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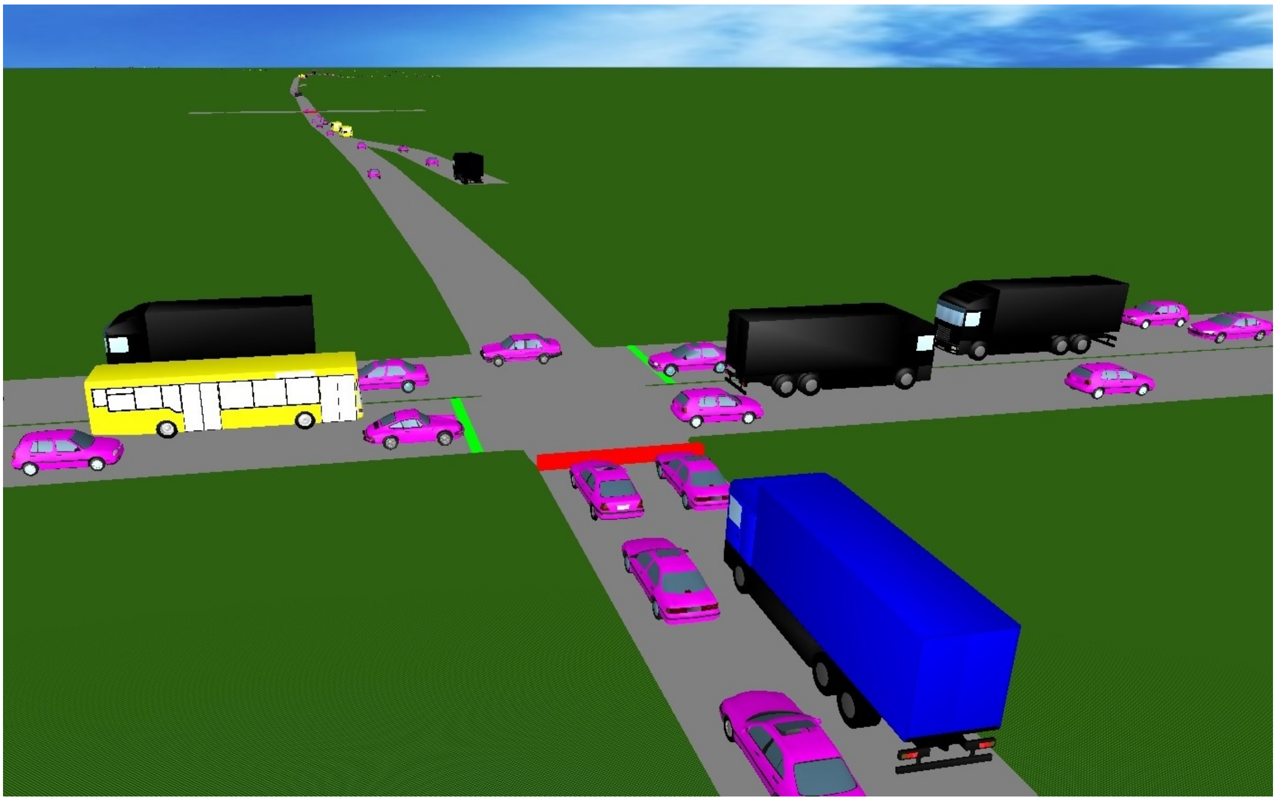

Drive Cycle Prediction Using Traffic Simulation Tool

Master's Thesis in Systems Control & Mechatronics

DANIEL KARLSSON
FREDRIK TILLMAN

Department of Signals & Systems
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Cover:
Automatically generated Vissim model.

Chalmers Reproservice
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Abstract

The development of vehicles is, to some extent, based on drive cycles, which consist of speed and altitude as a function of time and travel distance. The drive cycles which are currently being used is estimated based on measurements and the traffic conditions for those drive cycles are defined as either urban or freeway. There is a need of drive cycles which represents the future and the objective of this thesis is to estimate such drive cycles for three vehicle types, namely Distribution, Refuse and Haul truck. The proposed methodology is estimating the present traffic conditions based on analyses of the national road database (NVDB). The analyses of NVDB are required in order to generate realistic traffic models. Generated models are compatible with the commercial simulation software Vissim. The properties of the vehicle types which are covered in this thesis are estimated based on an analysis of measurements. The simulation result shows a traffic condition which is consistent with the configurations defined by the NVDB analysis. A validation of the simulation results for the Haul Truck in urban and freeway traffic condition shows a satisfying behavior of the vehicles. The future traffic conditions are based on a prognosis developed by the Swedish Transport Administration, Trafikverket. Drive cycles are successfully composed based on simulations of those traffic conditions.

Keywords: Vissim, Drive Cycle Prediction, Drive Cycle Generation, Traffic Simulation, NVDB

Acknowledgements

We would like to thank our supervisor at Chalmers, Balazs Kulcsar, for the support and discussions which often lead to an agreement of how to tackle problems. The meetings were often prolonged due to a generous concern for our work and social conversations. His support has been invaluable for us.

We would also like to thank our supervisors at WSP, Sebastian Hasselblom and Tobias Thorsson. The Vissim related support from Sebastian was helpful, making us aware of possibilities and restrictions in Vissim. Though we never implemented the level of detail which his Vissim models had due to our methodology and time span for the thesis, it was a great source of inspiration. His skill of persuasion to leave the office and have a social lunch time was also appreciated.

From Volvo we would like to thank our supervisor Niklas Thulin which have shown a great interest in our work and also made an effort to communicate our work within the company. His devotion for our work led us to getting in contact with Marcus Elmer among others, which we would like to thank for supplying us with data for validation and vehicle property estimation and showing his related work.

During our work with the C++ application we had an issue with the simulation speed due to our application not being optimized with respect to performance. Even though the desired simulation results were extracted, the application would run too slow when many Volvo vehicles entered the traffic model. The Vissim manual did not address our problem but by abusing a helpful brother and experienced C++ developer, Sebastian Karlsson, the performance of the application was greatly increased.

The Swedish Traffic Administration, Trafikverket, have also shown us great service. Katarina Holm spent a lot of time to look into our questions regarding traffic data and prognoses, and communicating our issues with the appropriate personnel within Trafikverket. We struggled with the National Road Database (NVDB) for a significant amount of time before we noticed the Mapping Toolbox within Matlab and during that time we were looking into Trafikverket's own application and its source code. We would like to thank Håkan Liljeholm from Trafikverket for his effort to introduce us to the source code of Trafikverket's NVDB application even though we decided to use Matlab for NVDB analyses.

Contents

Abbreviations

NVDB :	*Nationell Vägdatabas (National road database)*
GUI :	*Graphical User Interface*
P/M :	*Power/Mass*
HGV :	*Heavy Goods Vehicle*
AADT :	*Annual Average Daily Traffic*
AR :	*Auto Regressive*

1 Introduction

1.1 Project description

The scope of the project is to develop a method for prediction of future driving cycles and patterns for different types of hybrid vehicle applications. These cycles are used as an important input in designing and evaluating future powertrain systems and vehicle concepts.

As of today, obsolete drive cycles are used during the design phase which yields that changes in traffic conditions and infrastructure which has occurred during the last decade are not taken into account. Therefore, the need for new drive cycles representing today or the next few decades is great.

The goal of the project is to develop a tool to predict future drive cycle by integrating available measurement data, high-fidelity traffic simulators and traffic models for heavy vehicles. Desirably, traffic simulation models are automatically generated and used to collect predicted drive cycles.

1.2 Vehicle applications

This project covers three different types of Volvo vehicle applications, namely *Refuse Truck*, *Distribution Truck* and *Haul Truck*. The first one represents trucks driving mainly in city traffic at relatively low speeds and having a high frequency of stops. Also *Distribution Truck* has a high stop intensity but drives generally in traffic containing a mixture och urban roads and freeways. The last one, *Haul Truck*, rarely stops but drives relatively long distances on freeways. Predicted drive cycles for each and one of these vehicle applications will be generated.

1.3 Vissim objects

Vissim is a microscopic traffic simulation software. It has many objects with default behavior which is based on extensive research. The implementation of Wiedemann's car following model constitutes a large portion of the dynamics within the traffic models.

This is a list which states all properties of the Vissim objects which is made available in Matlab.

- Link - A road element which consists of intermediate points in 3D, road type and a number of lanes.
- Connector - A road element which connects two or more links.
- Parking Lot - A simple parking lot which consists of total length, length of parking spaces and distribution function for how long a vehicle will stop.
- Speed Decision - Controls the desired speed of passing vehicles.
- Reduced Speed Area - An area which locally reduces the speed of the vehicles. It consists of the desired speed which all vehicles passing the object receives.

- Routing Decision - Passing vehicles decides upon which route to choose, fractions defines how the vehicles are distributed among the routes.
- Vehicle Input - An element which spawns vehicles. A flow and traffic composition define its behaviour.
- Traffic Composition - Defines the fractions of how the vehicle types are distributed at the Vehicle Inputs.
- Signal Controller - A virtual control system which control traffic lights. Timing of different Signal Groups define it's behaviour
- Signal Group - Controlled by a Signal Controller, it is forwarding a signal state to all of the Signal Heads which is a member of the Signal Group.
- Signal Head - The traffic light which interacts with passing vehicles.

1.4 Driver model

The driver models used in Vissim is developed by R. Wiedemann. The Wiedemann 74 model is used in urban traffic and Wiedemann 99 model is used in freeway traffic. A complete description of the wiedemann models is not available for the public. A validation of Wiedemann model have been performed in [Wie91], showing the validity of the model with respect to measurements of a single car following another vehicle and macroscopic simulation results. The parameters are described verbally and a calibration methodology is presented in [MS]. Wiedemann model is also presented and compared with driver models used in other microscopic traffic simulation software in [TO04].

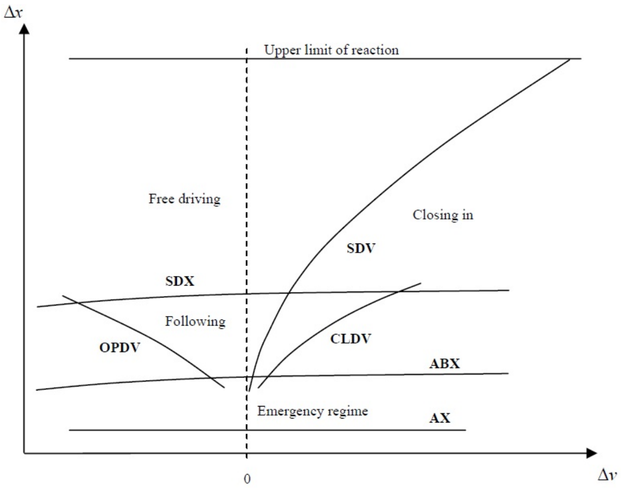


Figure 1.4.1: *State space of Wiedemann model, presented in [TO04].* $\Delta x, \Delta v$ *is the relative distance and speed difference between following and leading vehicle, respectively*

The behavior of the Wiedemann models are illustrated in Figure 1.4.1. There are four driver modes, *Free driving, Closing in, Following and Emergency.* According to [MS] and [TO04], the driver modes can be described as:

- Free driving: There are no leading vehicle. The driver tries to achieve the desired speed but fluctuates around the desired speed due to imperfect throttle control.
- Closing in: A leading vehicle is approaching in front of the following vehicle. The driver tries to decelerate in order to achieve the same speed as the leading vehicle and the desired safety distance, i.e. $\Delta v = 0, ABX < \Delta x < SDX$.
- Following: The driver tries to maintain the safety distance and keep the speed difference at a low value. This is done by accelerating or decelerating as low as possible whenever Δv and Δx is not within the desired region.
- Emergency: The distance to the leading vehicle is lower than the safety distance. The driver brakes as much as possible in order to avoid collision.

Wiedemann 74 and Wiedemann 99 uses thresholds to model the drivers perception but the thresholds are calibrated differently. The thresholds *ABX, AX, SDX, SDV, OPDV and CLDV* defines the regions in the state space for the different driver modes. The thresholds are unique for each vehicle, a normal distributed random value along with some calibration parameters is used to assign the threshold characteristics for each vehicle. The threshold ABX, which is the desired distance between following and leading vehicle at low speed difference Δv, is dependant on the absolute speed of the following and the leading vehicle. A thoroughly description of the thresholds is presented in [TO04].

1.5 Delimitations

The estimation of model generation parameters is based on data in areas near Gothenburg and the selected routes are considered to represent a typical infrastructure. The developed Matlab application is only compatible with road data on the shape format (*.shp) which is widely used in geographical applications. Data extraction is limited to several attribute values (speed limits, traffic data, geometry) and it is adapted to the structure defined by the Swedish Transport Administration, Trafikverket, though the application may easily be extended with extraction of more attribute values.

The vehicle types covered in this thesis is limited to Distribution, Refuse and Haul Truck. The vehicle property estimation is based on several data sets for Haul Truck; the properties of the other vehicles are interpolated based on specified acceleration with respect to Haul Truck.

The simulation is limited to only Vissim as a platform. The generated model is not mapped to other modeling frameworks or software. Due to this limitation, the driver model developed by Wiedemann is used and the vehicle dynamics is one dimensional and constrained by the static $a(v)$ function. All vehicles except the studied vehicle are assumed to have the default properties in Vissim. The geometry of the Volvo vehicles is also assumed to be the same as the default HGV vehicle type within Vissim.

The model generation is limited to a several amount of developed traffic objects (intersections, on ramps, off ramps). There are potential to generate even more content (trams, pedestrians, control logic of traffic lights, variable speed limits, etc.).

The future traffic situation is based on an extensive report, developed by Trafikverket, and no attempt to estimate the future traffic situation will be performed.

2 Theory

2.1 Markov Chains

A Markov chain is a mathematical model of a stochastic process. It is a memoryless system, meaning that how the system will evolve does only depend on the present state. This characteristic is called the *Markov property* and is formally expressed as [Len03]:

$$Pr(X_{n+1} = x | X_1 = x_1, X_2 = x_2 ..., X_n = x_n) = Pr(X_{n+1} = x | X_n = x_n)$$

Two other important properties of a Markov process is that there is a finite number of states and that the transition probabilities are constant over time.

A Markov process, having n number of states, has a *probability matrix* of dimension (n x n). If $P_{i,j}$ denotes the probability for a transition from state i to state j to occur, then the probability matrix $\mathbb{P}$ can be defined as:

$$\mathbb{P} = \begin{bmatrix} P_{1,1} & \cdots & P_{1,n} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,n} \end{bmatrix}$$

The entries of the transition matrix can be calculated according to: $P_{i,j} = \frac{T_{i,j}}{\sum_{k=1}^{n} T_{i,k}}$ where $T_{i,j}$ denotes the number of times a transition from state i to state j occurs.

2.2 Quadratic Programming

Quadratic programming is an algorithm used to solve optimization problems having a quadratic objective function, f(x). The objective function is to be minimized/maximized, subject to bounds and linear inequality and equality constraints.

The standard form for a quadratic optimization problem is:
$minf(x) = \{\frac{1}{2}x^T Hx + c^T x\}$

subject to the constraints:

$Ax \leq b$
$A_{eq}x = b_{eq}$
$lb \leq x \leq ub$

There are several different algorithms available to solve quadratic programming problems. Among the most widely used ones are the active-set, interior point and the trust region refelective algorithms. The two first ones solves optimization problems including all combinations of the previously mentioned constraints, meanwhile the latter one solves combinations of bounds and equality constraints. [08]

2.3 Dijkstra's algorithm

The optimization problem for Dijkstra's algorithm can be formulated as a set of nodes, which may be visited, at the expense of transition costs and given a starting node and destination node, find the path with least cost.

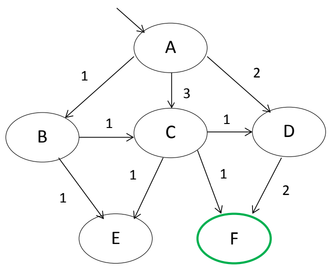


Figure 2.3.1: *Example of an optimization problem for Dijkstra's algorithm*

The nodes are the circles with the alphabetic notations $A, B, C, ...$, the node A is the starting node and the node F is the destination node. The lines between the nodes are transitions and the values at the lines are the associated cost for each transition.

Dijkstra's algorithm finds the optimal path by always searching in the path which have the lowest total cost, it is accumulating the cost for each transition and is therefore taking the total cost into account. For example, the relative cost for the transition $C \rightarrow F$ is 1 but the total cost $A \rightarrow C \rightarrow F$ is 4.

Another important feature is to always record the relations between the nodes when searching. For example, if a transition $C \rightarrow F$ is taken, F is then recorded as the child node to C. Given these relations, the algorithm can then backtrack from the destination node to the start node once the destination node is found.

The algorithm is also keeping track on which nodes it has visited, once a node has been visited, it is impossible to find a better path to that node at a later stage. Therefore, nodes which have been visited will not be added to the list containing all possible nodes to evaluate.

