merging is the preferable choice. The concept of late merging is shown in Figure 12.

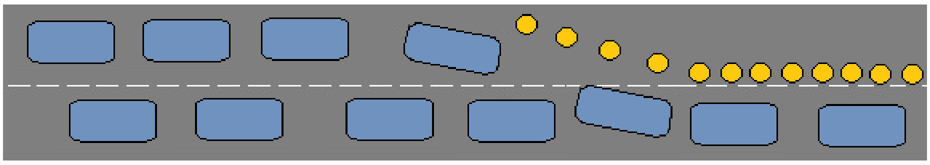


Figure 12: The concept of late merging

Dynamic merging

Dynamic merging is combining early and late merging by the help of real-time data. In other words, which strategy that is chosen is based on the current traffic conditions at the site. Driving instructions are given to the drivers via variable message signs (VMS) or flashing light indicators on static infrastructure along the roadside. The flow diagram displayed in Figure 13 describes how the choice between early or late merging is made.

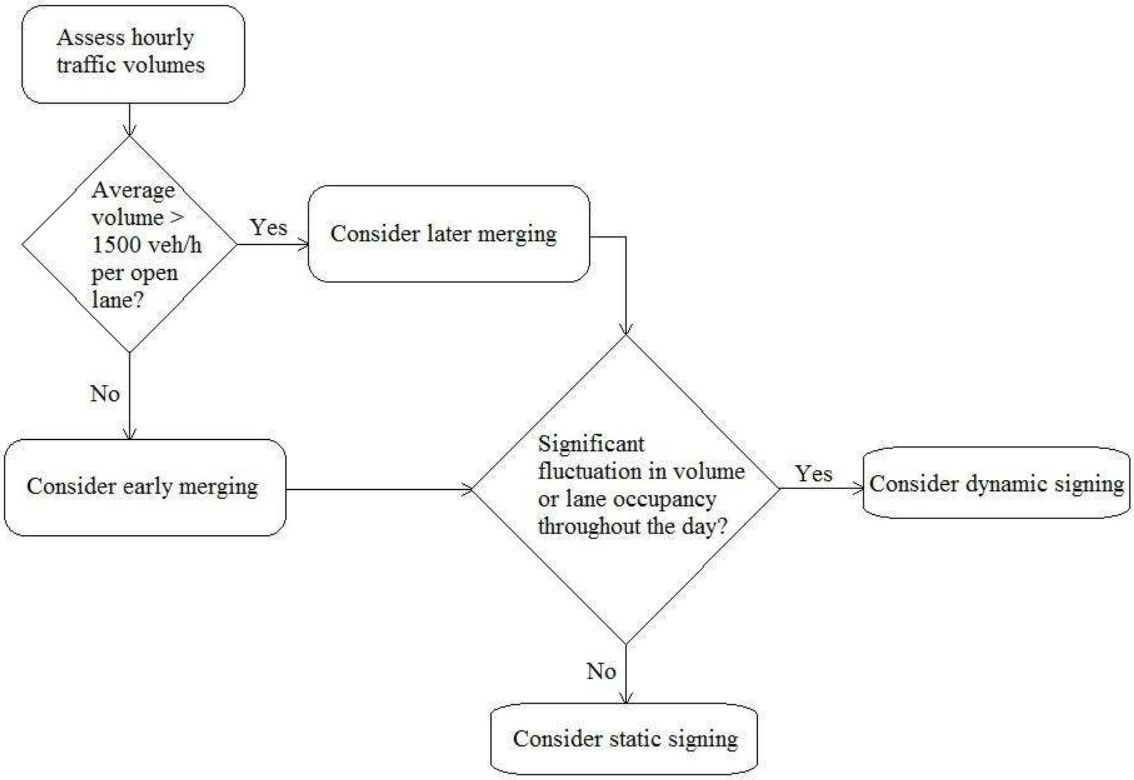


Figure 13: Flow diagram to illustrate the choice of early or late merging and choice of signing

2.2.4 Ramp metering

During the last decades, another tool to control the amount of vehicles merging into the expressway from the on-ramp has become increasingly popular. This tool is called ramp metering, and uses two-state traffic signals to manage the flow of vehicles entering the expressway. The traffic signals shows green light when the vehicles at the on-ramp are allowed to enter the expressway, and red when they have to wait at the ramp. A schematic sketch of on-ramp metering is presented by Olstam (2005) and shown in Figure 14. In the figure, q_{in} and q_{out} represents the in-going and outgoing traffic flow on the expressway, d the on-ramp the demand flow, and r the desired ramp flow.

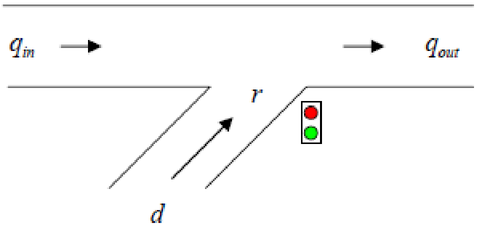


Figure 14: Ramp metering set-up, Olstam (2005)

In comparison to ordinary traffic signals, Shaaban et al. (2016) states that the signals used in ramp metering are usually operated with a shorter cycle time. In this way, only a single vehicle, or a small platoon of vehicles will be allowed per green phase. A strategy that both Olstam (2005) and Shaaban et al. (2016) claim can alleviate congestion caused by heavy on-ramp traffic flows on expressways.

The length of the green phase, i.e. how many vehicles that are allowed to enter the expressway, is decided based on the choice of control strategy. There are a considerable amount of control strategies for ramp metering. Most of them belong to either of the two groups fixed time strategies or traffic responsive strategies.

Fixed time strategies relies on historical data in order to estimate the optimal control settings. Most of the strategies seek to optimize the system performance by determine the desired flow rate (r), but the objective functions of the strategies differs. A common objective is for example to maximize the ramp flow.

In comparison with the fixed time strategies, the traffic responsive strategies uses real-time data. According to Olstam, (2005), the use of real-time data gives a more flexible control tool that can be used under various traffic conditions. In general, most traffic responsive strategies consider both up-stream and down-stream traffic, as illustrated in Figure 15.

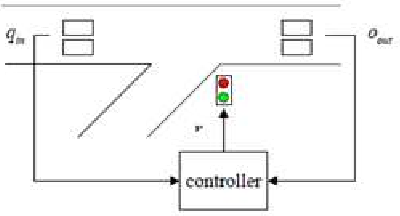


Figure 15: Traffic responsive ramp metering set-up, Olstam (2005)

However, the measurements to quantify the traffic conditions differs. In most cases, density or occupancy are used but some strategies also use the traffic flow rate.

2.3 Relevant studies on microscopic driving behavior modeling and merging

Throughout the last century a lot of research has been conducted on microscopic driving behavior characteristics around the world. However, a majority of these studies have been based on data from countries with a relatively homogeneous traffic stream, a phenomenon which, according to Paoprayoon (2004), cannot be found in Southeast Asian countries such as Thailand, Vietnam, and Indonesia. The traffic composition in these countries is characterized by a considerably large proportion of motorcycles and local vehicles (e.g. tuk-tuks), which gives rise to a more complex driving behavior. Several studies have been made on driving behavior modeling of this so called mixed traffic compositions, but since motorcycles are excluded from this study, earlier work on mixed traffic will not be further discussed.

More relevant to this study is the work presented by Kanagaraj et al. (2015), who used video photography to collect vehicle trajectory data for different vehicle types, including buses and private cars in Chennai, India. The result showed that there is a significant difference in travel speed, acceleration, distance keeping, and lateral movements among the vehicle types. In addition, the study found that a substantial share of the observed drivers, including private cars, did not strictly follow their lead vehicle. In summary, the study concludes that car-following is a critical component in driving behavior modeling.

When it comes to driving behavior studies in Thailand, Paoprayoon (2004) claims that only a few researchers have attempted to investigate the connection between the driving behavior and the country’s congestion problems. Moreover, he argues that the reason for the lack of studies on this field depends on the lack of reliable and sufficient driving behavior data available. To address this issue, Paopayoon (2004) performed a study in 2004 on car-following behavior of the Bangkok drivers, a study which he claimed to be the first of its kind. In his study, individual vehicle data was collected by the help of GPS devices installed in five passenger cars. Test drivers were then instructed to drive in a platoon on the urban expressway and urban street respectively. Thus, driving behavior characteristics for four different scenarios could be analyzed: congested and uncongested expressway, as well as congested or uncongested street. The collected driving characteristics included vehicle trajectories, distance headway, speed, and acceleration, which were used to evaluate GM:s first and fifth car-following model that were briefly mentioned in section 2.1.1 Car following models. The result showed a more aggressive driver behavior under congested conditions, and that the predicted speed values from both models agreed well with the measured speed data. Based on a sensitive analysis on both models, it was however concluded that GM:s first model was more suitable for modeling car-following behavior in Bangkok’s traffic conditions.

A study which more similarities to the one performed in this thesis was conducted by Jie et al. (2015). They investigated the traffic flow characteristics of a general expressway on-ramp area by the help of a microscopic simulation software similar to VISSIM. Within the software, a car-following model of the type Optimal Velocity Models as well as a set of lane changing rules were implemented. The main focus of the study was to investigate the competitive relationship of mainline and ramp drivers. Among the most interesting findings, the fact that on-ramp vehicles had a strong effect on the mainline traffic can be mentioned. It was also found that the merging-ratio at the merging area is significantly affected by driver characteristics such as the probability of lane changes, as well as road design factors like the length of the merging section.

Last year, Whaley (2016) published a study on freeway ramp merging using VISSIM. The goal was to develop a calibration technique for merging behavior to investigate impacts of ramp metering in Georgia. Different parameters related to lane changing and car-following were analyzed in order to find what impact each parameter had on the driving behavior, and to come up with a suitable calibration technique. Specifically, the effects of advanced merging, cooperative lane change, safety reduction factor, and cooperative braking was analyzed. It was found that including both cooperative lane change and advanced merging reflected the real driving behavior in the most satisfying way. After implementing the ramp metering scenario, the results showed that ramp metering generated an increase in both freeway throughput and average speed.

As mentioned in the introduction of this thesis, EXAT has performed two studies on merging control strategies to alleviate the congestion at Bangkok's urban expressways. Both studies were conducted using AIMSUN. The first project, EXAT (2016b), investigated the impacts of solid lines, the use of cones to move the merging point, and reversible lanes on an off-ramp at Charongrat Expressway. The length of the solid line was determined by visual observations of queue length. Similarly for the reversible lane, the distance of the lane was determined by field observations. The scenario in which cones were used to move the merging point was viewed upon as a short term solution, but was still included in the study since this method has been used in the past to control the traffic. The result from this study showed that the use of solid lines was the most efficient was to tackle the congestion problems at this site. However, as mentioned earlier, this study as well as the one mentioned below are based on the assumption that all drivers obey the traffic laws.

In the second study, EXAT (2016c), conducted experiments using ramp metering to deal with the congestion problems an on-ramp at Sirat expressway. A fixed time strategy was used in the model and the cycle time was set to 190 seconds. This cycle time was found to be the optimal one in terms of minimum delays, and was determined using SIDRA INTERSECTIONS software. The study concluded that ramp metering can reduce the congestion during the peak hours in terms of travel time and speed.

3 Site description and data collection

Data collection was performed at an on-ramp merging area at the Sirat Expressway in urban Bangkok. The specific on-ramp is located near Rama IX road, shortly after Kamphaeng Phet road and Phahol Yothin Toll Plaza, which is marked by the upper most point in Figure 1. The studied site consists of one on-ramp with two acceleration lanes and one shoulder lane, as well as a mainline with three lanes. The mainline also includes one shoulder lane which ends right before the on-ramp conjoins the expressway. According to EXAT, the dimensions of the studied site followed the standards given in the Highway Capacity Manual (HCM). Hence, the width of the standard lanes were set to 3.5 meters and for the shoulder lanes to 1.5 meters. The speed limit is 80 km/h and the total length of the studied site is approximately 265 meters.

Data was collected by mounting video cameras on three high-rise buildings from where the studied site could be seen and the driving behavior observed. The data collection was performed at three occasions between 9:00 and 12:00 at the 19/7-21/7 2017. At the first occasion, 19/7, recordings were made from Grand Tower Inn (Rama VI road). Three video cameras were used to capture different angles of the merging area, and recordings were conducted for approximately 2 hours. On 20/7, a similar set up was made at Tipco Building. However, this site was not equipped with power outlets and hence recordings could only be made for about 1.5 hours. At this location, 4 cameras were used. The last data collection occasion was made 21/7 from Intro Condo located right next to the merging area. This site only offered a small space to mount the equipment, and only two different angles could be captured. Hence, only two cameras were used at this occasion.

From the video recordings, data on vehicle composition (private cars and heavy vehicles, HV), total flow as well as flow per lane was extracted manually. In addition, the travel time of every 100:th vehicles per hour and segment were obtained, and from this also the average speed. All flows as well as number of merging occasions per merging segment where calculated as an average per hour. The data were later used to calibrate the model.

A summary of the data collected is shown in Table 7-9, which defines a data set. An overview photo from the studied site are presented in Figure 16. The sections A, B, and C that will be further explained in chapter 4 Model Development.