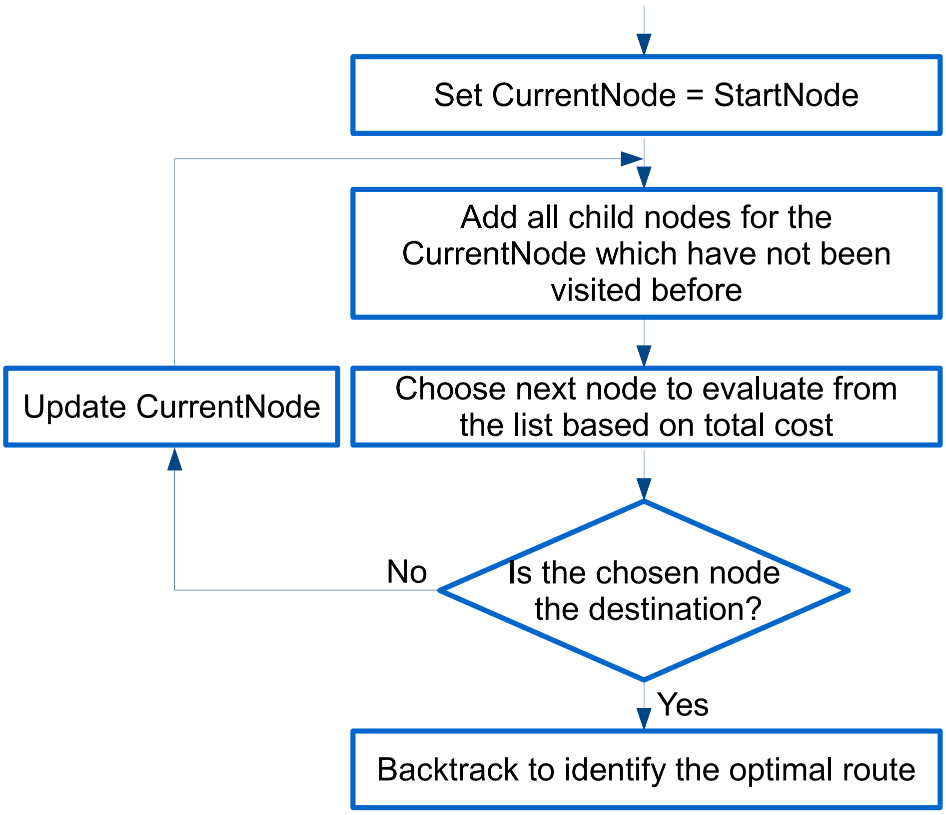
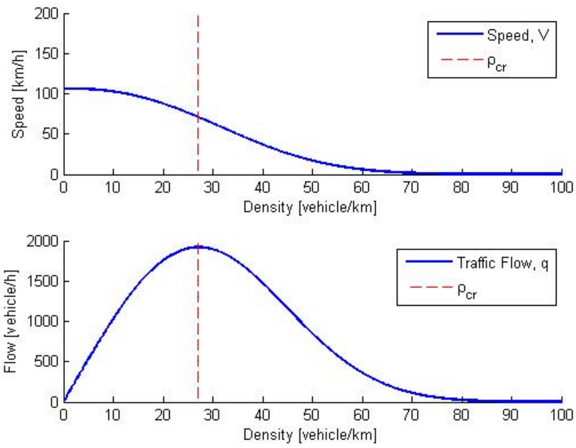


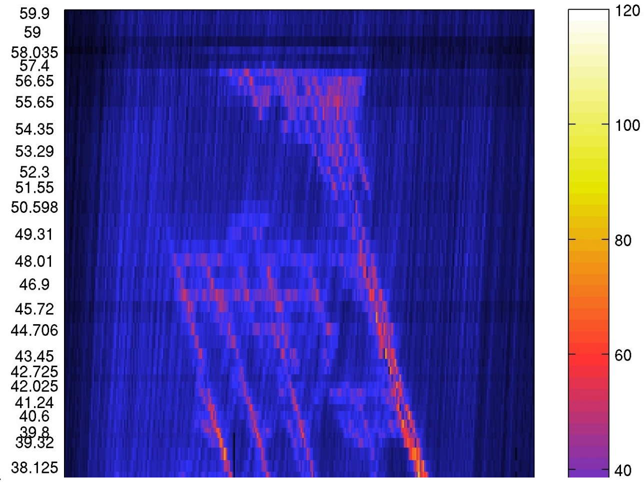
Figure 2.3.2: *Flow Chart for Dijkstra's algorithm*

2.4 Micro-/Macroscopic Traffic Modeling

There are many frameworks of how to model traffic and the traffic models are categorized as micro-, meso- or macro-scopic. Microscopic models have a high level of detail, the vehicles are distinguished and modeled individually as in Vissim. The macroscopic models does not distinguish the vehicles. The framework which was developed by P. Whitham [LW55] models the vehicles as a medium which passes the road with behavior which is similar to the fluid-dynamics, having quantities such as density [vehicles/km], flow [vehicles/h], space mean speed [km/h]. The concept developed by P. Whitham was extended with further improvements by Papageorgio [PB90], adapting the theory to its application. Measurements revealed effects of interaction between vehicles at higher speed and based on these findings, fundamental diagrams was suggested. The fundamental diagrams states that the density [vehicles/km] is influencing the average speed of the vehicles even more at high speeds.



(a) *Equilibrium speed function, showing the relationship between speed, density and flow.*



(b) *Density plot based on measurements.*

Figure 2.4.1

The fundamental speed diagram have been used to define the equilibrium speed function $V(\rho)$, which is shown at Figure 2.4.1a. The equilibrium speed function is defined as:

$$V(\rho) = v_{free} \exp\Big(-\frac{1}{a}\left(\frac{\rho}{\rho_{cr}}\right)^{a}\Big) \tag{2.4.1}$$

The equilibrium speed function indicates that there exists a critical density ρ_{cr} which maximizes the flow. A density $\rho > \rho_{cr}$ will reduce the flow.

The density plot in Figure 2.4.1b represents data collected on a road section in the Netherlands. The backward propagation of shockwaves which occur during congested traffic conditions are clearly visible in this graph. This means that when time evolves, the queue length is increased which in the figure is shown by the red density peaks moving upstream along approximately straight lines with negative slope.

Figure 2.4.1b also shows how cars are passing through the observed road section. A blue line pattern of forward propagation waves are visible due to the vehicles moving forward as time evolves. This section is heavily influenced by the authors' paper *Control Oriented Dynamic Speed Limit Design* [TK].

3 Methodology

3.1 Overview of methodology

A simplified description of the applied methodology is presented in Figure 3.1.1. Since the developed model generation application is of a stochastic manner, the quality of the input parameters strongly affects how realistic the generated models are. In order to achieve representative data, such as speed limits, geographical data and level of traffic, along the Swedish roads of today, data will be extracted from NVDB.

The extracted data can either be used directly as *model generation parameters* while generating models or be modified by the user if traffic models with other characteristics are to be generated.

In this project, a *sensitivity analysis* will be performed where the models will be generated while the model generation parameters are varied in a certain way, described in section 4.9. In this way, input parameters will be mapped to how they affect simulation results.

By use of NVDB, model generation parameters representing the situation of today for both freeways and urban roads in Sweden will be identified. For freeways, a road section between the cities of Gothenburg and Borås will be used. In the case of identifying parameters for urban roads, data extracted from NVDB along a route within the city of Gothenburg will be chosen.

While performing prediction, in order to achieve future drive cycles, the parameter sets describing today's situation will be modified according to predictions on upcoming changes in infrastructure and traffic conditions made by Trafikverket. Due to the chosen implementation, models for urban traffic and freeway traffic will be generated separately and composed into complete drive cycles according to specification from Volvo.

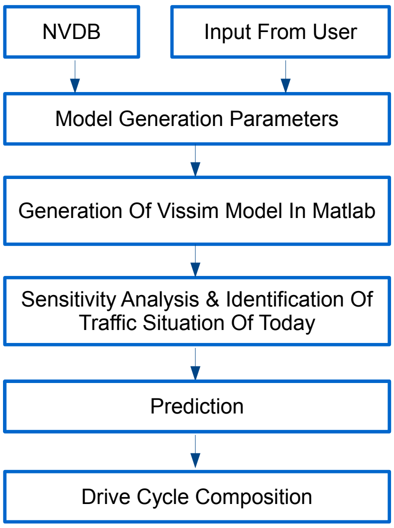


Figure 3.1.1: *General approach*

3.2 Assessment of infrastructure data

In order to generate realistic traffic models, an analysis of the national road database of Sweden (NVDB) will be performed. The outcome of the analysis will be a definition of how to stochastically generate traffic models. Patterns within the database will be captured and a set of parameters, describing the necessary characteristics of a route, will be defined. Another data of interest is the traffic situation along a predefined route, which is a mean value of the annual flow of vehicles within the database.

The database containing the swedish road net is structured with link elements, which consists of a set of coordinates. The order of the coordinates within a link corresponds to the direction of the link. Whenever there is a connection between two links, the end or start coordinates coincides. This is consistent and an intended implementation of the database [11].

A search algorithm can be implemented based on the assumption of coinciding coordinates whenever there is a connection between two links, finding a path between two links. Since it most likely exists many paths between two links, an optimization criterion should be stated, defining the optimal path. A general problem statement for the search algorithm can be expressed as given a set of links and transitions, find the path which has the lowest cost.

Dijkstra's algorithm solves this problem and finds the optimal path. Another alternative is the A* algorithm which also requires heuristics of the total cost to reach the destination link for all links. The benefit of the A* algorithm is the less amount of iterations before finding the optimal path. The amount of possible paths to reach the destination link is sometimes considerable high and the A* algorithm can solve the problem by not diverging from the optimal path when searching. There are conditions for the heuristics of the A* algorithm which must be fulfilled, otherwise the solution may not represent the optimal solution, i.e. the path with the lowest cost.

The time required to find the optimal path for Dijkstra's algorithm on an average modern computer for this application is considered to be low enough. The benefit of not relying on heuristics is a valid simplification.

Based on the geometry of the links and speed limit data, the cost may be expressed as travel distance, time consumption or speed limit. Depending on the properties of the desired route to analyse, the cost may be chosen differently (freeway, urban, etc.).

3.3 Sensitivity Analysis

The sensitivity analysis is investigating the correlation between parameters of the model and its response. For complex models it is often hard to analytically describe this relationship. An alternative is the experimental approach, to run simulations of the model with different parameter values and by means of statistical analyses determine the relationship.

The process of generating many sets of parameters and to run simulations for each set of parameter is known as Monte Carlo simulations. Due to limitations of simulation capacity it is impossible to achieve a significant amount of simulations within a reasonable time frame. Therefore, a linear parameter varying approach is more suitable. Range and resolution of all parameter values to include in the Sensitivity Analysis are defined. Then the parameters are varied in a deterministic way such that all possible combinations of parameter values are generated. The parameters chosen to vary, and the values for each parameter are decided with respect to the simulation capacity limitation.

4 Results

4.1 Model generation tool

4.1.1 Generate model process

While generating a model, a chain of processes are executed sequentially. Conceptually, Figure 4.1.1 shows the flow of how a model is created.

It all starts with stochastic generation of model data. This is done based on the specified input parameters, and at this stage, all information needed to build a Vissim model is created. The information is encapsulated in a struct called "*ModelDescription*" and covers the following properties:

- Geometrical data such as altitude and curvature.
- Vehicle properties for Volvo trucks, and vehicle compositions to use during simulations.
- Road characteristics such as road type and number of lanes, which are defined in the GUI.
- Specification of where to place generated traffic objects.

The *ModelDescription* struct now holds information about at which distance along the main road to place all traffic objects. Since they are generated in a stochastic way, it is very likely that some of them are to be placed very close to each other. Therefore, the next step is to redistribute the objects according to the placement algorithm described in section 4.3.

At the next step, the model description is converted into a struct, called "*VissimModel*". During this process, all Vissim specific objects needed to generate a Vissim model corresponding to the *ModelDescription* struct is generated.

At last, the input files to Vissim are created by use of a well sophisticated system. This process starts with a file representing an empty Vissim model which is containing all default settings in Vissim such as properties for the default vehicles, driver behavior parameters, evaluation parameters etc. For each Vissim object that needs to be created in order to build a generated model, a template file has been constructed. By use of a name convention, every object in the VissimModel struct uses one or more template to extend the empty model file and in this way, a complete Vissim model is built up.

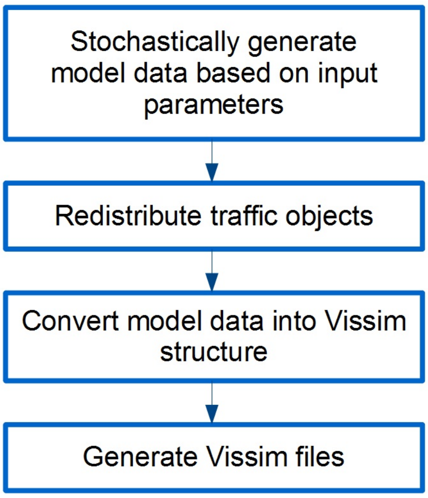


Figure 4.1.1: *Generate model flow*

4.1.2 Traffic Objects

To be able to automatically construct Vissim models, code to produce a number of different Vissim objects have been developed. Model characteristics described in *ModelDescription* are mapped into several different Vissim objects in the following way:

On-ramps

Each of the on-ramps in *ModelDescription* will give rise to several Vissim objects in the *VissimModel* struct. To model an on-ramp in Vissim, it takes that a new *link* is created and connected to the main road through a *connector*. The on-ramp link is assigned a *vehicle input* to simulate oncoming traffic. A *speed decision*, limiting the speed to the same level as the main road speed at where the on-ramp connects, is placed on the on-ramp link to affect the spawning vehicles. While entering the main road, oncoming traffic is affected by a *priority rule* causing them to yield to main road traffic.

Off-ramps

Off-ramps from the *ModelDescription* struct is, just like on-ramps, creating a new *link* and a *connector* to *VissimModel*. In addition to this, a *routing decision* is also needed to direct a certain fraction of the main road traffic to the off-ramp.

Intersections

Intersections are the kind of objects that creates most objects in *VissimModel*. To start with, four new *links* are created. Two of them leading towards the main road having *vehicle inputs*, and two leading away, making it possible for vehicles from the main road to leave the network. A total of six new *connectors* are created enabling new vehicles to either cross the intersection or join the main road traffic, and making it possible for the main road traffic to make a turn either to the right or to the left. 3 *routing decisions* are created in order to direct the traffic in a desired way. Vehicles entering the network through the vehicle inputs at intersections will, by use of two new *desired speed decisions*, be assigned a desired speed corresponding to the main road speed at where they connects to the main road.

The traffic flow and vehicle behavior at an intersection is also controlled by *priority rules* to avoid vehicles to interfere with each other. In addition to this, some intersections also have traffic lights to control the traffic.

Stops/Parking Lots

Since stops are important for drive cycles of hybrid vehicles, this has been implemented as a traffic object. Based on a user defined amount of average stops per km, λ_{Stop}, a number of parking lots are generated along the main road. The implementation is such that only Volvo trucks will use the parking lots, and all other vehicle types will continue to drive along the main road.

A stop in the *ModelDescription* struct, causes a new *link* to be created parallel to the main road. A *parking lot* is then placed on this link and two *connectors* are created to enable Volvo trucks to enter and leave the parking lot link.

4.2 Vehicle Parameters

Within Vissim, there are several different types of vehicles modelled. Each and one of them are specified by the following characteristics:

- Maximum acceleration
- Desired acceleration
- Maximum deceleration
- Desired deceleration
- Weight distribution
- Power distribution

Acceleration and deceleration are specified by three different curves within Vissim. See Figure 4.2.1 for an example of this. Vissim has two different ways of using this data depending on chosen vehicle category. One way to assign an acceleration profile to a vehicle is that based on a random number, generated from a normal distribution, linear interpolation within the interval of the three curves will define the acceleration profile to a specific vehicle. This procedure is used for all vehicle categories except HGV. For vehicles having the vehicle category HGV, the ratio between power and weight will decide where within the interval to define the acceleration profile.

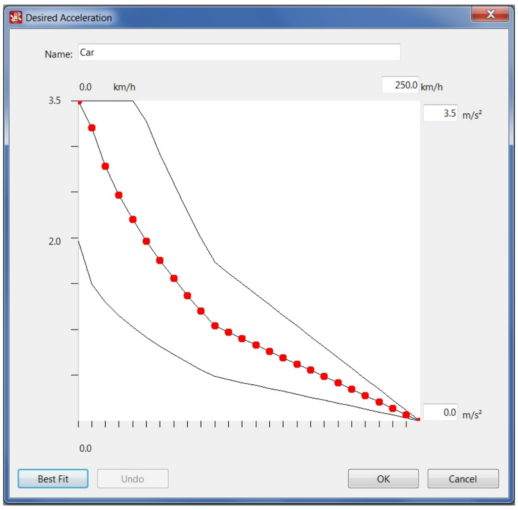


Figure 4.2.1: *Example of functions defining acceleration within Vissim.*

Since vehicle properties highly influences collected drive cycles from Vissim, a new vehicle type was defined for every Volvo Truck application covered in this project. To do so, the functions listed above had to be defined for every new vehicle application.

Logged data from 5 trucks representing the vehicle application *National Haul* was delivered from Volvo and used to identify acceleration profiles. At first, the logged speed data was filtered, see Figure 4.2.2, in order to smooth the curves and in that way reduce noise while deriving acceleration through numerical differentiation. The acceleration samples, as a function of speed and power/mass ratio, seen in Figure 4.2.3a was calculated in this way.

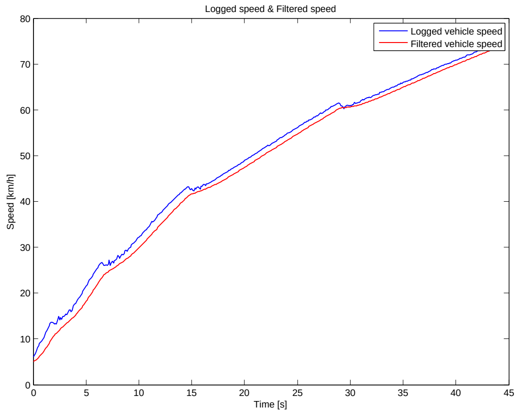
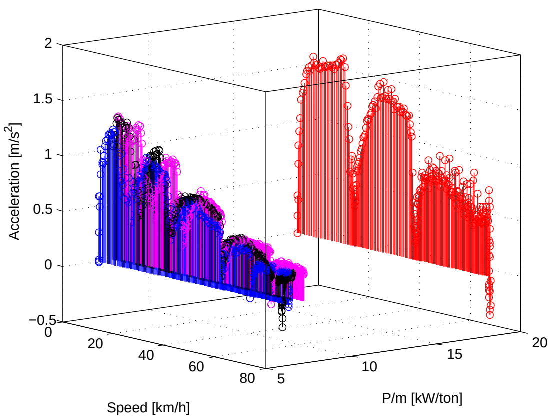
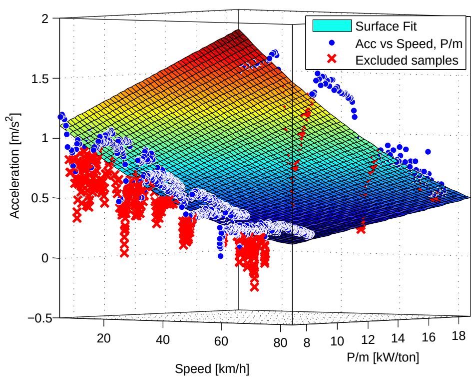


Figure 4.2.2: *Filtered speed*

Because of the speed filtering, derived accelerations for low speeds are significantly lower than the actual acceleration. Therefore, while fitting the surface seen in Figure 4.2.3b to the derived acceleration samples, a polynom of first order in P/M direction and second order in speed direction was used. In this way, accelerations for low speeds was kept at an appropriate level. The red crosses represents samples collected during gear shifting and were therefore excluded. The remaining samples, visualized as blue dots, were used to fit the surface which represents the acceleration over the whole speed, P/M ratio plane.



(a) *Acceleration samples vs Speed, P/M-ratio.*



(b) *Surface fitted to acceleration samples*

Figure 4.2.3

The vehicle parameter implementation is such that acceleration profiles for all types of Volvo vehicles origins from the identified surface. In combination with estimated data of typical acceleration values, presented in Table 4.2.1, acceleration profiles for *Distribution Truck* and *Refuse Truck* were defined.

The value representing a typical acceleration for *Haul Truck* was updated to the average surface value (1,0105 m/s^2) when $Speed \in [0\ 90] km/h$ and $P/M \in [(P/M)_{min}\ (P/M)_{max}]$.

Vehicle Type	Specified acceleration, $a^{specified}$ $[m/s^2]$	Power distribution $[kW]$	Mass distribution $[ton]$
Distribution Truck	1,2	175-375	8-26
Refuse Truck	1,2	190-330	15-26
Haul Truck	0,4 (1.0105)	300-550	20-40

Table 4.2.1: Typical Volvo vehicle parameters

The defined power and mass intervals in Table 4.2.1 leads to the following boundary values for the P/M ratios. One acceleration profile was defined for each and one of those P/M ratios in order to model the vehicles in Vissim.

Vehicle Type	$(P/M)_{min}$	$(P/M)_{mean}$	$(P/M)_{max}$
Distribution Truck	6,731	26,803	46,875
Refuse Truck	7,308	14,654	22,000
Haul Truck	7,500	17,500	27,500

Table 4.2.2: Minimum, mean and maximum values of the P/M ratio for different Volvo vehicle types.

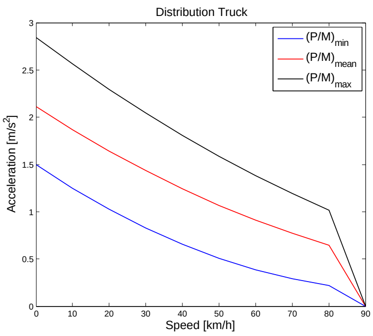
$$Let \quad i = \begin{cases} Distribution\, Truck \\ Refuse\, Truck \end{cases} \qquad and \;\; j = \begin{cases} (P/M)_{min} \\ (P/M)_{mean} \\ (P/M)_{max} \end{cases} \tag{4.2.1}$$

The acceleration profiles where then calculated according to:

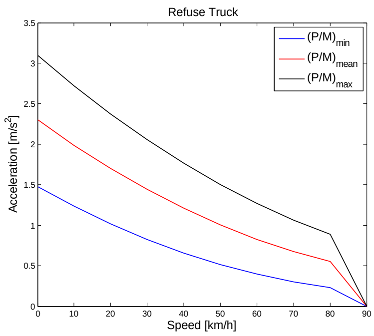
$$a_{i,j}(v) = \frac{\frac{a_i^{specified}}{a_{Haul}^{specified}} \cdot \bar{a}_{Haul,j}}{\bar{a}_{i,j}} \cdot a_{Haul,j}(v) \tag{4.2.2}$$

where $a_{i,j}(v)$ and $\bar{a}_{i,j}$ represents the acceleration vs speed profile and average acceleration respectively for vehicles of type i having the P/M ratio j.

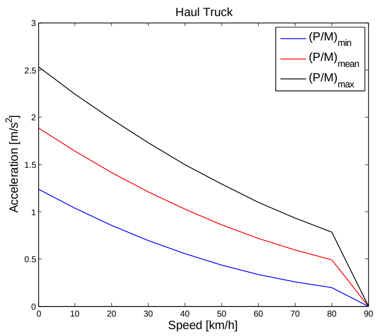
All types of Volvo trucks covered in this thesis have a software implemented speed saturation at 90 km/h which was taken into account. Achieved acceleration over speed profiles can be seen in Figure 4.2.4



(a) *Distribution Truck*



(b) *Refuse Truck*



(c) *Haul Truck*

Figure 4.2.4: *Identified acceleration vs speed profiles*

Concerning deceleration profiles for Volvo trucks, the logged data at hand was not sufficient to identify maximum and desired deceleration curves. Those profiles were instead achieved based on data from the default Vissim vehicle type *HGV* in combination with the previously mentioned defined mass intervals.

Deceleration profiles for Vissim's HGV vehicles are based on data collected in 1999 during the European research project CHAUFFEUR 2 [12]. Those profiles were linearly inter- and extrapolated as a function of the vehicle mass, and new deceleration profiles for min, mean and max mass values of each Volvo truck was identified.

4.3 Placement algorithm

Due to constraints within Vissim concerning the placement of traffic objects, such as intersections, on-ramps and off-ramps, a placement algorithm was developed. The placement problem arises if the stochastic model generation specifies that traffic objects should be placed too close to each other. In Vissim, every object needs to occupy a certain interval of the road in order to make sure that the traffic behaviour will be as expected. Example of troubles that could arise if this is not satisfied are vehicles missing making a turn at intersections or at off-ramps as well as achieving models having unrealistic infrastructure due to several traffic objects occupying the same space.

The placement algorithm redistributes traffic objects along the road in a way such that the Vissim constraints are satisfied. The rules that applies during redistribution are:

- Keep the sequence in which traffic objects occurs along the road
- Make sure that there is enough space between traffic objects
- All objects have to be placed within the generated road section

The problem of placing generated traffic objects in a way such that a certain set of constraints were satisfied was formulated as a quadratic optimization problem. The objective was to minimize the total distance objects were moved while making sure that all the above mentioned rules were followed.

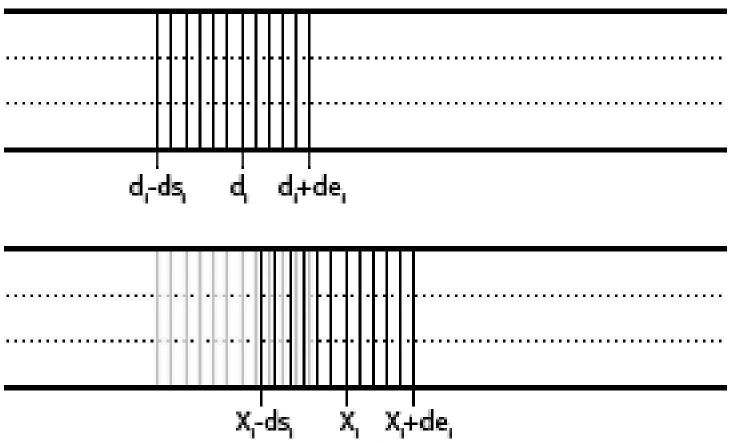


Figure 4.3.1: *Example of redistribution of a traffic object.*
d_i *= Distance to place object i at, before redistribution*
ds_i *= Distance upstream to reserve for object i.*
de_i *= Distance downstream to reserve for object i.*
x_i *= New distance to place object i at, after redistribution*

The standard function in Matlab for quadratic programming, Quadprog, was used to solve this optimization problem. The objective function was then formulated as: $f(x) = min \sum(d_i - x_i)$.

Avoidance of coinciding objects, assuring placement of objects within road boundaries as well as keeping the correct sequence of objects, were implemented as inequality constraints through the following expressions respectively:
$x_i + de_i \leq x_{i+1} - ds_{i+1}$
$0 < x_1 - ds_1,\ x_N < L - de_N$
$x_1 < x_2 < x_3 ... < x_N$

Since the problem at hand included combinations of constraints including inequalities, the interior-point convex algorithm was used during optimization.

4.4 Traffic Demand

The level of incoming traffic to a road, called *Traffic Demand*, significantly influences the traffic condition along the road, and strongly affects the degree of interaction between vehicles. In simulations, this input parameter is therefore an important factor to tune in order to achieve realistic traffic behaviour.

Traffic input to all simulations performed in this project origins from either measurement data collected by Trafikverket [11] or from NVDB. Representative traffic demands for the traffic situation of today was identified for both freeways and urban roads. Estimations of future traffic levels were then based on this.

It is assumed that all simulated trucks are driving in traffic conditions representing the average day time traffic during a time period between 07.00-16.00. To estimate the composition of different vehicle types during this time, data from NVDB was used where a small fraction of the registered trucks were changed to be Volvo trucks during simulations.

4.4.1 Freeway

For freeways, measurement data from Trafikverket was used to identify the traffic demand. Since the implementation is such that two different levels of desired traffic flow along the main road has to be assigned, two different measurement stations were used.

$Q_{UpperBound}$ represents the high traffic level, so the traffic demand estimation was in this case based on a measurement station located quite close to the city of Gothenburg, having a relatively high traffic flow. An annual average daily traffic, AADT, of 39 000 vehicles/day was identified and if driving between 07.00-16.00 with a traffic distribution according to Figure 4.4.1 a traffic flow of 2 400 vehicles/hour were calculated for $Q_{UpperBound}$.

For the lower traffic level, $Q_{LowerBound}$, a measurement station further away from the city was chosen. This gave rise to an AADT of 21 000 vehicles/day. Using the same hourly traffic distribution again, an average value of 1 300 vehicles/hour were calculated to represent the traffic flow between 07.00-16.00.

4.4.2 Urban Road

In the case of estimating traffic demand for urban roads, AADT from NVDB was used. When selecting a route representing urban traffic according to section 4.10, an upper and lower level for the AADT of approximetely 30 000 and 10 000 respectively were identified. Once again, the hourly traffic distribution in Figure 4.4.1 was used to calculate averaged upper and lower bound for the traffic flow during day traffic from 07.00-16.00. This gave $Q_{UpperBound}$ = 1 850 vehicles/hour and $Q_{LowerBound}$ = 650 vehicles/hour.

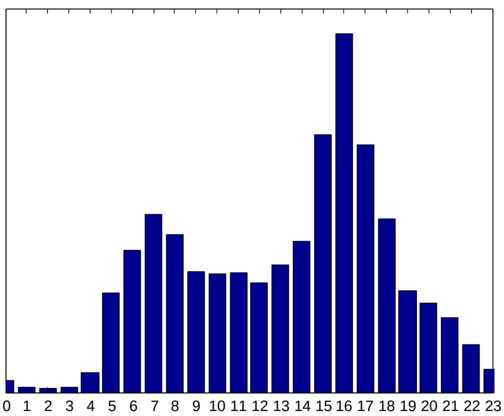


Figure 4.4.1: *Hourly distribution of traffic during one day.*

4.5 Traffic Assignment

The level of traffic flow along the main road is strongly affecting the collected drive cycle data. A high traffic demand may cause congestions and unwanted traffic situations, meanwhile a low traffic demand possibly will enable vehicles to drive unaffected by surrounding traffic.

To keep the traffic flow at an appropriate level along the whole main road, the Simulink model seen in Figure 4.5.1 was developed to balance the main road flow. This was accomplished by assigning traffic to the incoming and outgoing roads at on-ramps, off-ramps and intersections.

The model has the structure of a simple control system using negative feedback. As input to the model comes a sequence of numbers representing all nodes having oncoming and/or outgoing roads along the stochastically generated main road. When generating the Vissim model, an upper and lower limit for the desired flow on the main road is defined. All oncoming roads strives to reach the high traffic level, meanwhile outgoing roads is decreasing the traffic toward the lower limit. Therefore, the reference signal, denoted *"DesiredFlow"*, alternates between the user defined upper and lower limit depending on the previously mentioned sequence of connecting roads.

Every loop iteration calculates the new main road flow after a node with connecting roads has occurred. The Simulink block denoted *"Gain"* multiplies the number of incoming/outgoing roads (K) by a correction factor, meaning that the more oncoming roads there are at a certain node along the main road, the closer the traffic flow comes to the upper limit. The same thing applies to outgoing roads meaning that the more outgoing roads there are at a node, the closer the flow comes to the lower limit. The discrete transfer function simply adds/subtracts flow to the previously main road flow in order to achieve the new flow.

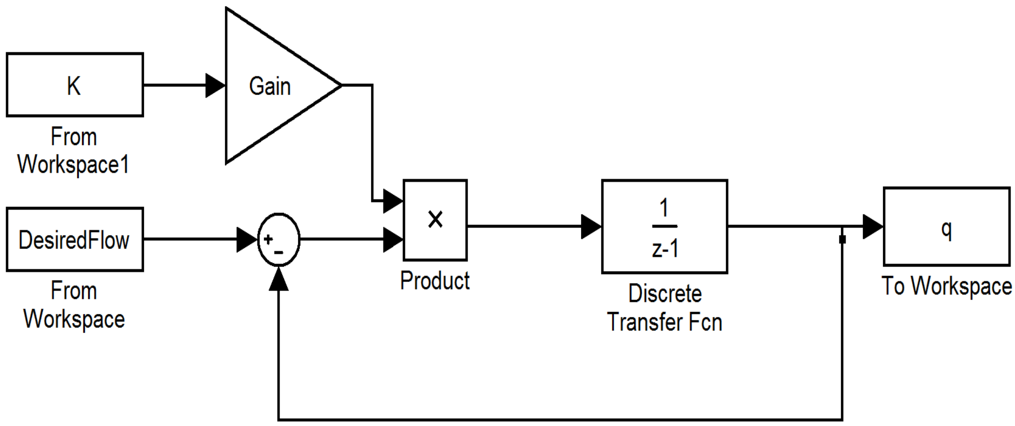


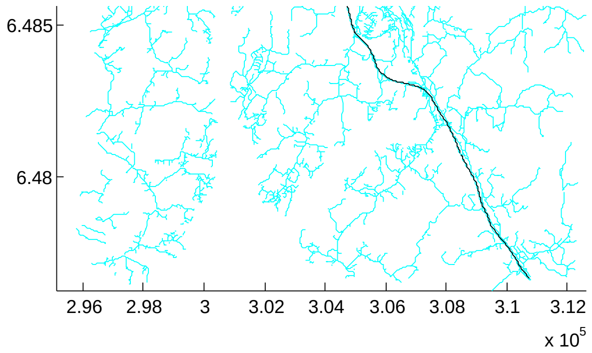
Figure 4.5.1: *Traffic assignment model*

4.6 Select Route And Data Extraction

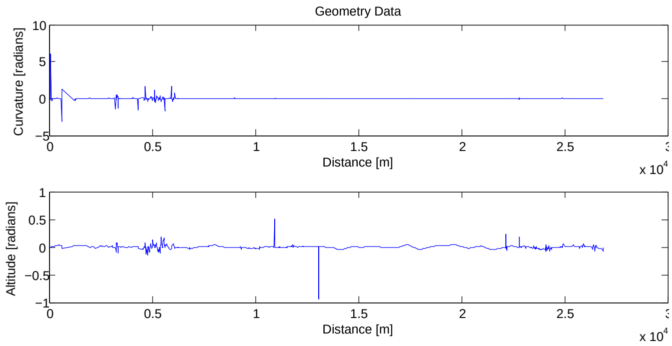
Dijkstra's search algorithm was successfully implemented in Matlab. When the user have selected start and destination link, a function based on Dijkstra's algorithm is called. The shortest, fastest, or path with the highest speed will be found. Data extraction along the route occurs when it is found.

The data extraction procedure begins with a flip of links which is in the wrong direction since the path could be in a opposite direction with respect to it's links. Since the altitude is not defined for all coordinates, it is linearly interpolated at these coordinates. All of the data samples are projected to the same distance vector $x = x_1, x_2, ..., x_i, ..., x_N$, and the step length between the samples are varying.

The geometry data along the selected route is extracted from the database, see Figure 4.6.1b. The geometry data is based on a linearly interpolation at the points where Z coordinates are not given. The altitude is the



(a) *The Selected Route*



(b) *Curvature and Altitude angles as a function of distance along the route*

angular slope and the curvature is an incremental angle in the X/Y-plane of the world coordinate system, both angles are in the unit [radians]. Positive curvature angle corresponds to a turn in the left direction, negative angle is in the right direction.

The extracted data shown in Figure 4.6.2 is not preprocessed except for the distance vector which is based on the interpolated Z coordinates. Whenever it does not exist any data for a coordinate along the route, the value will be undefined. Undefined values is not interpolated and therefore they show up as a discontinuity in the plots.

The speed limit data is extensive and it is rare to find undefined speed limit along the route. The speed limit data in Figure 4.6.2 is consistent with the selected route in Figure 4.6.1a. There are low speed limits at the beginning of the route and when it is on the freeway, the speed limit increases accordingly.

The unit of the traffic data is an annual average of vehicles passing over a day. The traffic data is also distributed between passenger cars and HGV. Traffic data is well defined at freeways, as seen in Figure 4.6.2, there are discontinuities at the beginning of the route where path have diverged from the freeway.

The last plot in Figure 4.6.2 represents the on- and off-ramps and it is based on the difference between the amount of incoming and outgoing links. Either an on-ramp, off-ramp or intersection is detected whenever this difference is not equal to zero, this is described at section 4.7.

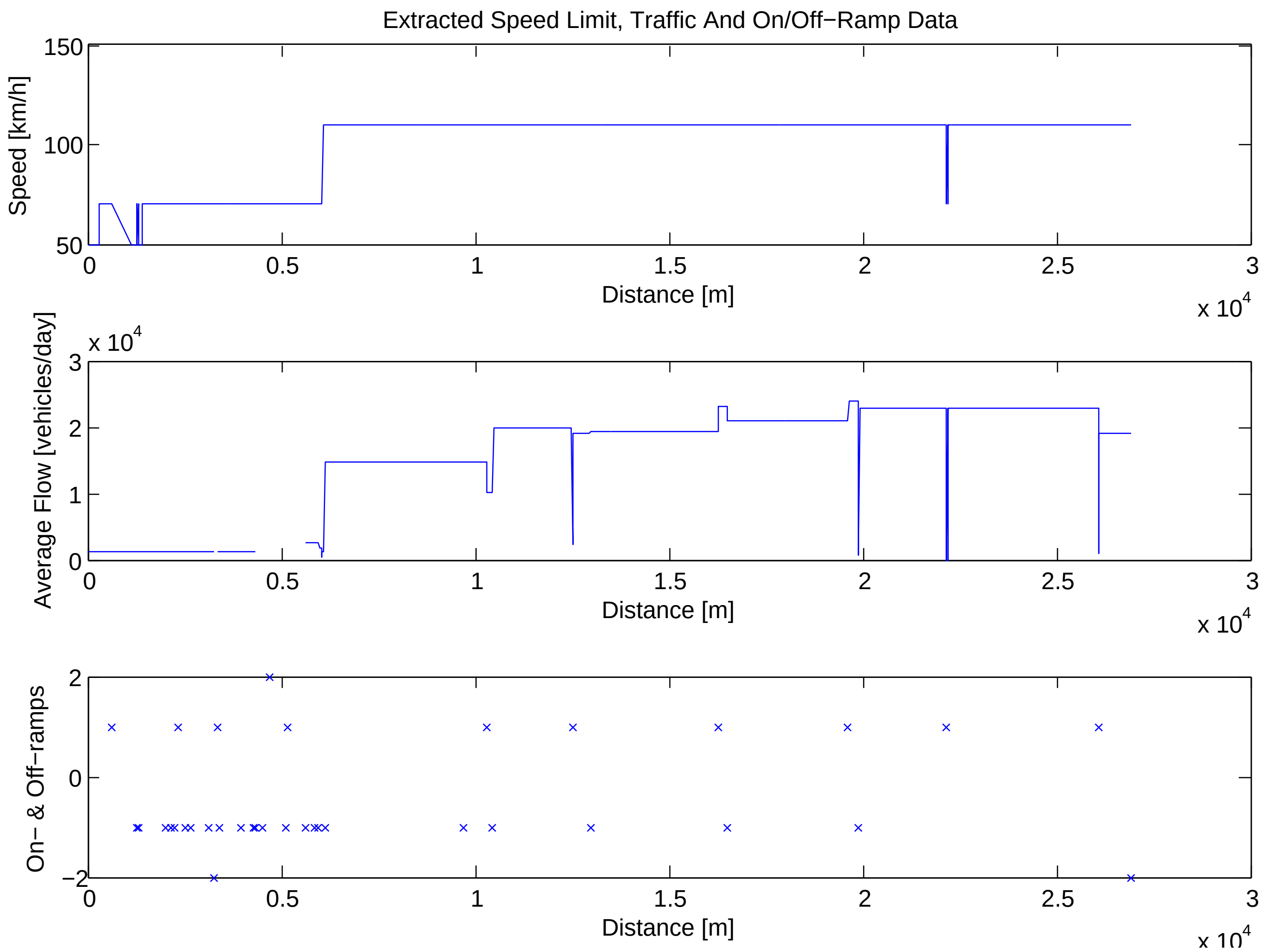


Figure 4.6.2: *Data extracted from a selected route*

4.7 Route Analysis

Auto-Regressive models are estimated based on the curvature and altitude. Since the distance vector x is not linearly spaced, it has to be interpolated. The resolution of the interpolation is increased until aliasing is not occurring. When the data set is interpolated an estimation of a 10th order AR-filter is performed with the default 'Modified Covariance Method' within Matlab. If we denote the curvature angle ϕ and the altitude angle θ, then the noise driven Auto-Regressive model can be defined as:

$$\begin{aligned}\varphi_k &= \sum_{i=1}^{10} a_i\varphi_{k-i} + \varepsilon_k, where\, \varepsilon_k \sim\ \mathcal{N}(\mu_{Curvature},\, \sigma^2_{Curvature})\\ \theta_k &= \sum_{i=1}^{10} b_i\theta_{k-i} + \delta_k, where\, \delta_k \sim\ \mathcal{N}(\mu_{Altitude},\, \sigma^2_{Altitude})\end{aligned} \tag{4.7.1}$$

The Gaussian noise ε and δ is the noise which generates the curvature and altitude, respectively. The parameters $a = (a_1, a_2, ..., a_{10})$ and $b = (b_1, b_2, ..., b_{10})$ is the polynomial parameters for the denominator of the filter's transfer function in descending order.
The intensity of the Gaussian noise is also estimated based on the low frequency gain of the filter, having the transfer function $H(z)$, and the spectrum of the extracted geometry data, denoted $\Phi(\Omega)$:

$$\sigma = \sqrt{\frac{\Phi(\Omega = 0)}{\Delta x\ |H(z = 1)|}} \tag{4.7.2}$$

The speed limit generation for a traffic model is done by the means of a Markov Chain. To account for the duration of the speed limit levels, the sequence for the Markov Chain estimation is done by performing a zero order hold interpolation of the extracted data. Undefined speed limit data values are zero order hold interpolated as well. After interpolation, the sequence have the discrete levels as the extracted data but with a fixed step length Δx, where $\Delta x = min(x_{i+1} - x_i), 1 \leq i \leq (N - 1)$.