Vehicle composition

Table 7: Data on vehicle composition from field observations

Flows [veh/h]	Car	HV	Total	Cars [%]	HV [%]
Mainline	5808	156	5964	0.9738	0.0262
On-ramp	1035	13	1048	0.9875	0.0125

Figure 16: Sections at the studied site

Travel times

Table 8: Data on travel times [s] from field observations

Section	Main	Ramp
A	22.14	18.09
B	22.56	17.63
C	11.40	15.18
Total	56.09	50.90

Lane changes

Table 9: Data on the share of lane changes from field observations

Section	A	B	C	Total
Lane changes/h	2931	589	2043	5563
Share (%)	0.52	0.11	0.36	-

4 Model Development

The created VISSIM model represents the on-ramp merging area described in section 3 Site description and data collection. Originally, the expressway and on-ramp on this site consist of three and two lanes respectively. In this study, the expressway was however modelled as a four lane segment and the on-ramp as a three lane segment. The reason for this modification was that the field observations showed that motorist utilized both shoulder lanes as ordinary lanes on a regular basis.

From filed observations, two major and one minor merging section could be identified in the network, as illustrated in Figure 16. The areas corresponding to these sections in the created model is shown in Figure 17.

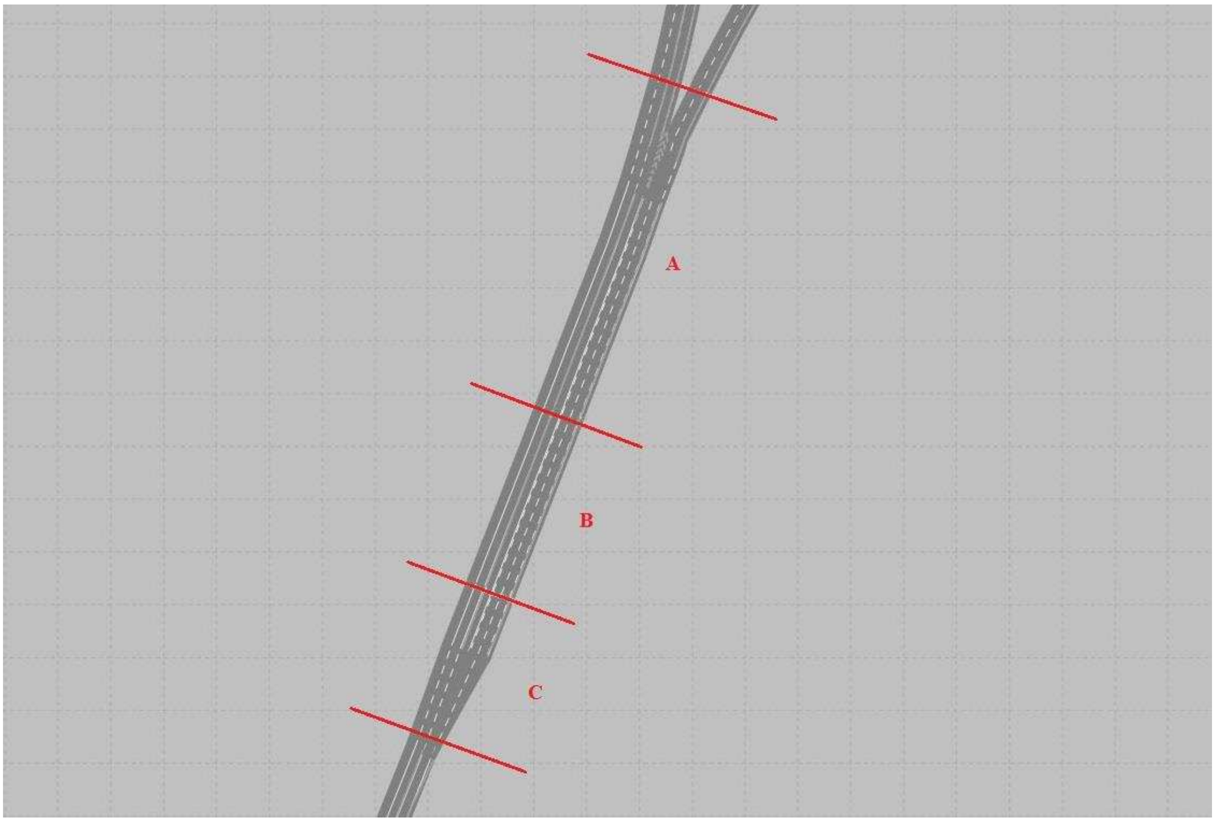


Figure 17: The created VISSIM model with the merging sections A, B, and C.

The first major merging section (section A) is located where the on-ramp and mainline traffic first conjoin, see Figure 16. At this point, the mainline shoulder lane cease to exist, forcing the vehicles in it to merge into either the on-ramp acceleration lanes or the neighboring mainline lanes. The initial part of section A is marked with striped lines prohibiting vehicles to traverse between the mainline and the on-ramp. These markings are however ignored by the motorists.

Next merging section, section B, is mainly a transition stretch consisting of six lanes running in parallel (three mainline lanes and three on- ramp lanes). It ends just before the two rightmost on-ramp lanes start to merge into the mainline traffic. The second major merging section, section C, runs from where B ended until the on-ramp acceleration lanes end. At this point, the shoulder lane is the only lane that still remains from the ramp after the merging is completed.

The network model consists of four links and nine connectors. In section A, two links are used to represent the mainline and on-ramp respectively. Where the striped area ends, these links are connected to a new six lane-link that runs throughout section B. In total, six connectors are used to represent the transition between these links.

The first connects the three run-through lanes of the mainline segment to the corresponding lanes in the next link. Similarly, a second one is used to connect the three on-ramp lanes to their matching lanes. Since the mainline shoulder lane cease to exist at the start of the striped area, the motorists traveling in this lane have to choose between two routes: either merge into the mainline traffic; or merge into the on-ramp traffic. From the observations an additional route used by the motorists of the mainline could be identified. This route runs from the leftmost mainline lane (not the shoulder lane), across the striped area, to the rightmost lane at the on-ramp. The connectors representing these three routes are displayed in Figure 18.

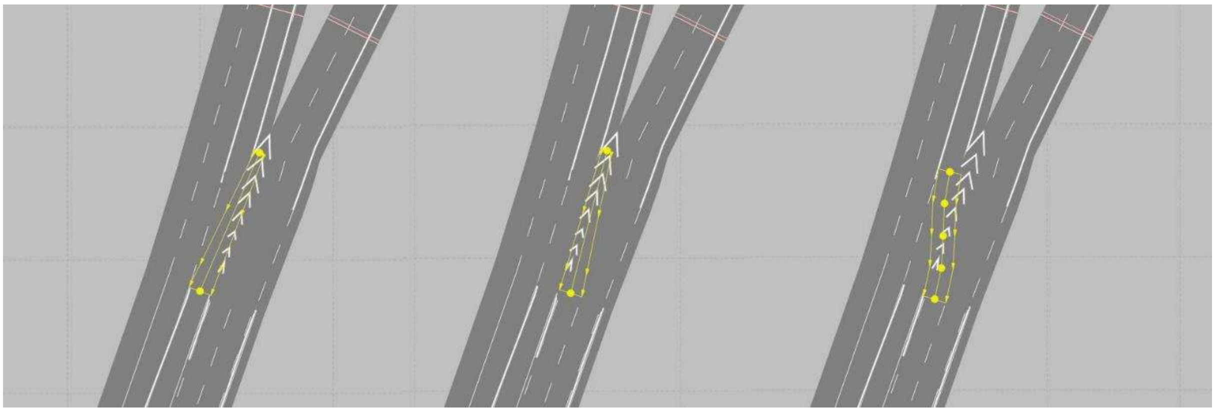


Figure 18: The three connectors representing the non-run-through transition routes from the mainline to the next link

Lastly, a sixth connector was used to represent the motorists changing lane from the rightmost to the middle lane of the on-ramp.

The remaining three connectors in the network are placed in the transition between section B and C. In line with the former case, one connector is used for the three mainline lanes. For the on-ramp however, a two-lane connector is used for the lanes merging into the mainline. The shoulder lane, which remain in the network also after the transition, is modeled with a separate connector.

Next, vehicles were added to the network by using flow data from the field observations. Two separate input flows were assigned: one for the mainline and one for the on-ramp. For each, the total flow and vehicle composition were set according to Table 7. The default values for personal car and heavy vehicle properties were used.

With the aim of reflecting the lane changing behavior observed in section A, a set of static vehicle routes were defined on the mainline. The routes were created in accordance with the three connectors displayed in Figure 18 as well as a route for run-through traffic.

To enable data collection on vehicle flow and speed, data collection points were placed at the beginning of section A. Lane changing occurrences and their location where collected by utilizing the sections function, and vehicle travel times by the help of the vehicle travel time measurement function in VISSIM.

4.1 Scenarios

In this study, two alternative scenarios including one merging control strategy each were created and compared to the base scenario. Based on field observations, the merging control strategies suggested by EXAT (2016b) and EXAT (2016c) were found irrelevant to the studied site. The main reasons are:

1. Shoulder lane driving is used on a permanent basis
2. Motorists do not respect the solid lines at the site
3. The on-ramp is already equipped with cones to move the merging point
4. The on-ramp flow is not enough to motivate the use of ramp metering

Hence, two new merging control strategies are suggested.

4.1.1 Scenario 0: Base scenario

The base scenario in this model is the one described in the section above. It consists of a four lane expressway and a three lane on-ramp, were the separation between these inflows are made up by striped areas and solid lines. However, as observed from the video recordings, the drivers neglect the traffic rules concerned with these markings. To capture this behavior, a share of the simulated driver-vehicle units were instructed to follow the predefined routes which implies breaking the traffic rules. The default shares per route were taken from the filed observations and are presented in Table 9.

4.1.2 Scenario 1: Center barrier

In the first alternative scenario, a center barrier is installed along the striped area. This action is made to reinforce the obedience of the traffic laws in order to see if this would have a significant impact on the congestion. The exact placement of the barrier is illustrated in Figure 19.

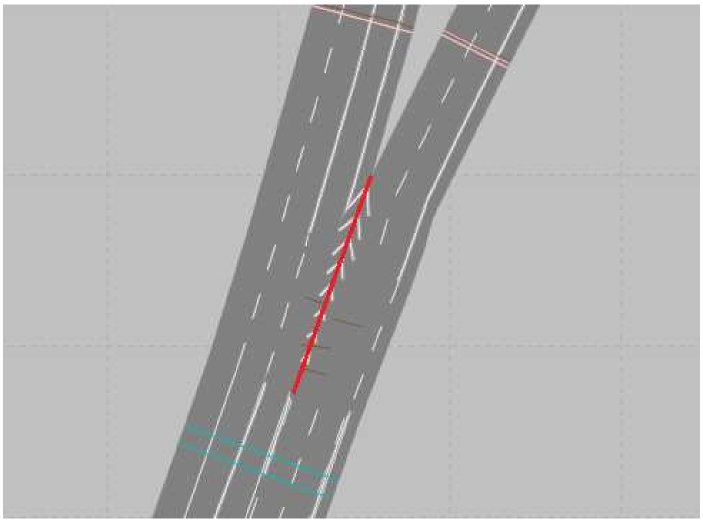


Figure 19: Placement of center barrier

To represent the effects of a barrier, the two rightmost routes presented in Figure 18 was removed. Consequently, the vehicles earlier assigned to the removed routes were instead assigned to the first route in Figure 17. More specifically, 20% of the vehicles are assigned to traverse from the shoulder lane to the mainline and 80% to use the through route.

4.1.3 Scenario 2: Successive merging

In the second scenario, the merging are in section C were replaced by a two smaller merging areas, one in B and one in C. By merging one of the on-ramp lanes already in section B, the vehicles are forced to merge successively instead of all at once in section C. This alternative is investigated in order to see if the two lane merging area in C has a major effect on the total travel time. Three new connectors and one new link were used to create the new arrangement. The successive merging layout is presented in Figure 20.

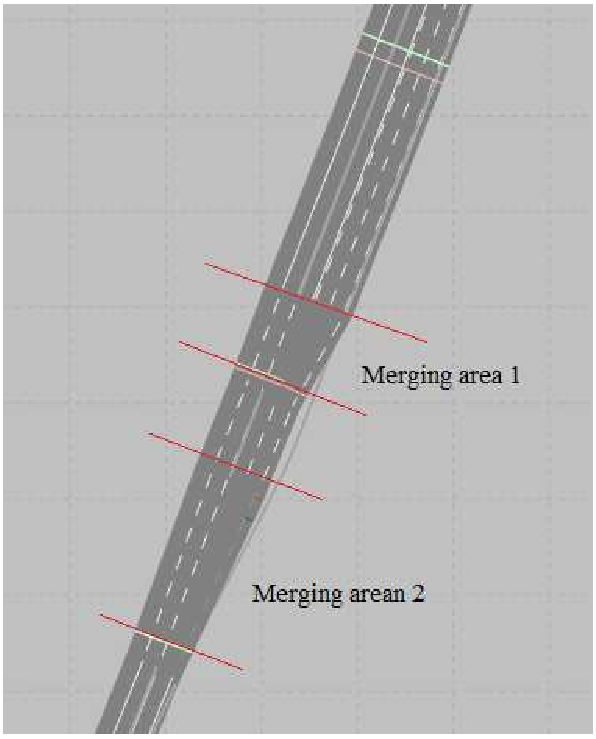


Figure 20: The alternative network layout with two new merging sections

4.2 Verification

A visual verification of the model was made by comparing the driving behavior in the animations with the ones observable in the video recordings. The model was assessed as accurate enough when the animation replicated the real life traffic conditions in a satisfying way.