The estimated Markov Chain will then have many self-loops and generate a large number of samples. Since the speed signs in Vissim is modeling the change of speed limit along the main road, the samples generated from this Markov Chain needs to be filtered with a flank triggering logic.

The extracted traffic data is used to estimate the distribution of passenger cars and HGVs. The annual average of vehicles passing per day along the selected route is not used to automatically calculate $Q_{UpperBound}$ and $Q_{LowerBound}$ which is used for traffic assignment along the main road. It is the responsibility of the user to specify appropriate desired flow on the main road and the plots at Figure 4.6.2 can be helpful for the user.

The extracted data which represents the difference between incoming and outgoing links can be used to estimate a distribution of how often on-ramps, off-ramps and intersection occurs.

The following interpretation of the difference between incoming and outgoing links $\Delta_{In/Out}$ is applied:

$$VissimTrafficObject = \begin{cases} Intersection\, With\, Decreasing\, Main\, Road\, Flow, & \text{if } \Delta_{In/Out} < -1\\ Off - Ramp, & \text{if } \Delta_{In/Out} = -1\\ On - Ramp, & \text{if } \Delta_{In/Out} = 1\\ Intersection\, With\, Increasing\, Main\, Road\, Flow, & \text{if } \Delta_{In/Out} > 1 \end{cases} \tag{4.7.3}$$

The implementation and description of the Vissim traffic objects is explained at subsection 4.1.2.

There is a clear pattern of the occurrences of on-ramps and off-ramps with regards to the sequence in Figure 4.6.2, whenever it occurs an off-ramp it is a high chance that the next traffic object is an on-ramp and vice versa. Therefore, the pattern is modelled with a Markov Chain which decides whether a sample is an on-ramp, off-ramp or intersection. The relative distance between the samples for these objects are considered to be beta distributed. The properties of the beta distribution is convenient in the sense that it's interval is finite, having the interval $[0;1]$, and it's density may have an intensity at low and high values.

If we denote N observed distances $d = d_1, d_2, ..., d_N$, where $d_i = x_{i+1} - x_i$, then the implementation of the beta function can be defined as:

$$
\begin{aligned}
K_{Intersections} &= max(d) \\
d_\beta &= d/K_{Intersections} \\
d_\beta &\sim \mathrm{Beta}(\alpha, \beta),\ where\, d_\beta \in [0;1]\, is\, the\, normalized\, distance
\end{aligned}
\tag{4.7.4}
$$

The scaling factor $K_{Intersections}$ is used to convert the samples generated by the beta function into relative distances $d = d_1, d_2, ..., d_N$ and vice versa for estimation of the beta function.

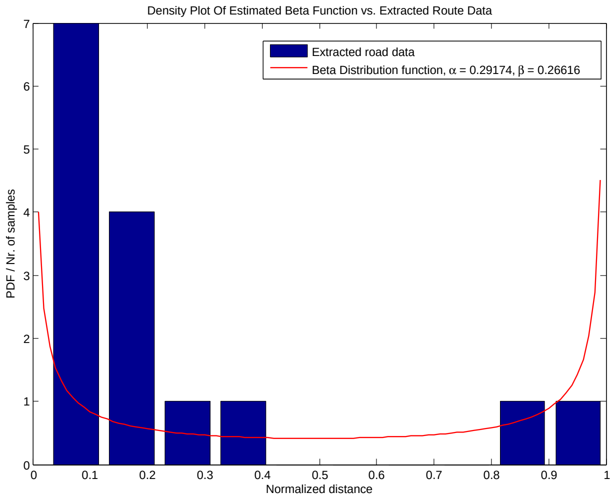


Figure 4.7.1: *Comparison of probability density function with extracted data from database*

The extracted data which is compared with the estimated beta distribution in Figure 4.7.1 is taken from a freeway. The extracted data is the normalized relative distance between occurrences of $\Delta_{In/Out} \neq 0$, a normalized distance of 1 corresponds to the highest observed distance.

4.8 Simulation Process

Once a model with vehicle characteristics are generated and all of the necessary files are written to a folder, an application developed in C++ will perform the simulation. The application is executed within Matlab with run commands. The run commands consists of search paths to the where the model files resides, where to save the simulation results and how many simulation iterations the application should run.

The simulation application is reading the following data from Vissim for each simulation iteration:

- Travelled distance for all Volvo vehicles [m]
- Speed for all Volvo vehicles [km/h]
- X,Y and Z coordinates for all Volvo vehicles [m]
- Density for all segments of the main road [vehicles/km]
- Average Speed for all segments of the main road [km/h]
- Traffic Flow for all segments of the main road [vehicles/h]

Vehicle ID and spawn time is recorded whenever a new Volvo vehicle is found by the application. The lengths of the segments are included in the Vissim model and are read by the simulation application at the start up process.

The vehicle, main road and segmentation length records are stored within different text files. The format of the text files are convenient for Matlab and it is easy to extend with more records if necessary.

The acceleration is estimated by means of numerical derivation of the acceleration in Matlab.

The density, average speed and traffic flow for all segments may be plotted as a function of time and space. The spawn time of all vehicles may be used to exclude those that enters the main road before steady state of traffic flow has occurred.

4.9 Sensitivity Analysis

4.9.1 Specification of the Linearly Varied Parameters

The selection of parameters to vary for the Sensitivity Analysis is based on the expected effect on the response. The parameters chosen to vary is listed in Table 4.9.1.

Parameter description	Values
Curvature, std. deviation of noise, $\sigma_{Curvature}$	[0, 0.025]
Altitude, expected value of noise, $\mu_{Altitude}$	[-0.02, 0, 0.02]
Intersection distances, scaling factor, $K_{Intersection}$	[4000, 7000]
Stop intensity, amount of stops per km λ_{Stop}	[0, 0.25]
Traffic demand, expected flow at main road $Q_{Desired}$	[2000, 4000]
Speed limits, markov chain selector, S	[1 2]

Table 4.9.1: Linear Parameter Varying Specification

The parameters which are not varied during this analysis is constant and based on a typical freeway in Sweden. The parameters $\sigma_{Curvature}$, $\mu_{Altitude}$, $K_{Intersection}$ and λ_{Stop} are described at section 4.7. The parameter $Q_{Desired}$ is defined as:

$$\begin{aligned} Q_{UpperBound} &= 1.2 * Q_{Desired} \\ Q_{LowerBound} &= 0.8 * Q_{Desired} \end{aligned} \tag{4.9.1}$$

$Q_{UpperBound}$ and $Q_{LowerBound}$ is configuration parameters for the traffic assignment process, described at section 4.5.

The Markov Chain selector S is choosing among 2 different Markov Chains. The first Markov Chain is estimated based on a selected route in the city of Gothenburg. The second Markov Chain is estimated based on a selected route between two major cities in Sweden, Gothenburg and Borås.

4.9.2 Simulation Results of The Linearly Varied Parameters

The parameters chosen to vary and the amount of levels for each parameter results in 96 Vissim models to simulate. The models were successfully simulated and for each simulation, data for all Volvo vehicles as well as macroscopic data along the route was logged. Statistical analysis of the macroscopic and Volvo vehicle data was performed in order to define the response as a scalar value.

Since the model generation based on a set of parameters is a stochastic process, the result of a simulation may not necessarily meet expectations due to this behaviour.

There is an intensity of the mean speed for all vehicles at the typical speed limit values 30,50,60 and 90 [km/h]. It is reasonable since the behavior of the driver model within Vissim [Wie91] is such that the vehicles strive to achieve a desired speed. The desired speed of the vehicles is changing everytime it passes a speed limit

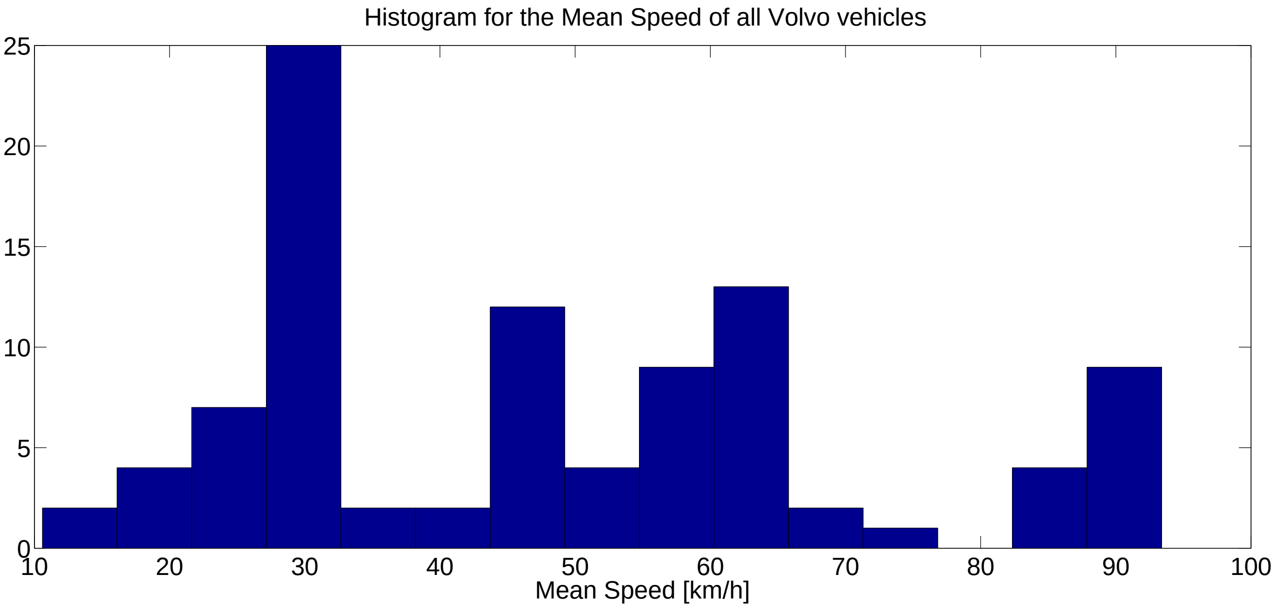


Figure 4.9.1: *Histogram of the Mean Speed of all Volvo vehicles for all simulations*

sign and the new value is defined by a distribution function. The distribution function for the desired speed is the default function in Vissim.

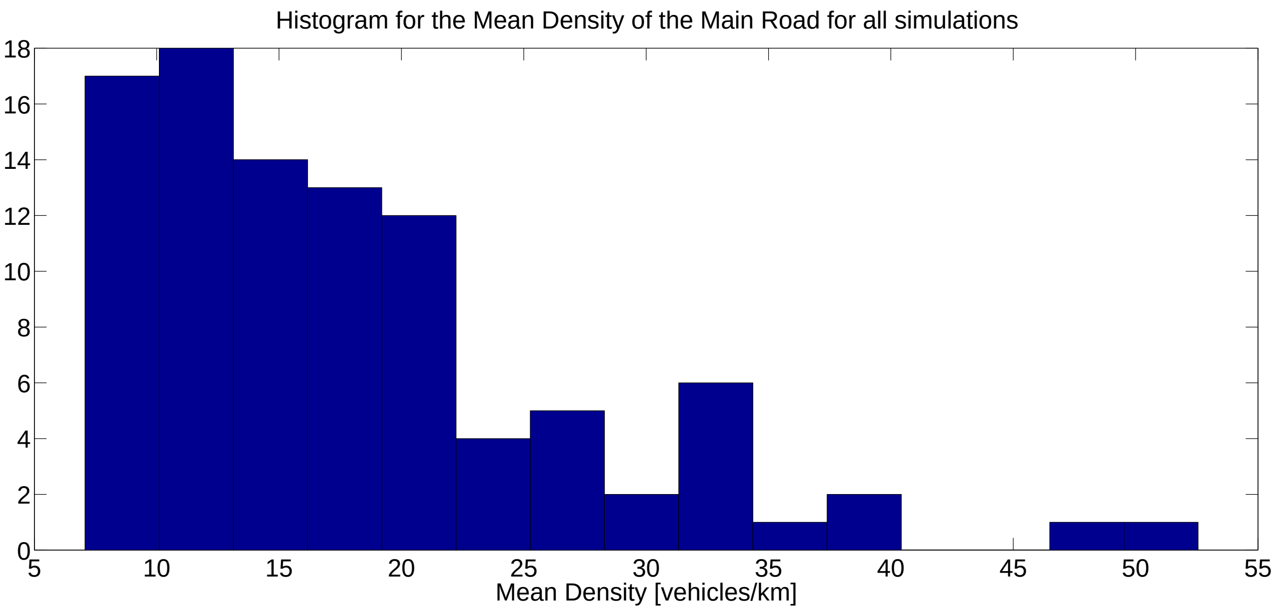


Figure 4.9.2: *Histogram, illustrating the simulation results for the mean density of the main road.*

There is an intensity of simulation results having low mean density in the range of 7-20. There are few simulation results with mean density around 50 [vehicles/km].

Parameter description	Volvo Vehicles' Mean Speed	Main Road's Density
Curvature, std. deviation of noise, $\sigma_{Curvature}$	No effect	No effect
Altitude, expected value of noise, $\mu_{Altitude}$	-	Unknown
Intersection distances, scaling factor, $K_{Intersection}$	+	-
Stop intensity, amount of stops per km λ_{Stop}	Unknown	-
Traffic demand, expected flow at main road $Q_{Desired}$	-	+
Speed limits, markov chain selector, S	+	Unknown

Table 4.9.2: Parameters effect on volvo vehicles' mean speed and main road's density

The effect of the parameters on the simulation result is shown in Table 4.9.2. The table is based on evaluation of the settings which results in the 3 highest and lowest response with respect to mean speed of volvo vehicles or mean speed of main road, shown at Appendix C as a set of Pareto charts. A negative or positive effect is defined whenever the parameter appears consistently with low or high value at the corresponding observed responses in the Pareto charts. The effect of a parameter is unknown if there are no clear correlation between its value and the responses. This is also the case for $\sigma_{Curvature}$ but there are documentation which proves that it has no effect since the driver and vehicle model is one dimensional. The opposite contribution with respect to Volvo vehicles' mean speed and density of the main road is expected based on the flow equation $v = q/\rho$, where v, q and ρ is the space mean speed, flow and density, respectively.

4.10 Definition of present traffic situation

The selected route for estimation of the model generation parameters is consistent with the validation data for freeway model generation. The urban model generation parameters is estimated based on a route going through Gothenburg with the least amount of travel time as search criterion for Dijkstra's algorithm.

The complete specification of the parameter values received from the *Route Analysis* based on the routes previously described is presented at Appendix B.

4.11 Macroscopic simulation results

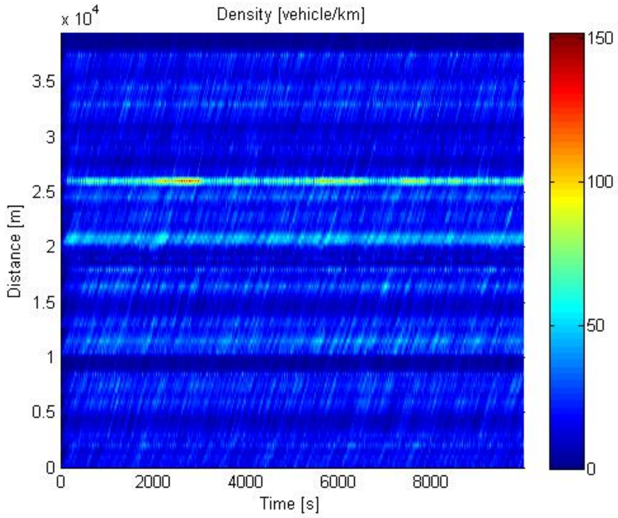
The present traffic situation and vehicle properties needs to be modelled and validated in order to perform a prediction. Since the model generation and vehicle properties is based on measurements from the real world, the parameters which are considered to be reliable should not be changed in order to have a good fit with validation data. The validation data is measured between Gothenburg and Borås, Sweden.

Three models for each vehicle type and traffic environment was generated.