Initially, it could be observed from the animations that some vehicles disappeared from the network when reaching certain connectors. More specifically, the vehicles disappeared from the system when they reached the end of a connector. In section A, this issue was solved by extending the mainline and on-ramp links, and increasing the lane changing distance for the specific connector. In this way, the motorists were given more time and space to plan their lane change. However, it was also required that the static vehicle routes were modified manually by entering the exact sequence of link and connectors involved. For section C, the problem could be solved by changing the lane changing distance alone.

Another problem that could be observed from the animation were that vehicles were colliding, or driving on top of each other. This phenomenon were mostly found in section C where the two on-ramp lanes merge into the adjacent lanes. To overcome this issue, conflict areas were defined and supported by additional priority rules. In addition, the parameter keep lateral distance to vehicles on next lane(s) were activated. The conflict areas and priority rules defined are presented in Figure 21.

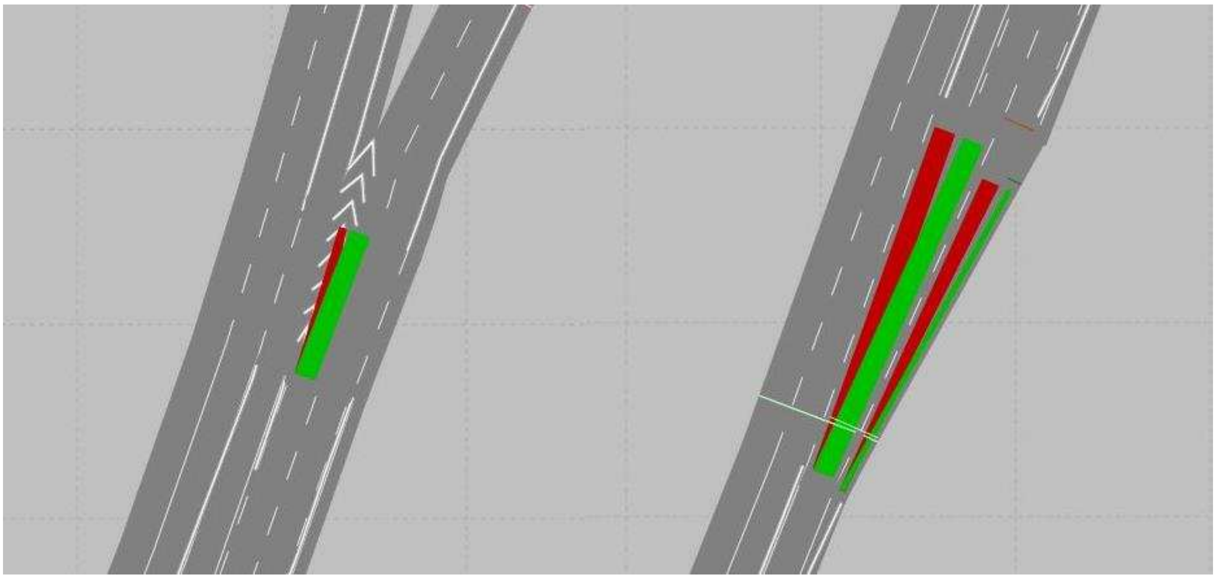


Figure 21: Red and green conflict areas plus red and green priority rule lines

The last issue that could be found from the visual verification were standstill vehicles. These vehicles drove in normal pace until they reached the beginning of a conflict area. At this point they stopped, waiting for vehicles with right of way to clear the defined area. However, the standstill times were too long which caused major queues in the system. To tackle this problem the conflict area-specific parameters AvoidBlockMajor, FrontGapDef, and RearEndDef were adjusted. The default setting for each of these parameters as well as the applied values are presented in Table 10.

Table 10: Comparison of parameters values concerned with conflict areas

	Default	Applied
AvoidBlockMajor	Active	Inactive
FrondGapDef (m)	0.5	0.0
RearEndGap (m)	0.5	0.2

4.3 Calibration

The calibration process consists of several parts: number of simulation runs, travel times, merging behavior and vehicle flows and adjustment of driving behavior parameters. Each part is further discussed below.

Number of simulation runs

The minimum number of simulation runs n was decided based on the method presented by Trafikverket (2013) where

$$n = \left(\frac{s * t_{\alpha/2}}{\bar{x} * \epsilon}\right)^2 \tag{4.1}$$

s the standard deviation and $\bar{x}$ the average value based on an initial set of replications (commonly 4-6). $t_{\alpha/2}$ represents the student t-value for the confidence level $\alpha/2$ and ϵ allowed margin of error expressed in percent of the mean value.

As the calculations required the standard deviation and average value from a parameter that will be included in the calibration process, the total travel time was used. Since the travel time is measured for both mainline and on-ramp traffic, the total number of simulation runs required for each of them were calculated separately as N1 and N2. The final number of simulation runs, N, was determined by using the average value of N1 and N2. The calculation results are presented in Table 11. Three runs were made to retrieve s and $\bar{x}$, and the value of ϵ was randomly assigned a value, between 2% and 5%, that would generate a relatively low value of N. The interval is based on the margin of error used in the simulation studies Bernhardsson (2017) and Bernhardsson & Olstam (2017), and the desire of a low N-value depends on the extensive time required to extract the data from each run in VISSIM.

Table 11: Results from calculations of number of simulation runs

	s	$t_{0.05/2}$	$\bar{x}$	ϵ	N1	N2	N
Main	8.66	4.30	39.54	3	7.99		
Ramp	17.93	4.30	67.26	3		11.84	9.92

As can be seen from the results, 10 simulation runs are required.

Travel time

The vehicle travel time was calibrated by comparing the simulation output to the average travel time estimated from the video recordings. Since there are only a few sets of real world observations available, the prediction interval method presented by Trafikverket (2013) was applied. The prediction interval was calculated as:

$$\bar{x} \pm t_{n-1}\left(\frac{\alpha}{2}\right) s \sqrt{1 + \frac{1}{N}} \tag{4.2}$$

where $\bar{x}$ is the average travel time value and s the standard deviation for the N simulation replications. $t_{n-1}\left(\frac{\alpha}{2}\right)$ represents the t-value at the confidence level $\frac{\alpha}{2}$ with N-1 degrees of freedom.

The model is considered okay when the average travel time from the real world observations falls within the calculated prediction interval.

Since the observations show that the travel time differs widely among the merging sections, and also between the on-ramp and the mainline traffic, prediction intervals were calculated for each part respectively. In addition, corresponding calculations were made for the complete network (section A, B and C combined). The results from the travel time calibration is presented in Table 13. In VISSIM, it was only possible to extract data on the mainline and on ramp traffic combined, not separately, for section B. Hence, the value used to calculate the prediction interval was set to the average between the one observed at the mainline and at the on ramp in B. Similarly, the total on ramp travel time in VISSIM had to be estimated by combining data obtained from two different data collection points. The prediction intervals as well as the data from the observations are presented in Table 14.

Merging behavior

The data on percentage of merging occasions as well as their location was used in the calibration process of the merging behavior. From the video recordings it is clear that merging happens on several points in the studied system. However, the majority of the lane changes occur shortly after the on-ramp conjoins with the mainline (section A), as well as at the end of the acceleration lane (section C). Hence, these two locations were the main subjects of interest when the merging behavior was calibrated.

To support the visual verification of the driving behavior, a prediction interval for the share of lane changes occurring in each merging section was estimated. The prediction intervals were calculated by using Equation 4.2. To obtain the number of lane changes in VISSIM, the sections function was used. While going through the data it was however discovered that vehicles using some of routes defined in section A were not included. Since the 20% of the total mainline vehicles are assigned to use the routes that require lane changes, these 20% (equal to 925) were added to the total number of lane changes. The obtained output data and the corresponding prediction intervals for the share of lane changes are shown in Table 15 and 16.

Vehicle flows

In addition to calibrating the merging behavior and the travel times, a throughput calibration in terms of vehicle flows was performed. The GEH formula presented by ODOT (2011) was used for this purpose.

$$GEH = \sqrt{\frac{2(m-c)^2}{m+c}} \tag{4.3}$$

where m is the simulation output [veh/h/ln] and c the field data observations [veh/h/ln].

Since two vehicle inputs are used in the model, one GEH value were estimated for each input. The VISSIM output and the GEH values are presented in Table 17. In the calculations, the mainline flow per lane is calculated as the total flow divided by four. In the case of the on ramp, the total flow is divided by three.

Adjustment of driving behavior parameters

During the calibration a number of driver behavior parameters were adjusted to achieve an acceptable simulation output. Three different driving behaviors were defined in VISSIM: E1, E2, and Freeway. Both the initial mainline and on-ramp links were assigned Freeway, as well as all the connectors related to the mainline in section A. The two connectors on the on-ramp were however set to E1. The long link running from section A to section C was assigned E2. The on-ramp lanes merging into the mainline in section C were assigned E1, while mainline connector were assigned Freeway. The final link, downstream section C, was set to Freeway.

How the final set of driving behavior parameters and their corresponding values differ from the default settings are listed in Table 12. Only parameter values that differs from the default are included in the table.

Table 12: Differences in parameter values for the defined driving behaviors

	Default	E1	E2	Freeway1
Car-following				
Min. Look ahead distance [m]	0	100		20
Max. Look head distance [m]	250	150	150	
Min. Look back distance [m]	0	100		
Max. Look back distance [m]	150			
Smooth closeup behavior	Inactive	Active	Active	
Lane changing behavior				
Accepted deceleration trailing vehicle [m/s2]	-0.50	-1.00	-3.00	
Waiting time before diffusion [s]	60	30		
Cooperative lane change	Inactive Max. speed diff. 10.80 km/h	Active Max. speed diff. 3 km/h	Active Max. speed diff. 3 km/h	Active Max. speed diff.10.00 km/h
1 m/s2 own and trailing [m]	200		100	
Lateral behavior				
Keep lateral distance to veh. On next lane [s]	Inactive	Active	Active	
Minimum lateral distance standing [m]	0.2	0.8	1.00 m	
Minimum longitudinal speed [km/h]	3.60 km/h		1 km/h	
Overtake on same lane	Inactive		Active left, right	
Desired position at free flow	Middle of lane	Right	Any	Any

In addition to the driving behavior parameters, lane changing distance and parameters for conflict areas were adjusted during the calibration. The default lane change distance for a connector is 200 meters. In section A, the connectors attached to the mainline shoulder lane use a distance of 800 meters. This is also the case for the on-ramp connectors. The only exception in A is the connector going from lane three on the mainline to the on-ramp. This connector is assigned a distance of 200 meters. In section C, the mainline connector uses 600 meters and the on-ramp connectors 200 meters.

During the calibration process it was discovered that too many lane changes occurred in section B. On a closer look, it was found that a lot of vehicles on the mainline changed to the on-ramp. To decrease the number of lane changes occurring in this section, lane changes to the left were forbidden for lane one, two and three on the mainline. Based on the same reasoning, lane changes from the on-ramp shoulder lane to the right were prohibited. As a consequence of these restrictions, the number of lane changes decreased rapidly and yielded more accurate results.

5 Results

In this chapter, the results from the calibration process as well as the alternative scenarios are presented. Throughout this chapter, a red colored cell indicates that an observation falls outside its predicted interval, and a green within.

5.1 Driving behavior characteristics

Based on visual field observations and collected data, the following driving behavior characteristics can be identified at the studied site:

- The shoulder lanes are utilized as an extra, ordinary lanes at all times.
- Drivers do not obey the traffic regulations. Solid lines and striped areas are completely ignored.
- Overtaking is made both to the left and to the right throughout the area.
- Vehicles from the mainline, in particularly the leftmost lane and the shoulder lane, purposely change to the on-ramp lanes where it is less congested.
- The vehicles on the on-ramp tend to prefer driving as far to the left as possible, leaving the rightmost on-ramp lane relatively unoccupied. This lane is hence targeted by the mainline traffic.
- On the mainline, the maximum average speed can be found in section A, followed by C and B. Similarly the maximum average speed on the on-ramp, can be found in section A. In comparison, section B is found to have a higher average speed than C.
- Most lane changes are performed in section A, followed by C and B.

5.2 Calibration

In this chapter, the calibration results following from section 4.3 Calibration are presented. Each variable is further discussed below.

Individual travel time

In Table 13 the average individual travel time from the 10 simulation runs are presented. A comparison between the observed travel times and the prediction intervals corresponding to Table 13 are presented in Table 14. A red colored cell indicates that the observation falls outside the predicted interval, and a green within.

Table 13: The average individual travel time [s] of the 10 simulation runs

Run #	A main	A ramp	B main	C main	C ramp	Total main	Total ramp 1	Total ramp 2	Total ramp (avg.)
Avg.	23.33	15.63	14.62	8.79	16.71	44.91	62.13	58.32	60.24

Table 14: Travel time prediction intervals[s]

	Lower	Upper	Obs. data
A main	13.859	32.793	22.135
A ramp	6.912	24.336	18.090
B main	-	-	22.560
B ramp	-	-	17.630
B avg.	15.868	24.322	20.950
C main	8.163	9.411	11.400
C ramp	14.356	19.070	15.180
Total main	33.235	56.583	56.095
Total ramp	36.947	83.512	50.901

From the results it can be seen that the observed travel time (Obs. data) is within the calculated prediction intervals for all sections as well as the total, except from C main.

Merging behavior

Visual inspection:

Initially, the merging behavior was calibrated through visual inspection. It showed that the vehicles entering the merging area in section A drove according to the observed driving patterns, both on the mainline and the on-ramp. However, a small number of vehicles did still, despite the actions made to prevent it, drive on top of each other. Regarding the merging behavior in section C, it was found to be relatively close to the observed driving behavior.