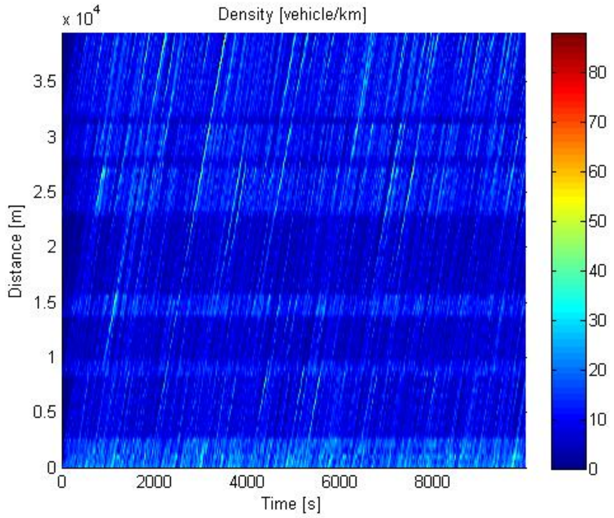
The density, flow and average speed function surfaces illustrates the traffic situation within Vissim for which the Volvo vehicles have been subjected to.

The density surface for urban traffic, which can be seen at Figure 4.11.1a, shows the effect of traffic lights as a periodic congestion over time at a distance of 2.6 km. The timing of the traffic lights and the traffic demand is such that the congestion is fading rather than evolving. The average speed surface for urban traffic, which can be seen at Figure 4.11.1c, is consistent with the speed limit levels, i.e. the states (30,50,70,90) of the *Speed Limit Markov Chain.* No occurence of 90 [km/h] as speed limit is a reasonable result based on the probability matrix of the *Speed Limit Markov Chain*, having a low transition probability to 90 [km/h]. The traffic flow in Figure 4.11.1e is consistent with the desired flow values 650, 1850 [vehicles/h] as lower and upper bound, respectively, for the traffic assignment .

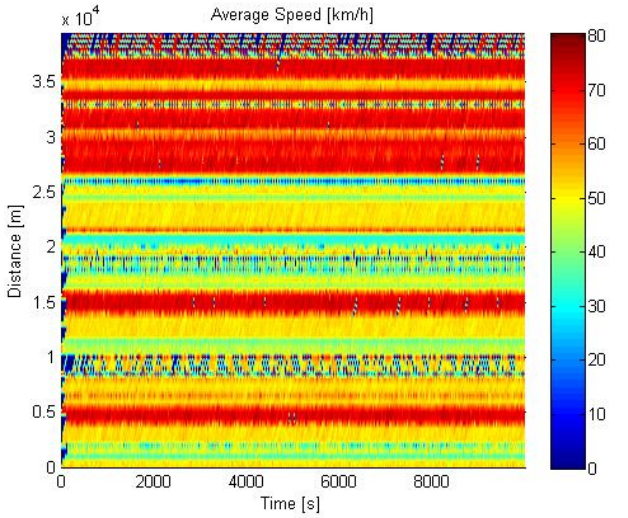
The density surface for the freeway traffic, which can be seen at Figure 4.11.1b, shows no congestions and it is steady after approximately 500 seconds. The average speed in Figure 4.11.1d is at around 100 [km/h] over the majority of the main road which is a reasonable traffic situation at a freeway with constant traffic demand. Based on Figure 4.11.1f, the flow at the beginning of the main road is at the highest level of roughly 2000 [vehicles/h]. The configuration parameters for traffic assignment are 1300, 2400 [vehicles/hour] as lower and upper bound, respectively. The flow is satisfied within a reasonable tolerance with respect to $Q_{UpperBound}$ and $Q_{LowerBound}$.



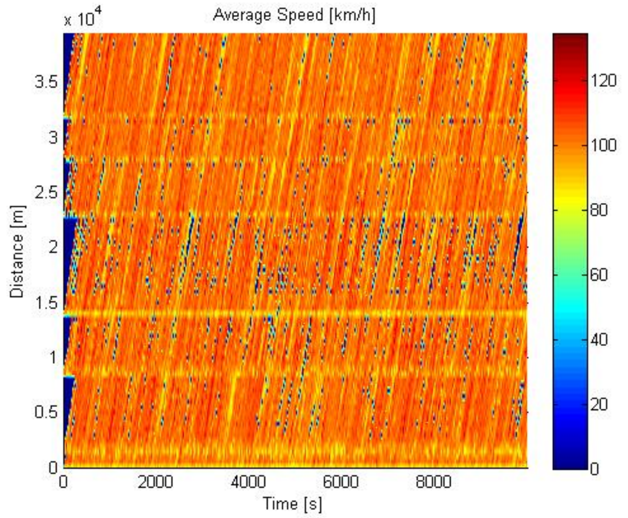
(a) *Density - Urban*



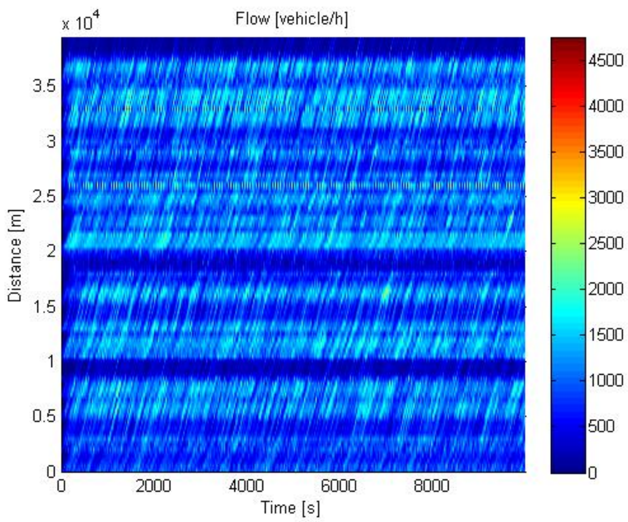
(b) *Density - Freeway*



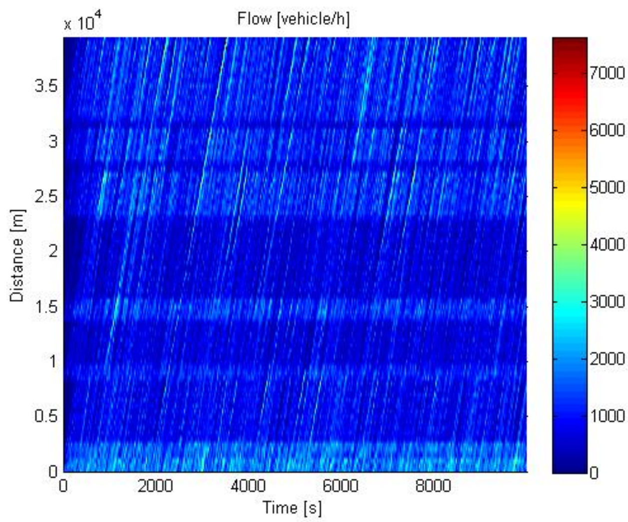
(c) *Average Speed - Urban*



(d) *Average Speed - Freeway*



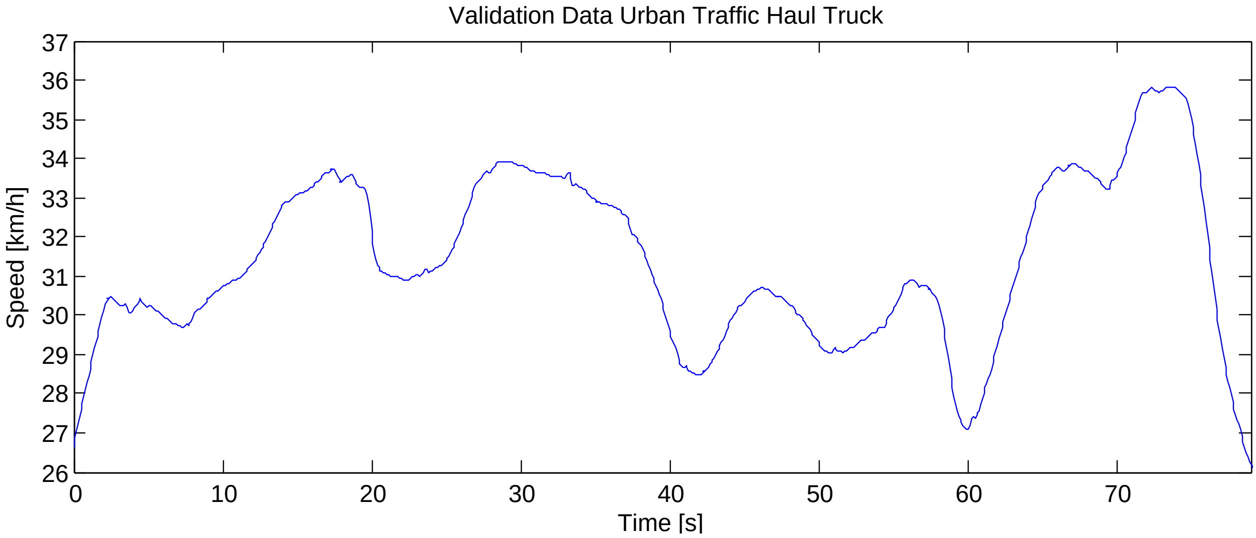
(e) *Traffic Flow - Urban*



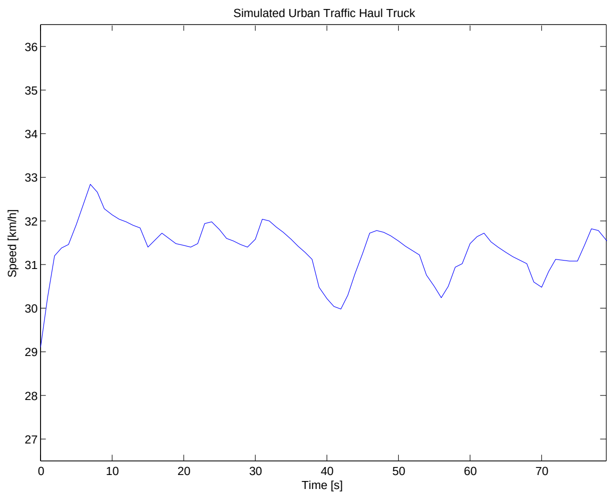
(f) *Traffic Flow - Freeway*

Figure 4.11.1: *Macroscopic data for present simulation of Haul Truck*

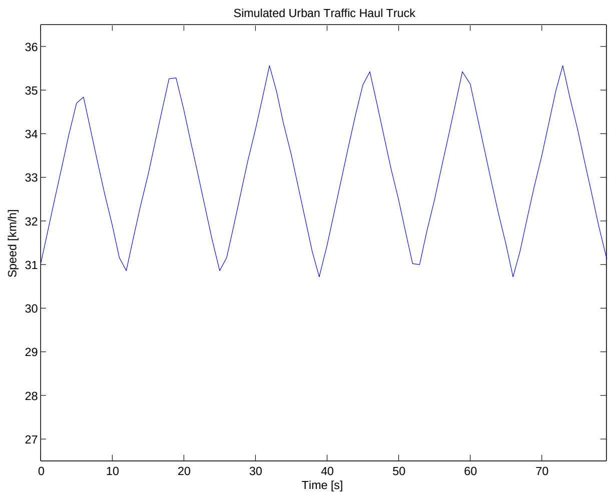
4.12 Validation of Urban Speed Profile



(a) *Speed - Urban Validation Data for Haul Truck*



(b) *Speed - Simulated Urban Traffic for Haul Truck*



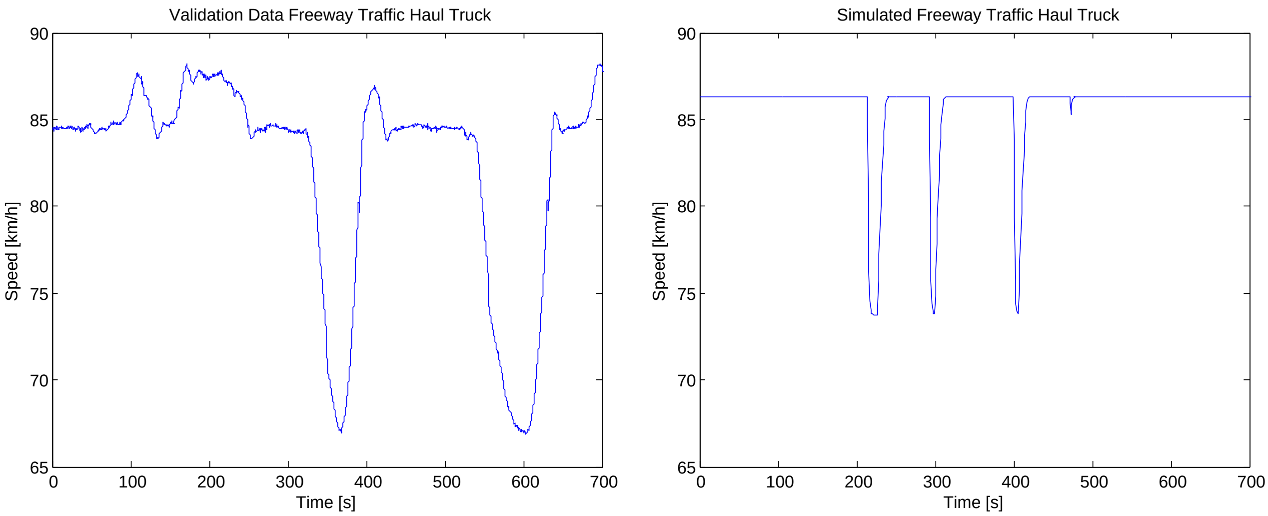
(c) *Speed - Simulated Free Flow Urban Traffic for Haul Truck*

Figure 4.12.1: *Comparison of Speed Profiles for Haul Truck in Urban Traffic*

The time and speed axes of all the plots of Haul Truck profiles in Figure 4.12.1 are set to be within the same interval. The validation data in Figure 4.12.1a is captured within Gothenburg and the exact location is undefined but it is considered to represent a typical urban traffic scenario. The simulation of Haul Truck in urban traffic in Figure 4.12.1b is in an environment which represents the present, based on the previously described route analysis in section 4.10. The characteristics of the simulation under normal condition in urban traffic is similar to the validation data. There is a difference of the amplitude of the oscillations, the simulated amplitude is 3 [km/h] and the amplitude of the validation data is roughly 5 [km/h]. The centre of the oscillations are time varying for the validation data which is not the case for both of the simulated profiles. The free flow urban simulation of Haul truck, which can be seen at Figure 4.12.1c, has a clear pattern which reminds of a triangular wave. The period is roughly 10 seconds and it is not time varying.

The dynamics of the Wiedemann 74 model is crucial in order to simulate realistic drive cycles in Urban traffic. The comparisons in Figure 4.12.1 may not be representative since the validation data is not properly defined. The driver model is describing the dynamic relationship between the acceleration and the distance to the next vehicle, subject to a constraint which is described by the $a(v)$ function described at section 4.2. Neither the distance to the next vehicle, nor the theoretical $a(v)$ for this particular Haul truck, are known and therefore it is not possible to do further development of the driver model based on this analysis. The free flow characteristics of the simulated Haul truck is troublesome since it could lead to cycle beating. The characteristics of the simulated Haul truck in normal traffic is satisfying but the centre of the oscillations being time invariant is explained by the assumption that the driver always strive to achieve a desired speed which is constant. It could be that this is not the case, the driver may strive to achieve a certain desired speed but the driver's perception of this speed may be varying over time.

4.13 Validation of Freeway Speed Profile



(a) *Speed - Freeway Validation Data for Haul Truck* (b) *Speed - Simulated Freeway Traffic for Haul Truck*

Figure 4.13.1: *Comparison of Speed Profiles for Haul Truck in Freeway Traffic*

The validation data from freeway traffic conditions, which can be seen at Figure 4.13.1a, have some measurement noise but there are some small fluctuations which could be due to unknown dynamics or disturbances. The temporary speed increase in the beginning of the speed profile could be during an overtake. The speed is immediately decreased when the peak is reached and the scenario is only 20 seconds long. None of these transient behaviour may be found in the speed profile for simulated Haul truck in freeway environment, see Figure 4.13.1b. The vehicle is only overtaking if the speed difference with the vehicle in front is large enough. The majority of the other vehicles are passenger cars and their speed is higher than the Haul truck. It is of importance to have a realistic distribution of vehicle types and traffic density. The speed drops in the simulated data is consistent with the vehicle properties in section 4.2. The driver model is decelerating at full capacity until the lower speed level is reached, the acceleration is also at its maximum level until the original speed is reached. The speed drops in the validation data have a varying deceleration, the deceleration is decreasing until the lower speed level is reached. The acceleration have a overshoot which does not exist in the simulation data.

4.14 Prediction

The prediction is based on assumptions of how the infrastructure and traffic situation will change by 2030. The authority responsible of the infrastructure in Sweden, Trafikverket, have established official prognoses [al13b] and [al13a]. The prognoses are extensive and all of the assumptions are presented. The prognoses are based on simulations of the The Swedish National Travel Demand Forecasting Tool (SAMPERS). The prognoses suggests an individual increase of traffic for each vehicle type. The conversion of present traffic demand parameters to prediction parameters is based on:

- Cars will increase by 34 %
- Buses will increase by 5 %
- Trucks will increase by 57,5 %

The prediction of number of truck in year 2030 is assuming that loading capacity for trucks will not change during this time.

In addition to this, the prediction parameters are set to decrease freeway speeds from 110 km/h to 100 km/h. This prediction is based on measurement data seen in Figure 4.14.1 which shows a decrease in average speed over the last decade.

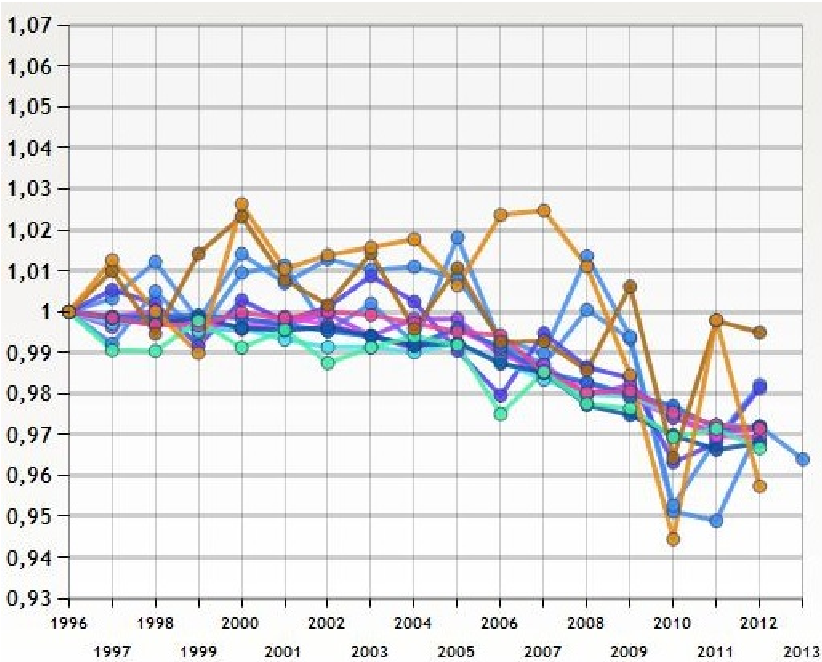


Figure 4.14.1: *Evolution of average speed on Swedish roads during 2006-2013. Each colored curve represents measurements collected during a specific month. This graph is provided by Trafikverket.*

4.15 Drive Cycle Composition

The drive cycles consists of speed, altitude, distance and time history. Since there are many simulations and for each simulation, there are many vehicle records, a selection of a representative vehicle record needs to be defined. An exclusion of vehicles which have spawned before steady state (500 seconds) and those which have not passed through the main road is implemented as well.