Share of lane changes:

Table 15: The average number of lane changes per section

Run #	A [veh/h]	B [veh/h]	C [veh/h]	Total [veh/h]
Avg.	2179	663	1439	4281

Table 16: Prediction intervals for the share of lane changes per section

	A	B	C
Obs. data (%)	0.52	0.11	0.36
Pred. low	0.40	0.12	0.19
Pred. high	0.61	0.26	0.41

The result shows that section A and C are within the prediction intervals while B is slightly too low.

Vehicle flows

Table 17: The average vehicle flows from the 10 simulation runs and the corresponding GEH

Run #	Main [veh/h/ln]	Ramp [veh/h/ln]
Avg.	1156	270
GEH	9.2	4.5

As the GEH value has to be below three in order to be acceptable and below five to be conditionally accepted, it is clear that the vehicle flow calibration of the mainline flow failed. The GEH for the on-ramp flow is however acceptable.

A detailed discussion of the calibration results is given in chapter 6 Discussion and further work.

5.3 Impacts from merging control strategies

In Table 18 the average individual travel time recorded, and the corresponding 95% confidence interval, for each scenario is presented. The result is graphically illustrated in Figure 22 and 23.

Table 18: Average total travel time [s] per scenario and the corresponding confidence intervals

Travel times [s]	Scenario 0			Scenario 1			Scenario 2		
	Obs.	Low	Up	Obs.	Low	Up	Obs.	Low	Up
Total main	44.91	41.39	48.43	37.46	35.97	38.95	42.75	39.26	46.25
Total ramp 1	62.13	53.36	70.91	21.82	21.28	22.38	27.25	26.61	27.89
Total ramp 2	58.32	52.95	63.69	22.45	21.71	23.18	29.54	28.66	30.42
Total ramp (avg.)	60.23	53.21	67.25	22.14	21.50	22.78	28.40	27.67	29.12

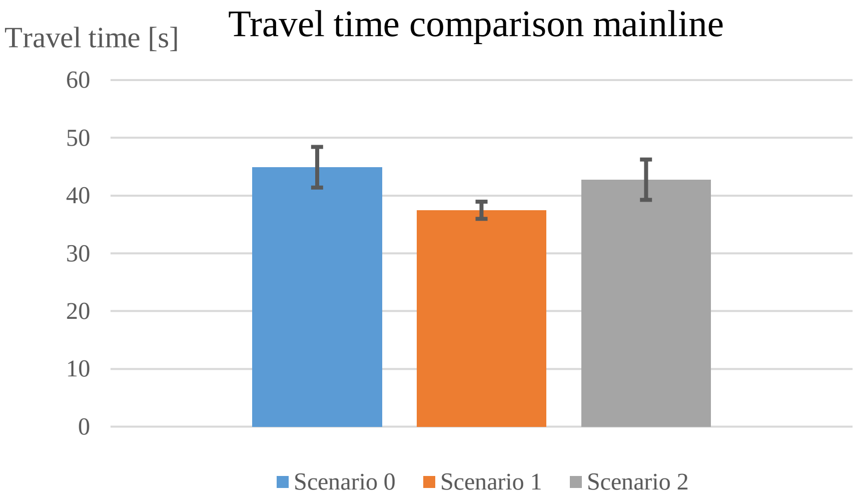


Figure 22: Comparison of mainline travel times and confidence intervals of the scenarios

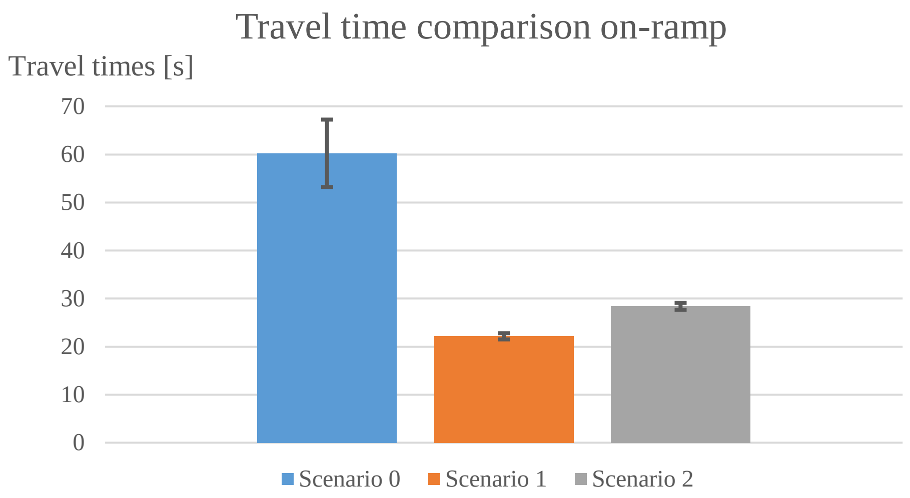


Figure 23: Comparison of on-ramp travel times and confidence intervals of the scenarios

From the results it is clear that both scenario 1 and 2 yield a reduction in travel time, especially for the on-ramp traffic. However, the confidence intervals of the base scenario and scenario 2 overlap each other in Figure 21, implying that the scenarios cannot be said to be significantly different from each other. One can also note that the confidence interval for scenario 2 is relatively wide compared to scenario 1, which suggests that the results from the former might be less reliable than those from the latter. In the case of the on-ramp, as shown in Figure 22, both the alternative scenarios are significantly different to the base scenario.

The greatest effect on both mainline and on-ramp traffic is generated by scenario 1, which also is the only alternative scenario that is significantly different from the base scenario on both the mainline and on-ramp. By installing a center barrier, the mainline travel time could be reduced by 7.45 seconds and the corresponding number for the on-ramp is 31.83 seconds. This equals a reduction of 16.58 % and 63.24 % respectively.

6 Discussion

The data used in this study was collected by the help of video cameras. Even though data were collected during three days, only one set of useful data could be extracted. This was partly caused by physical limitations and regulations on some of the mounting sites, but also due to the extensive amount of time required to extract the data. The lack of sample data, in combination with insufficient information on actual travel demand, have affected the calibration process in a negative way. In addition, human error might have affected the quality of the data and hence the accuracy of the result can be questioned.

Due to my limited experience in VISSIM, the developed model might not be the optimal way to represent the studied site. A different arrangement of links and connectors might have been beneficial in terms of data collection and the possibility to change the driving behavior in specific areas or individual lanes. For example, some of the links in the current model are running through several sections, which means adjustments of the driving behavior on one link will change the driving behavior in two sections. This shows that calibrating a model for a network of this size is rather complex, and probably impossible for even larger networks. Hence, constructing a model with links and connectors arranged as in this study is only recommended for minor networks or small segments of a network.

It would have been desirable to arrange the network layout, e.g. change the link lengths, to better fit the section boundaries. To achieve a more realistic driving behavior it might also be better to limit the use of priority rules, since these controls the drivers' actions instead of making them drive based on the driving behavior settings. This is also true for the static routes that had to be defined in order to make vehicles from the mainline traverse to the on-ramp.