The vehicle types which are covered in this project are described at section 1.2 and based on the application of the vehicle types, the specification with fractions of urban and freeway traffic conditions can be seen at Table 4.15.1.

Vehicle Type	Urban [%]	Freeway [%]
Distribution Truck	56.5	43.5
Refuse Truck	74	26
Haul Truck	12.5	87.5

Table 4.15.1: Specification of the traffic environments for the vehicle types

The fractions are defined as percentages over a distance. A freeway-urban-freeway pattern of the drive cycles is assumed for all vehicle types.

The distribution of urban and freeway traffic conditions for a vehicle type is satisfied by means of concatenation of simulation results from both urban and freeway traffic conditions. This is done after the selection of a representative vehicle record. Segments are graphically selected among the representative vehicle record for both urban and freeway simulations. In order to concatenate the segments of urban and freeway simulation data without any discontinuities, a simulation of full acceleration/deceleration is performed in Matlab based on the vehicle properties $acc(v)$ and $dec(v)$. If a segment i with final speed v_N^i, distance d_N^i and altitude z_N^i is concatenated with the next segment $i+1$, having initial speed v_0^{i+1}, then the simulated speed $\hat{v}$, distance vector $\hat{d}$ and altitude vector $\hat{z}$ may be defined as:

$$\begin{aligned}
a(v) &= \begin{cases} acc(v), & \text{if } \; v_N^i \leq v_0^{i+1} \\ dec(v), & \text{if } \; v_N^i > v_0^{i+1} \end{cases} \\
\hat{v}_0 &= v_N^i \\
\hat{v}_{t+1} &= \hat{v}_t + \Delta t * a(\hat{v}_t) \\
\hat{d}_0 &= d_N^i \\
\hat{d}_{t+1} &= \hat{d}_t + \Delta t * \hat{v}_t \\
\hat{z}_t &= z_N^i \\
& 0 < t < T, \, where\, T\, is\, such\, that\, \hat{v}_T = v_0^{i+1}
\end{aligned} \tag{4.15.1}$$

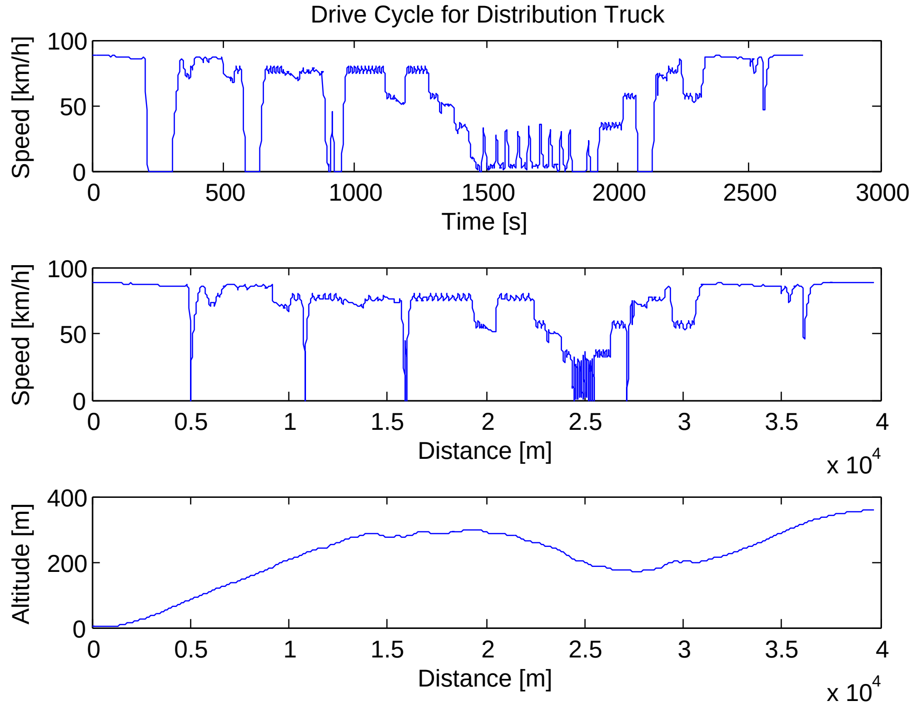
The simulation of the speed interval $[v_N^i, v_0^{i+1}]$ is during the relative time interval $0 < t < T$. The simulation result may be concatenated between the segments i and $i+1$ with a few modifications. It is of importance to keep the amount of transitions between segments as low as possible since the assumption of max acceleration/deceleration is having an impact on the result.

Simply put, the predicted drive cycles in Figure 4.15.1 are based on the following:

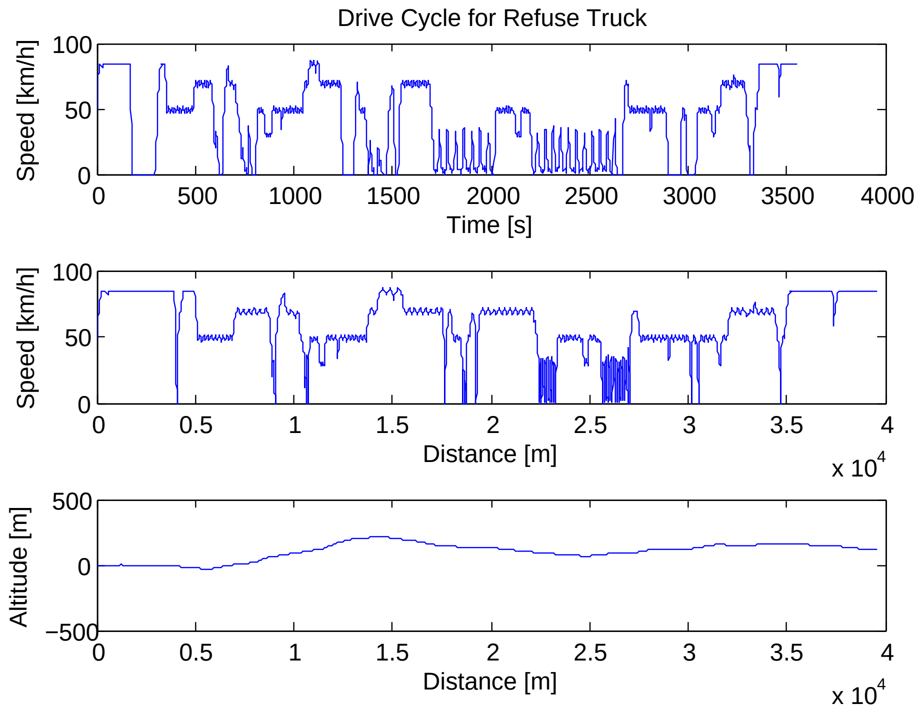
- Wiedemann driver model within Vissim, described at section 1.4.
- Analysis of acceleration profiles to define the vehicle properties, described at section 4.2.
- Route analysis to define the present traffic situation, described at section 4.10.
- Generation of Vissim model, described at subsection 4.1.1.
- Prognosis of present traffic situation, described at section 4.14.
- The drive cycle composition, described at section 4.15.

The simulation of the speed profile at the transitions between the urban and freeway simulation results is consistent with the vehicle properties. The altitude is constant during these intervals and it is properly concatenated with the segments. An expected result of this implementation can be seen at Figure 4.15.1c, there is a jerk at the first transition from freeway to urban traffic conditions in the altitude profile. The jerk is considered to be within acceptable tolerance for all of the predicted drive cycles.

The transient behaviour of the drive cycles is validated at section 4.12 and section 4.13. There are drive cycles which are currently being used and they may be used as evaluation to some extent for the predicted drive cycles Figure 4.15.1. The drive cycles that are currently being used is not for each vehicle type, they are divided based on environment. The resolution of the current drive cycles are poor but comparisons such as stop frequency, stop time and speed levels is possible. The stop frequency of the current freeway drive cycles are nearly 0.05 [stops/km] and its stop time is varying between 5 and 15 seconds. The predicted drive cycles have different settings for the stop frequency and since the length of the drive cycles is finite, the stop settings may not be seen in the drive cycles. The stop settings of the vehicle types are varying and they are not based on the current drive cycles but rather its application. The setting of 0.02, 0.033, 0.0033 [stops/km] for Distribution, Refuse and Haul Truck, respectively on freeway, is considered to be reasonable. The expected stop time setting of 2 minutes is quite different from the current drive cycles but it is based on the assumption of representing the drivers need of a break. The stop time is also considered to not be of importance for the use of the drive cycles. The predicted drive cycle for Haul Truck consists in majority of freeway simulation result and the setting for its stop frequency is low, therefore there are not so much transients. It is wrong to assume that all stops in the current drive cycle should be modelled with parking lots and therefore it is hard to

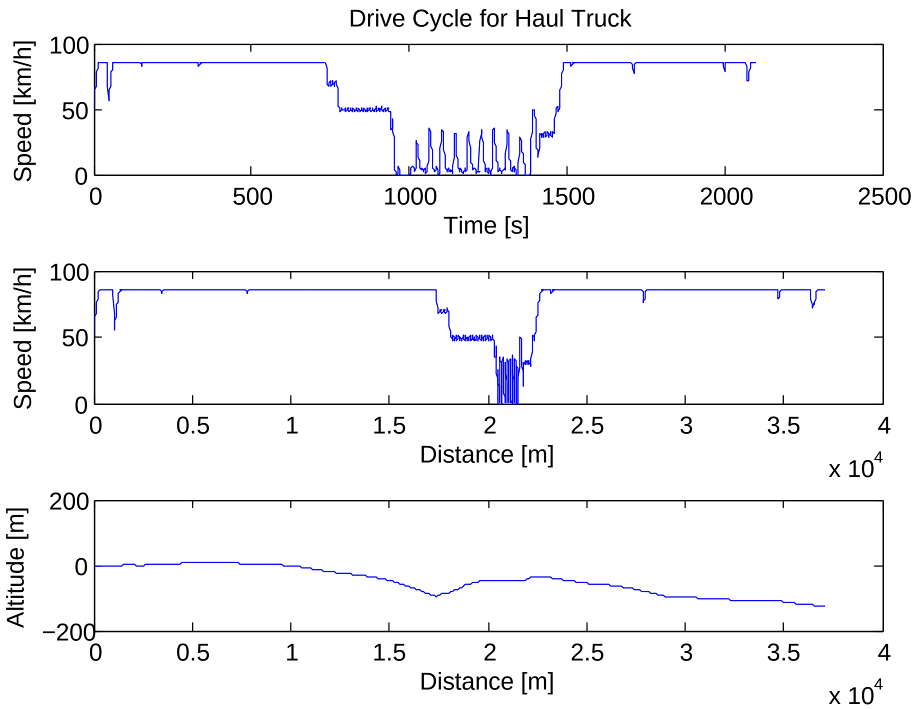


(a) *Predicted Drive Cycle - Distribution Truck*



(b) *Predicted Drive Cycle - Refuse Truck*

Figure 4.15.1: *First and second prediction of drive cycles*



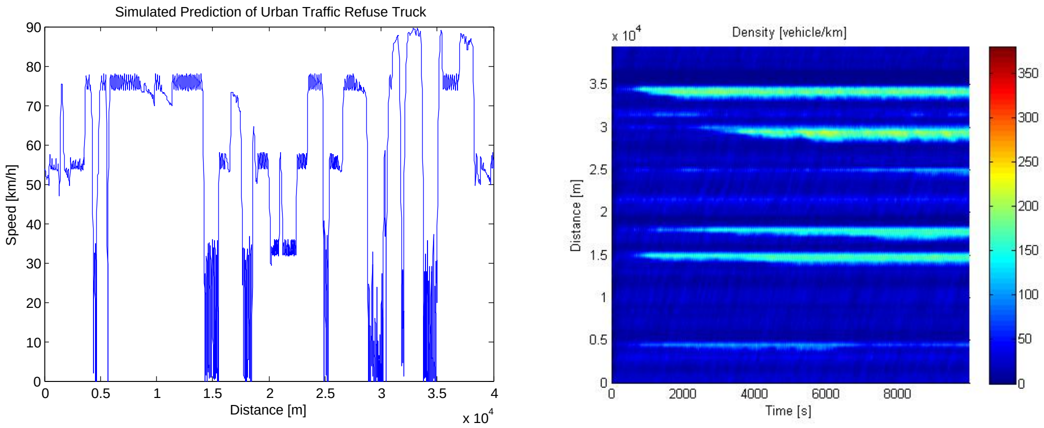
(c) *Predicted Drive Cycle - Haul Truck*

Figure 4.15.1: *Predicted Drive Cycles for Distribution, Refuse and Haul Truck*

compare the freeway segments of the predicted drive cycles with the current freeway drive cycles. The speed levels of the freeway segments for the predicted drive cycles are consistent with the current drive cycles. The reduced speed limit for the predicted traffic situation is not reducing the desired speed for the vehicle types covered in this project since they are saturated at 90 [km/h].

The urban segments of the predicted drive cycle for Refuse Truck has similar speed levels and stop frequencies as the urban segments of current drive cycles. A significant difference is the occurences of repeating transient patterns at low speed levels. The cause of this pattern is traceable, see Figure 4.15.2.

The congestions at a distance of 15, 17, 30 and 35 [km] is the cause of the transients at low speed limits in the drive cycle. The congestions appears at the distance where intersections with traffic lights are placed. The congestions does not dissolve since the traffic demand is higher than the capacity of the intersections. The implementation of the traffic lights is a simple timing and the configuration is reasonable but it is having a significant impact on this phenomenon. This characteristic could not be found in the corresponding simulation of present traffic situation.



(a) *Speed - Predicted Urban Traffic for Refuse Truck* (b) *Density - Predicted Urban Traffic for Refuse Truck*

Figure 4.15.2: *Transient pattern in speed profile due to congestion*

5 Discussion and Conclusion

The methodology is using road data in order to define the present traffic situation. This motivates a less dependence of current drive cycles which would result in a calibration of the model generation parameters. Such calibration could lead to a simulation of present drive cycle which fits well with the drive cycles which is currently being used but that would not necessarily motivate a correct model of present traffic situation. There are most likely many parameter sets which would produce a correct drive cycle but all of those does not represent the present traffic situation well. For example, no traffic demand but high frequency of stops with parking lot would lead to many speed drops which could fit a current drive cycle well, but the opposite could also be a solution. Such calibration would reduce the trustworthiness of the prediction due to an incorrect parameter set which produces a promising present drive cycle but does not describe the present traffic situation in a reasonable manner.

The composition of segments representing both urban and freeway simulation results is distorting the drive cycle to some extent. Rather than composing simulation result, a generation of traffic model with a finite number of parameter sets should be implemented. A traffic model could then have different properties (road type, lanes, etc.) and represent different traffic environments along the main road. The desired flow for the traffic assignment could also be varying along the main road. This improvement would make it possible to generate traffic models which represents both urban and freeway in a very realistic way. The settings for such generation could be based on many route analyses of NVDB, representing different cities and freeways.

The validation of the simulation result in high resolution shows some discrepancies. The idealization of the reality which is due to the Wiedemann driver model and vehicle properties is revealed when the speed profile is compared to the validation data. The triangular wave pattern in the urban speed profile could lead to unwanted cycle beating. Further evaluation of this behaviour should be done in order to decide whether the pattern should be altered by either filtering or developing the driver and vehicle model. Similar patterns can be found in other research thesis [Gao08]. The same behavior is found for simulation of default passenger car settings in Vissim, therefore it is independant of vehicle properties to some extent. Wiedemann 74, which is used in urban traffic conditions, has a noise driven component which is normally distributed according to [TO04]. Such implementation could produce the speed profile which have a triangular wave pattern.

The comparison of the predicted drive cycles with the current drive cycles shows a reasonable change with respect to urban traffic environment. The freeway behaviour shows no remarkable differences. The speed is still steady under normal conditions even though the increase of traffic demand and fraction of heavy vehicles is implemented, based on the prognoses presented in section 4.14. The on-ramps in freeway models have priority rules which is constraining the vehicles which tries to enter the main road. The vehicles on the main road are not properly disturbed by incoming vehicles from on-ramps, a gap time of 3 seconds between vehicles on main road are required in order for a vehicle to enter from an on-ramp. The dynamic behaviour of freeway traffic conditions would be improved if an on-ramp is merged with the main road where there is a temporary increase of lanes.

The result of this thesis consists of both the presented findings and the Matlab application. If it is of interest to evaluate other scenarios (other route data analyses, prediction conditions, vehicle properties, etc.), it could easily be done by the use of the application.

The application was developed with respect to the methodology and objective of this project but it could be used in more areas. There is a potential to generate replicas of road net in NVDB. Such usage of the application would require further development and the required development time is highly dependant on the delimitations of what data to include (geometry, speed limits, lanes, connection of links, etc.).

6 Future Work

6.1 Time varying traffic demand

An implementation that would, most likely, give a good pay-off is the implementation of time varying traffic demand. In this way, more dynamic and realistic traffic models could be generated since variations in traffic over the day, possibly having peaks in the morning and afternoon as in Figure 4.4.1, could be captured.

6.2 VMS - Variable Message Signs

A way to simulate speed limit affection from the predicted increase of traffic is by implementing Variable Message Signs, VMS [TK]. This approach would instead of lowering speed limits deterministically, account for the change in traffic density and update speed limits based on that.

6.3 Reduced speed areas

As shown in the sensitivity analysis in section 4.9, Vissim does not decrease speed of vehicles due to road curvature. One way to achieve this dynamic could be to use the Vissim object *Reduced Speed Areas*. Possibly there could be threshold values for road curvature where the speed limits are lowered to an appropriate level.

Today's implemented intersections could be extended with *Reduced Speed Areas* to get a more realistic speed profile while making a turn. Speed bumps and similar objects where a temporary change of speed should occur could also be modelled by use of *Reduced Speed Areas*.

6.4 Vehicle properties

The implementation of vehicle properties such as acceleration and deceleration profiles could possibly be improved if having better vehicle data at hand. This would give improved transient behaviour in the predicted drive cycles.

6.5 Composition of generated models

As of today's implementation, models are generated with a main road having a specified road type over its whole length. In order to achieve drive cycles having varying road types, simulation results are currently being composed into a complete drive cycle. To avoid this, it would be possible to implement composition of generated models in order to achieve a complete traffic model where the road type is changed in a desired way.

A GUI - Graphical User Interface

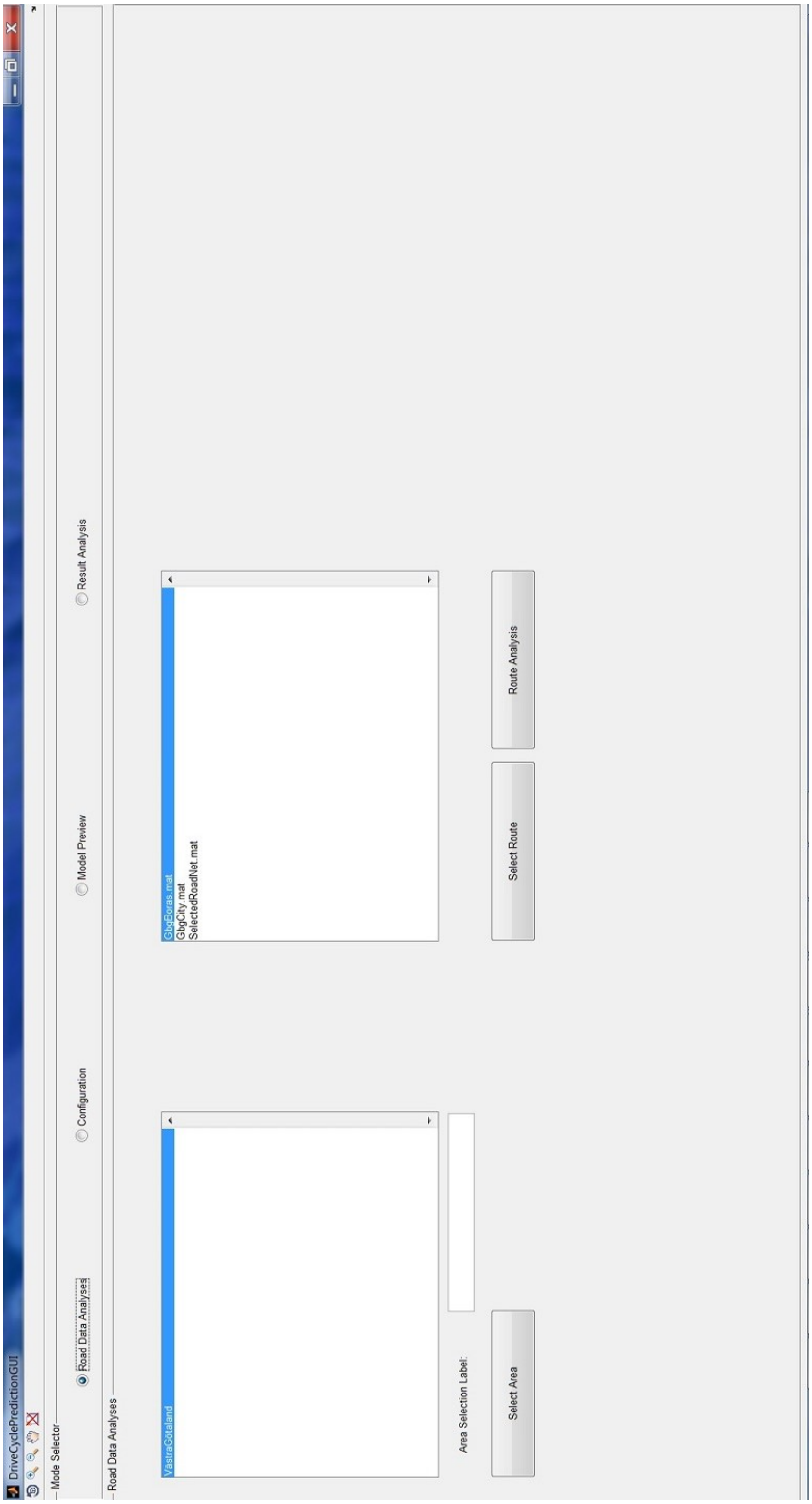


Figure A.0.1: *Road Data Analyses Tab. In this tab, data extracted from NVDB can be loaded and presented as a map. Graphical selection of a route to analyze is enabled as well as the ability to perform the route analysis in order to achieve route parameters.*

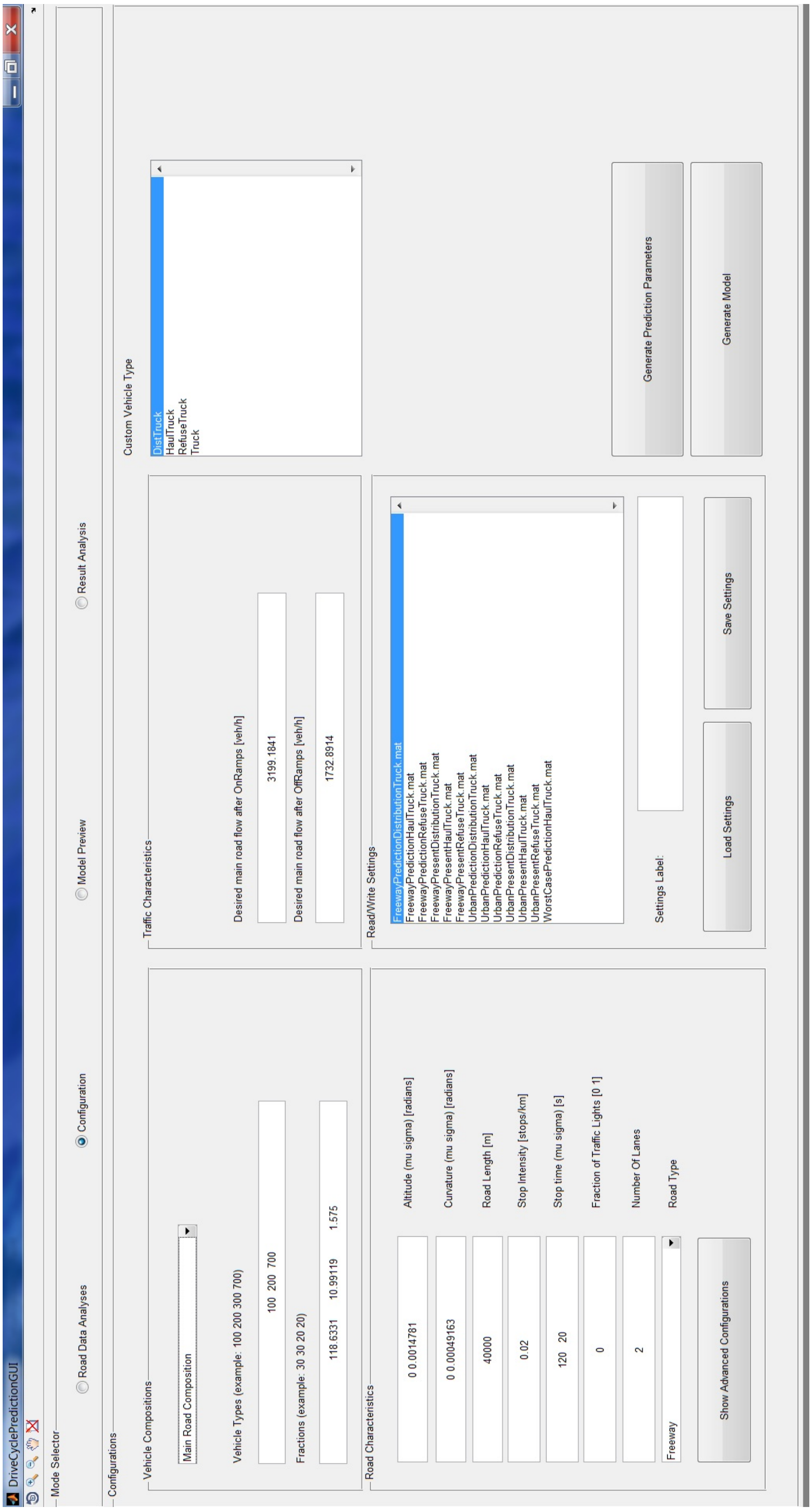


Figure A.0.2: *Configurations Tab. From this tab, it is possible to manage all model generation parameters as well as actually generate Vissim models. Parameters extracted from a selected route in NVDB will be presented and editable here. Parameters can also be updated according to predicted changes.*

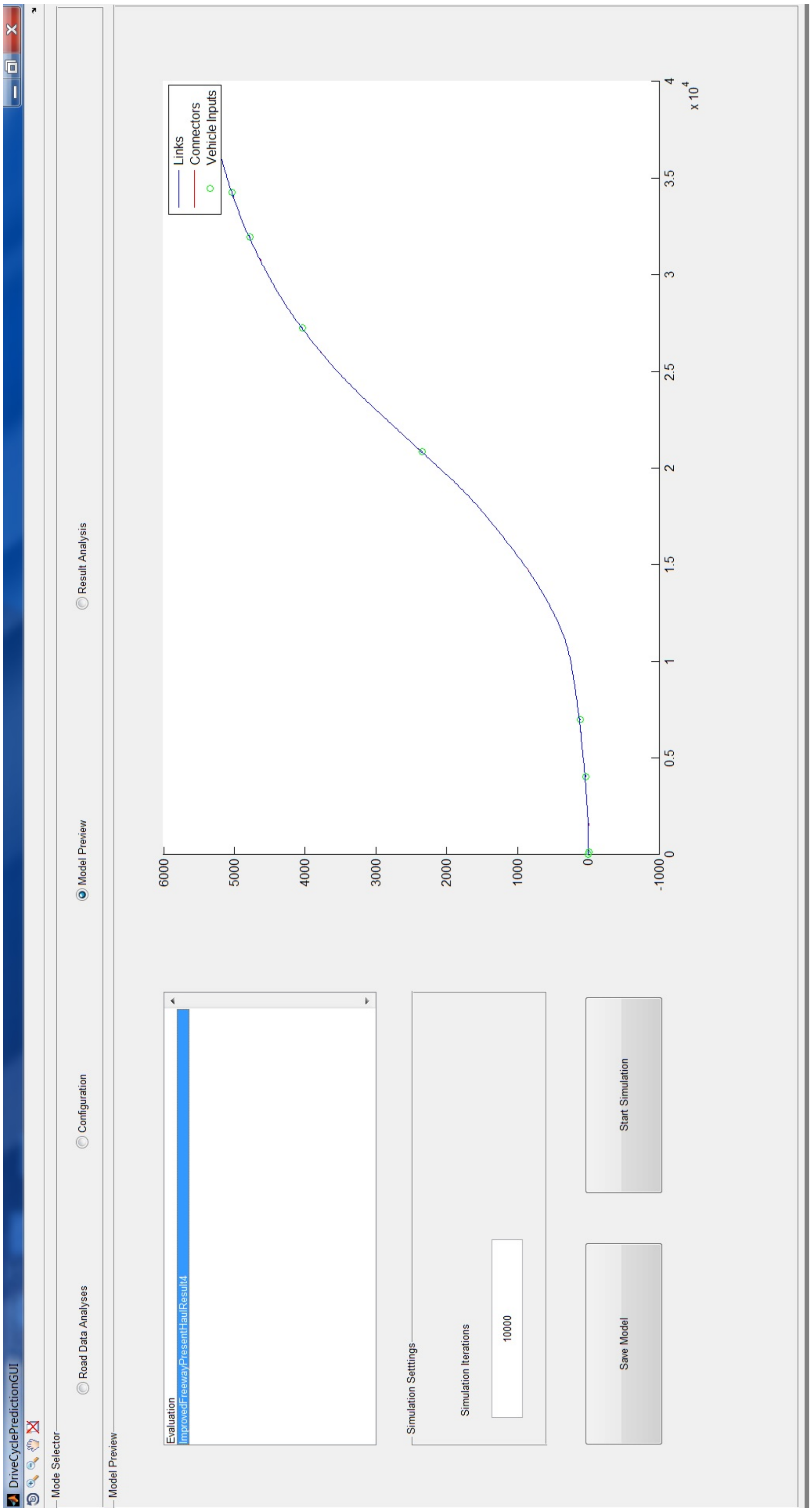


Figure A.0.3: *Model Preview Tab. Generated models can be previewed. Vissim simulations can also be started from here by use of the COM module.*

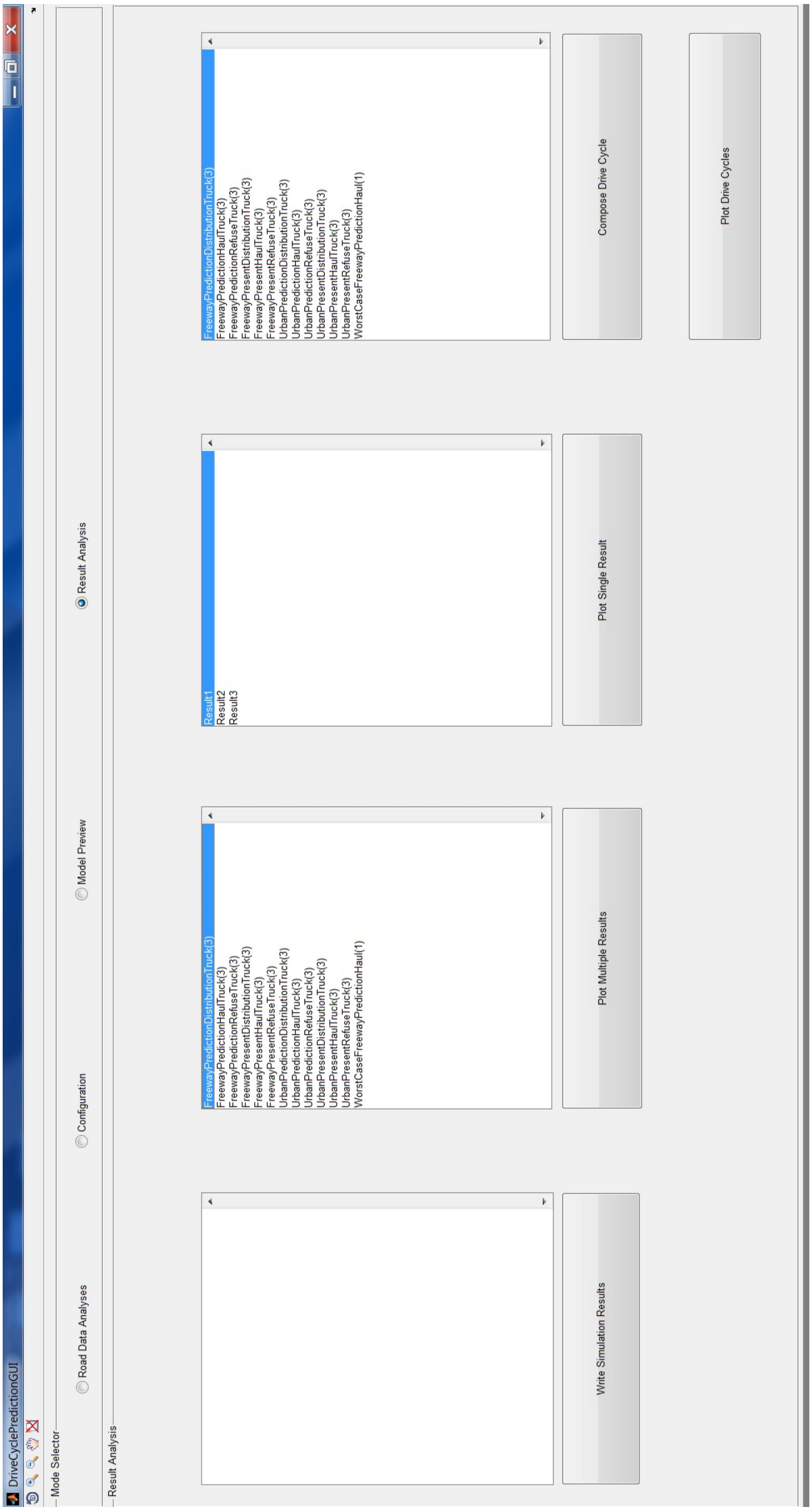


Figure A.0.4: *Result Analysis Tab. Simulation results can be categorized, visualized as well as composed to complete drive cycles from this tab.*

B Estimated Model Generation Parameters

B.1 Present Freeway Settings

–Curvature Filter Data–

Parameter values for denominator, A(z) in descending order:
1 -1.3629 0.43675 0.083222 -0.012596 -0.053615 -0.050514 0.025229 -0.0079115 0.0086127 -0.041832
Step length: 8

–Altitude Filter Data–

Parameter values for denominator, A(z) in descending order: 1 -1.3312 0.54109 -0.17232 -0.030846 0.07696 -0.090031 0.033885 -0.051232 0.097765 -0.067208
Step length: 8

–OnRamp, OffRamp and Intersection Data–

Fraction of Intersections with Traffic Lights=0
Beta Distribution Parameters:
$\alpha = 0.31225$
$\beta = 0.35046$
$K_{Intersections} = 7858.507$
Markov Chain State Names, $X_{Intersections} = \begin{pmatrix} -1.0 & 1.0 \end{pmatrix}$
Markov Chain Probability Matrix, $P_{Intersections} = \begin{pmatrix} 0 & 1.0 \\ 1.0 & 0 \end{pmatrix}$

–Parking Lot Stop Data–

Stop Intensity $= \begin{cases} 0.0033 & \text{if } VehicleType = HaulTruck \\ 0.02 & \text{if } VehicleType = DistributionTruck \\ 0.033 & \text{if } VehicleType = RefuseTruck \end{cases}$

Expected stop time$= \begin{cases} 120 & \text{if } VehicleType = HaulTruck \\ 120 & \text{if } VehicleType = DistributionTruck \\ 120 & \text{if } VehicleType = RefuseTruck \end{cases}$

Standard deviation of stop time$= \begin{cases} 20 & \text{if } VehicleType = HaulTruck \\ 20 & \text{if } VehicleType = DistributionTruck \\ 20 & \text{if } VehicleType = RefuseTruck \end{cases}$

–Speed Limit Data–

Speed Limit Step Length: 0.094393
Markov Chain State Names, $X_{SpeedLimits} = \begin{pmatrix} 70.0 & 110.0 \end{pmatrix}$
Markov Chain Transition Matrix, $P_{SpeedLimits} = \begin{pmatrix} 0.999 & 0.00133 \\ 9.64 \cdot 10^{-6} & 1.0 \end{pmatrix}$

–Traffic Data–

Main Road Vehicle Types $= \begin{pmatrix} 100.0 & 200.0 & 700.0 \end{pmatrix}$
Main Road Vehicle Fractions $= \begin{pmatrix} 88.5 & 10.5 & 1.0 \end{pmatrix}$
Incoming Roads Vehicle Types $= \begin{pmatrix} 100.0 & 200.0 & 300.0 \end{pmatrix}$
Incoming Roads Vehicle Fractions $= \begin{pmatrix} 88.5 & 6.47 & 5.0 \end{pmatrix}$
Desired Maximum flow on Main Road =2400
Desired Minimum flow on Main Road =1300

–Miscellaneous–

Amount of lanes on Main Road=2
Road Type on Main Road=Freeway
Road Length=40000

B.2 Present Urban Settings

–Curvature Filter Data–

Parameter values for denominator, A(z) in descending order:
1 -1.4029 0.66267 -0.22284 0.026273 -0.043301 0.064485 -0.074419 0.015856 -0.041558 0.054178
Step length: 8

–Altitude Filter Data–

Parameter values for denominator, A(z) in descending order:
1 -1.1806 0.4445 -0.12445 -0.007063 -0.078216 0.16462 -0.20932 0.10376 -0.036491 0.00034698
Step length: 8