As mentioned earlier, insufficient data affected the calibration process. Since only one set of data was available, the prediction interval method had to be used. However, some of the resulting prediction intervals include a wide range of values. An observed value that falls within a narrow prediction interval implies a more realistic model. The broad intervals might be a consequence of the relatively low number of simulation runs, as well as the unpredictable driving behavior of individual vehicles. When the number of simulation runs were calculated, a marginal error of 3% was arbitrary chosen between 2% and 5%. If a different value was used, that resulted in a higher number of required simulation runs, the prediction intervals might have become narrower. However, due to the time limitations of the study, it was not an option to calibrate based on a large number of runs. In addition, using the maximum value of N1 and N2, when deciding the number of simulation runs N might have been a better approach. This would ensure that a sufficient number of runs were made both for the mainline and the on-ramp traffic. How large the effect from two additional simulation runs would be can however be questioned. Regarding the unpredictable driving behavior, the range of individual travel times affects the average travel time used to calculate the prediction intervals. Hence, individual travel times that differs greatly from the remaining might give rise to wider prediction interval.

From the calibration results it can be concluded that a majority of the individual travel times falls within the corresponding prediction intervals. The only exception is the mainline in section C which has shorter travel time compared to the observations. This might be caused by the fact that lane changes to the right had to be prohibited for the three mainline lanes just upstream of section C. It might also be a consequence of the applied driving behavior, which main focus was to capture the realistic behavior of drivers in the merging area. Hence, the travel time on the mainline might in this case have been easier to calibrate if it was possible to assign specific driving behavior per lane instead of per link. It is also possible that other combinations of driving behavior parameters than the ones implemented would have given a more accurate result. The travel time observed for the total main is near the upper limit of its prediction interval, which is probably caused by the low average value obtained from the simulation. As the simulated travel time is rather short in relation the real value, one can guess that it might be a result of the too short travel time obtained in section C. The average travel time obtained in C does however only differ a few seconds compared to the observed travel time. This means that other factors also contribute to the fast travel time. In accordance with the argument stated for main C, the prohibition of lane changes to the right in section B as well as the fact that no lane changes are allowed either before section A or after section C might have cause a faster total travel time than desired.

Regarding the share of lane changes performed per section, both A and C are within their corresponding prediction intervals. Section B on the other hand is one percent too low. This means that too many lane changes are made in this section in relation to the input flow, despite the effort to limit them by prohibiting lane changes to the right for the mainline traffic. Two possible explanations for this is: The input flow is too low, or the desire to change lane is too high. From the simulation output it is clear that the vehicle flow is significantly lower than the observed flow, which means that the share of lane changes in section B might be outside the interval due to this. Yet, section A and C are still within their corresponding intervals, even with the lower vehicle flow. The other reason might be a too aggressive driving behavior that generates more lane changes than normally would occur. By continue to adjust the driving behavior parameters it might have been possible to obtain a lower value, bur due to the limited time of the study, a more accurate result could not be achieved.

The vehicle flow calibration were successful for the on-ramp traffic, but not for the mainline where the GHE value was significantly higher than required. This is because the vehicle input on the mainline is considerably lower than the actual. After applying a number of different driving behavior sets as well as vehicle input values, the system seems to be saturated before a large number of vehicles can enter the network.

This indicates that there is a bottleneck somewhere in the network that prevents vehicles from traveling smoothly. After studying the simulation animations one such bottleneck can be identified at the end of section C. At this point, when the link connecting section C to the last part of the network ends, some vehicles stop for a few seconds, for no obvious reason, before continuing out of the system. This is probably due to the driving behavior settings or the lane changing distance. However, other settings resulted in even more unnatural driving behavior such as collisions and reversing vehicles. In addition, when the lane changing distance was adjusted, some vehicles disappeared from the network. Hence, the decision to keep the current driving behavior and lane changing settings were made.

Both merging control strategies applied improves the traffic situation in terms of individual travel time. The installation of a center barrier turned out to have the greatest impact, in particular on the on-ramp traffic. Replacing the merging area in section C with two smaller merging areas also decreased the total travel time, but only with a minor impact on the mainline traffic. This shows that the main problem at this site is not the congested merging area in C, but the driving behavior of the mainline traffic in section A. Based on the outcome of this study it could be assumed that the earlier merging control strategies implemented by EXAT would not have been effective on this site, since they all address a situation where the problem is at the on-ramp. This also explains why the congestion remains at the studied site despite the current strategy of placing cones to move the merging point at the on-ramp.

7 Conclusions and future work

In this study, an investigation was made on how the relatively complex driving behavior on an on-ramp merging area in Bangkok could be included in the microscopic traffic simulation models available in VISSIM. The study also investigated how this driving behavior in combination with two different merging control strategies affected the congestion at the studied site.

The driving behavior at the studied area is characterized by drivers who disrespect traffic regulations by ignoring solid lines and overtaking on both sides. In addition, the shoulder lanes are utilized as ordinary lanes on a regular basis. Drivers on the mainline also tend to traverse to the on-ramp, while the on-ramp drivers prefer to position their vehicle as far to the left as possible. As a consequence, a large amount of unnecessary lane changes are made, in particular in the beginning of the ramp.

The microscopic models in VISSIM can be adapted to reflect the driver behavior at the studied site by adjusting the driving behavior parameters in accordance with Table 12. However, the accuracy of the model can be questioned due to the less successful parts of the calibration. It is for example not possible to adjust the driving behavior on an individual lane within a link, which makes the calibration process a complex task. In addition, priority rules and static routes had to be used in order to achieve the desired driving pattern and prevent vehicles to collide. By introducing these components, some of the actions performed by the drivers will be made based on the imposed rules instead of the driving behavior settings.

Both merging control strategies implemented improves the traffic situation in the studied area in terms of reduced travel times. The installation of a center barrier reduces the number of lane change at the start of the first merging area drastically, and hence a lower travel time is obtained. The successive merging layout offers two merging points instead of one, resulting in a smoother flow towards and to the end of the final merging area. The most effective of the implemented merging control strategies, in terms of travel time reduction, is the installation of a center barrier. This is true for both the mainline and the on-ramp area whom decrease with 16.58 % and 63.24 % respectively. This result clearly shows the importance of prompting drivers to obey traffic regulations in order to decrease the number of unnecessary lane changes, and enhance the congestion.

During this study several points that can be helpful in future work have been identified. One of the major weaknesses with this study is the lack of reliable data and tools to process it. Hence, more data and preferable detailed data on vehicle trajectories and spot speeds would constitute a more reliable base of the project. It is also advisable to try modeling the driving behavior without using static vehicle routes and priority rules, which might be possible for someone with deeper knowledge and experience in VISSIM. For example, the car-following behavior and lane changing behavior can be manipulated by using COM programming.

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