–OnRamp, OffRamp and Intersection Data–

Fraction of Intersections with Traffic Lights=0.8
Beta Distribution Parameters:
$\alpha = 0.30511$
$\beta = 0.55873$
$K_{Intersections} = 1961.0208$
Markov Chain State Names, $X_{Intersections} = \begin{pmatrix} 1.0 & -1.0 & -2.0 & 2.0 \end{pmatrix}$
Markov Chain Probability Matrix, $P_{Intersections} = \begin{pmatrix} 0 & 0.8 & 0.12 & 0.08 \\ 0.917 & 0 & 0 & 0.0833 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0.75 & 0.25 & 0 \end{pmatrix}$

–Parking Lot Stop Data–

Stop Intensity $= \begin{cases} 0.025 & \text{if } VehicleType = HaulTruck \\ 0.2 & \text{if } VehicleType = DistributionTruck \\ 0.1 & \text{if } VehicleType = RefuseTruck \end{cases}$

Expected stop time$= \begin{cases} 120 & \text{if } VehicleType = HaulTruck \\ 60 & \text{if } VehicleType = DistributionTruck \\ 60 & \text{if } VehicleType = RefuseTruck \end{cases}$

Standard deviation of stop time$= \begin{cases} 20 & \text{if } VehicleType = HaulTruck \\ 10 & \text{if } VehicleType = DistributionTruck \\ 10 & \text{if } VehicleType = RefuseTruck \end{cases}$

–Speed Limit Data–

Speed Limit Step Length: 0.7901
Markov Chain State Names, $X_{SpeedLimits} = \begin{pmatrix} 50.0 & 70.0 & 90.0 & 80.0 & 30.0 \end{pmatrix}$
Markov Chain Transition Matrix, $P_{SpeedLimits} = \begin{pmatrix} 0.999 & 7.4 \cdot 10^{-4} & 0 & 0 & 2.47 \cdot 10^{-4} \\ 4.09 \cdot 10^{-4} & 0.999 & 8.17 \cdot 10^{-5} & 8.17 \cdot 10^{-5} & 0 \\ 0 & 0.0029 & 0.997 & 0 & 0 \\ 7.61 \cdot 10^{-4} & 0 & 0 & 0.999 & 0 \\ 0.00288 & 0 & 0 & 0 & 0.997 \end{pmatrix}$

–Traffic Data–

Main Road Vehicle Types $= \begin{pmatrix} 100.0 & 300.0 & 700.0 \end{pmatrix}$
Main Road Vehicle Fractions $= \begin{pmatrix} 92.0 & 7.01 & 1.0 \end{pmatrix}$
Incoming Roads Vehicle Types $= \begin{pmatrix} 100.0 & 200.0 & 300.0 \end{pmatrix}$
Incoming Roads Vehicle Fractions $= \begin{pmatrix} 93.0 & 2.0 & 5.01 \end{pmatrix}$
Desired Maximum flow on Main Road =1850
Desired Minimum flow on Main Road =650

–Miscellaneous–

Amount of lanes on Main Road=2
Road Type on Main Road=Urban

Road Length=40000

B.3 Predicted Freeway Settings

–Curvature Filter Data–

Parameter values for denominator, A(z) in descending order:

1 -1.3629 0.43675 0.083222 -0.012596 -0.053615 -0.050514 0.025229 -0.0079115 0.0086127 -0.041832

Step length: 8

–Altitude Filter Data–

Parameter values for denominator, A(z) in descending order:

1 -1.3312 0.54109 -0.17232 -0.030846 0.07696 -0.090031 0.033885 -0.051232 0.097765 -0.067208

Step length: 8

–OnRamp, OffRamp and Intersection Data–

Fraction of Intersections with Traffic Lights=0

Beta Distribution Parameters:

$\alpha = 0.31225$

$\beta = 0.35046$

$K_{Intersections} = 7858.507$

Markov Chain State Names, $X_{Intersections} = \begin{pmatrix} -1.0 & 1.0 \end{pmatrix}$

Markov Chain Probability Matrix, $P_{Intersections} = \begin{pmatrix} 0 & 1.0 \\ 1.0 & 0 \end{pmatrix}$

–Parking Lot Stop Data–

Stop Intensity $= \begin{cases} 0.0033 & \text{if } VehicleType = HaulTruck \\ 0.02 & \text{if } VehicleType = DistributionTruck \\ 0.033 & \text{if } VehicleType = RefuseTruck \end{cases}$

Expected stop time$= \begin{cases} 120 & \text{if } VehicleType = HaulTruck \\ 120 & \text{if } VehicleType = DistributionTruck \\ 120 & \text{if } VehicleType = RefuseTruck \end{cases}$

Standard deviation of stop time$= \begin{cases} 20 & \text{if } VehicleType = HaulTruck \\ 20 & \text{if } VehicleType = DistributionTruck \\ 20 & \text{if } VehicleType = RefuseTruck \end{cases}$

–Speed Limit Data–

Speed Limit Step Length: 0.094393

Markov Chain State Names, $X_{SpeedLimits} = \begin{pmatrix} 70.0 & 100.0 \end{pmatrix}$

Markov Chain Transition Matrix, $P_{SpeedLimits} = \begin{pmatrix} 0.999 & 0.00133 \\ 9.64 \cdot 10^{-6} & 1.0 \end{pmatrix}$

–Traffic Data–

Main Road Vehicle Types $= \begin{pmatrix} 100.0 & 200.0 & 700.0 \end{pmatrix}$

Main Road Vehicle Fractions $= \begin{pmatrix} 119.0 & 11.0 & 1.58 \end{pmatrix}$

Incoming Roads Vehicle Types $= \begin{pmatrix} 100.0 & 200.0 & 300.0 \end{pmatrix}$

Incoming Roads Vehicle Fractions $= \begin{pmatrix} 119.0 & 6.79 & 7.88 \end{pmatrix}$

Desired Maximum flow on Main Road =3199.1841

Desired Minimum flow on Main Road =1732.8914

–Miscellaneous–

Amount of lanes on Main Road=2

Road Type on Main Road=Freeway

Road Length=40000

B.4 Predicted Urban Settings

–Curvature Filter Data–

Parameter values for denominator, A(z) in descending order:

1 -1.4029 0.66267 -0.22284 0.026273 -0.043301 0.064485 -0.074419 0.015856 -0.041558 0.054178

Step length: 8

–Altitude Filter Data–

Parameter values for denominator, A(z) in descending order:

1 -1.1806 0.4445 -0.12445 -0.007063 -0.078216 0.16462 -0.20932 0.10376 -0.036491 0.00034698

Step length: 8

–OnRamp, OffRamp and Intersection Data–

Fraction of Intersections with Traffic Lights=0.8

Beta Distribution Parameters:

$\alpha = 0.30511$

$\beta = 0.55873$

$K_{Intersections} = 1961.0208$

Markov Chain State Names, $X_{Intersections} = \begin{pmatrix} 1.0 & -1.0 & -2.0 & 2.0 \end{pmatrix}$

Markov Chain Probability Matrix, $P_{Intersections} = \begin{pmatrix} 0 & 0.8 & 0.12 & 0.08 \\ 0.917 & 0 & 0 & 0.0833 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0.75 & 0.25 & 0 \end{pmatrix}$

–Parking Lot Stop Data–

Stop Intensity = $\begin{cases} 0.025 & \text{if } VehicleType = HaulTruck \\ 0.2 & \text{if } VehicleType = DistributionTruck \\ 0.1 & \text{if } VehicleType = RefuseTruck \end{cases}$

Expected stop time= $\begin{cases} 120 & \text{if } VehicleType = HaulTruck \\ 60 & \text{if } VehicleType = DistributionTruck \\ 60 & \text{if } VehicleType = RefuseTruck \end{cases}$

Standard deviation of stop time= $\begin{cases} 20 & \text{if } VehicleType = HaulTruck \\ 10 & \text{if } VehicleType = DistributionTruck \\ 10 & \text{if } VehicleType = RefuseTruck \end{cases}$

–Speed Limit Data–

Speed Limit Step Length: 0.7901

Markov Chain State Names, $X_{SpeedLimits} = \begin{pmatrix} 50.0 & 70.0 & 90.0 & 80.0 & 30.0 \end{pmatrix}$

Markov Chain Transition Matrix, $P_{SpeedLimits} = \begin{pmatrix} 0.999 & 7.4 \cdot 10^{-4} & 0 & 0 & 2.47 \cdot 10^{-4} \\ 4.09 \cdot 10^{-4} & 0.999 & 8.17 \cdot 10^{-5} & 8.17 \cdot 10^{-5} & 0 \\ 0 & 0.0029 & 0.997 & 0 & 0 \\ 7.61 \cdot 10^{-4} & 0 & 0 & 0.999 & 0 \\ 0.00288 & 0 & 0 & 0 & 0.997 \end{pmatrix}$

–Traffic Data–

Main Road Vehicle Types $= \begin{pmatrix} 100.0 & 300.0 & 700.0 \end{pmatrix}$

Main Road Vehicle Fractions $= \begin{pmatrix} 123.0 & 11.0 & 1.58 \end{pmatrix}$

Incoming Roads Vehicle Types $= \begin{pmatrix} 100.0 & 200.0 & 300.0 \end{pmatrix}$

Incoming Roads Vehicle Fractions $= \begin{pmatrix} 125.0 & 2.1 & 7.9 \end{pmatrix}$

Desired Maximum flow on Main Road =2490.0707

Desired Minimum flow on Main Road =874.8897

–Miscellaneous–

Amount of lanes on Main Road=2

Road Type on Main Road=Urban

Road Length=40000

C Results From Sensitivity Analysis

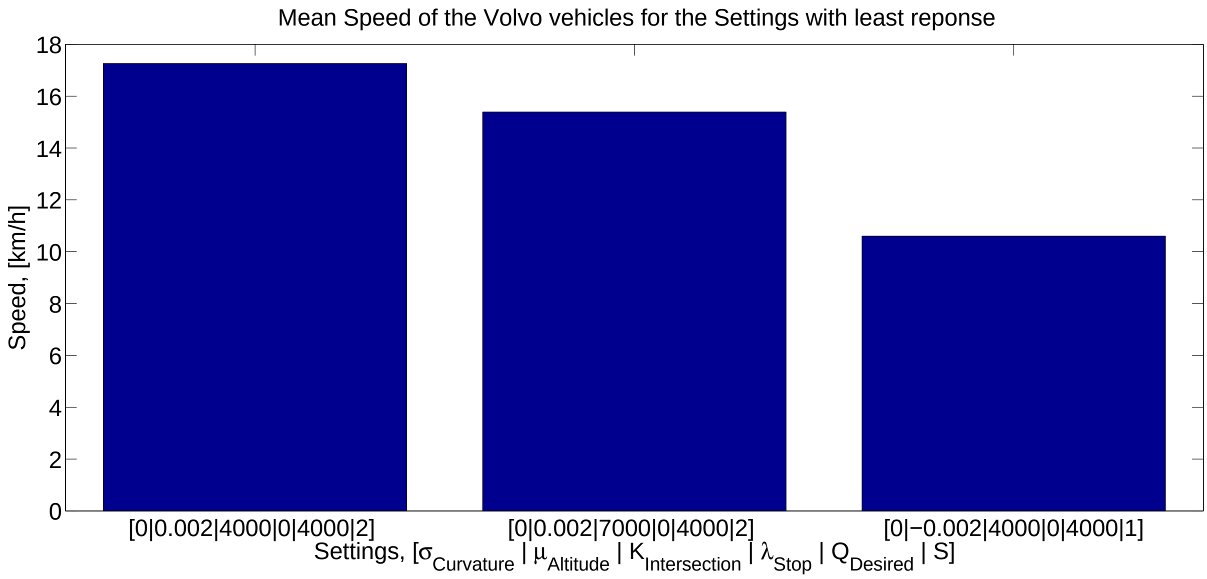


Figure C.0.1: *Pareto chart, showing the lowest mean speed of Volvo Vehicles for all simulations.*

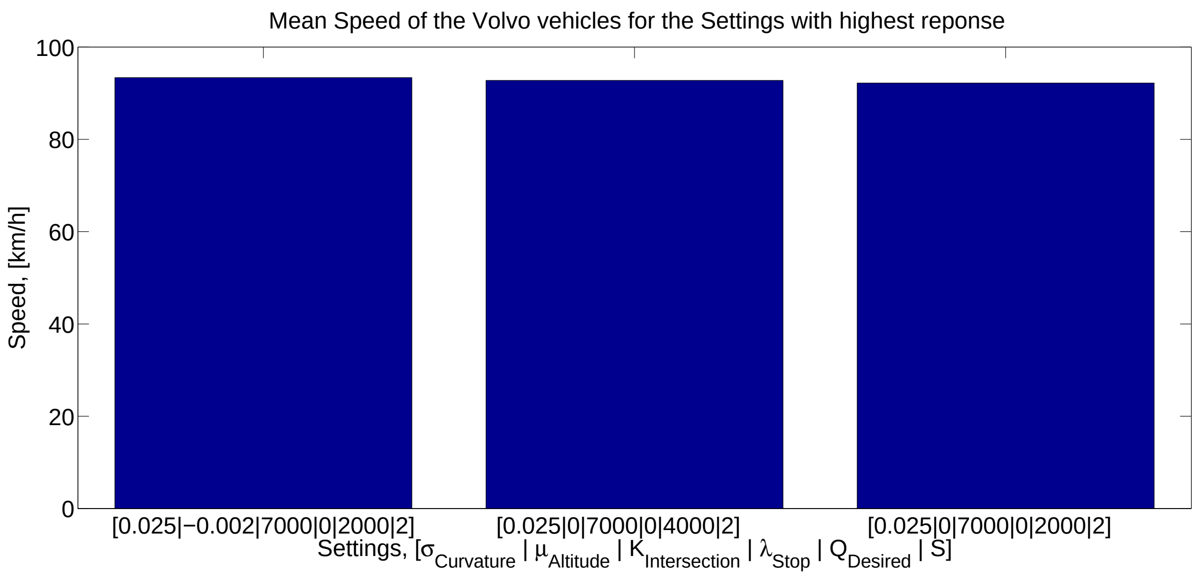


Figure C.0.2: *Pareto chart, showing the highest mean speed of the Volvo vehicles for all simulations.*

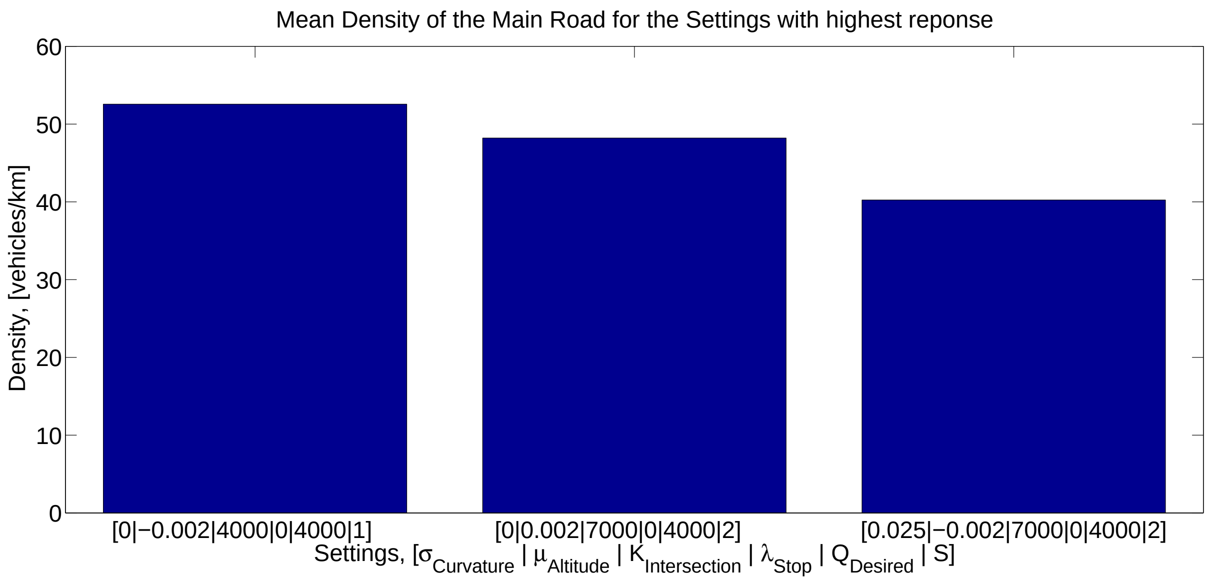


Figure C.0.3: *Pareto chart, showing the highest mean speed of Volvo Vehicles for all simulations.*

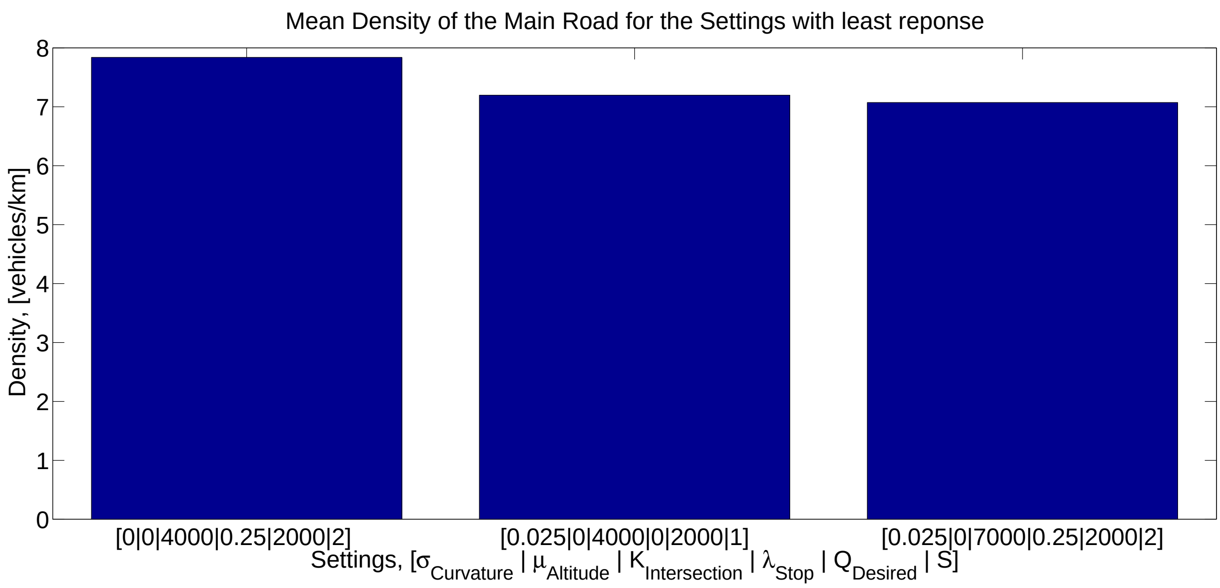


Figure C.0.4: *Pareto chart, showing the lowest mean density of main road.*

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