# A mesoscopic simulation model for dynamic network loading and spillback queuing assessment in a multiclass environment

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RISK AND ENVIRONMENTAL, TERRITORIAL AND BUILDING DEVELOPMENT

Ph.D. Program

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**Final Dissertation**

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Referees:

Prof. Irina Jackiva

Prof. Borja Alonso Oreña

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# *EXTENDED ABSTRACT*

Traffic flow modelling is the most significant component undertaken by the static and the dynamic network loading (DNL) models in the traffic assignment. Dynamic network loading models represent a non-linear relationship between each link flow and its path flow, as they are the fundamental element in estimating the dynamic interaction between demand and supply in oversaturation condition. Moreover, the solution for dynamic network loading problems is necessary for generating the dynamic traffic assignment (DTA) models.

Dynamic models can be characterized according to the simulation details level: microscopic, macroscopic or mesoscopic models. Accordingly, microscopic simulation models fit well in small-scale planning determinations with interest addressed to entities' interactions as these models describe the interaction between vehicles, and between vehicle themselves and transportation infrastructure.

Instead, macroscopic models are capable of the general planning purposes adopting large-scale simulations. As they assume the traffic as a continuous fluid and the flow is subject to the congruency and to the continuity constraints. Finally, the mesoscopic approach simulates most of the entities at a high level, but activities and interactions at a low level of details.

In this context, for a reasonable level of details, coupled with entities interaction information at once, mesoscopic models simulate each link considering the traffic as a set of continuous or discrete packets: a continuous packet is defined by its head and tail, conversely to the discrete packet which is defined by its head, regardless of the tail position.

Many different aspects can be included within the dynamic network loading models such as the multiclass property. It includes the vehicular type in the mesoscopic simulation, which generates different dynamics on the same link considering more than one vehicle type at the same time.

With this complication, once the supply becomes unable to meet the demand (oversaturation condition), evaluation of the queuing spillback is necessary to prevent excessive delays and to forecast the new trip travel time. For this aim, this thesis proposes a new dynamic network loading model which simulates traffic dynamics (speed, density, flow, queue, etc.) explicitly, through modelling the traffic flow considering a discrete mesoscopic simulation model in a multiclass environment.

The proposed model is capable of using two speed-density relations to simulate flow dynamics: the Greenshields and the triangular-shaped fundamental diagram. FIFO rule holds between the vehicles in the same class and creeping speed is assumed to avoid circulation blockage in oversaturation conditions. Moreover, three vehicle classes (private car, bus, truck) have been considered in the simulation.

The proposed model has been validated in undersaturation conditions by comparing model estimations with real observations collected by ATC sensors for Maliha Highway in the United Arab Emirates. For assessing the dynamic queue spillback, the proposed model has been applied to a simple network for easily assessing its capabilities in oversaturation conditions. Moreover, a comparison with a commercial traffic simulation software, Aimsun Next, has been carried out to evaluate the performance of the proposed model.

The comparison has shown a relatively similar behaviour and simulation time for all classes in the case of using the triangular fundamental diagram relation but with much more fluctuation for the Aimsun model. On the contrary, using Greenshields relations provided the same behaviour but with much longer simulation time.

As a result, the proposed model has presented the mesoscopic simulation in a more reliable way since Aimsun seems to include other microscopic characteristics in the mesoscopic traffic simulation like start-and-stop behaviour. Finally, it can be used with confidence as a tool to quantify the traffic dynamics of each class in oversaturation conditions including queue spillback.

***Keywords—congestion, flow propagation, Greenshields model, queue spillback, multiclass mesoscopic simulation.***

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# *CHAPTER 1. INTRODUCTION AND MOTIVATION*

## *1.1 BACKGROUND*

In the recent years, traffic analysis operations, i.e. traffic modelling have taken a great role in order to decrease traffic congestion worldwide, which in turn provides a better life quality. Furthermore, traffic modelling provides a vision to minimize time wasted in the traffic delay, taking into consideration the user's satisfaction and environmental sustainability. Traffic congestion could be evaluated based on time wasted in the traffic delay. For instance, (Cookson, 2018) stated that Italy was the 18$^{th}$ country on the global ranking scale of congested countries by 26 average peak hours spent in traffic congestion.

In general, the transportation system consists of a set of interrelated activities and entities which act together to facilitate the transportation process of goods and people from one place to another (Paul *et al.*, 2016). Consequently, the transportation system should meet a perceived quality level in terms of the economic and social requirements of users. As these requirements change, the system has to evolve itself accordingly. Otherwise, it fails in achieving public satisfaction. Again, it is worth mentioning that traffic congestion has a significant impact on transportation systems, as it occurs whenever demand exceeds the capacity of the road lane, which consequently forms queues causing more aggravated time delay.

As such, congestion adversely affects the user, health, economy, the environment, etc. As an illustration, the commuter who faces unexpected congestion needs more travel time to reach the workplace. This assuredly affects work productivity negatively, regardless of fuel consumption. More or less, congestion causes an increasing demand on the citizen budget.

On the other hand, the discrete driving represented in continuous stopping and resuming during congestion, lunches more amount of harmful carbon's emissions that are resulted from big fuel amounts burned with a more toxic gases production. Finally, the production of these gases conflicts with sustainable environment principles.

In addition, emergency and delivery services may also be affected, besides; the negative effects psychological situation of the driver. Thus, inefficient work productivity as mentioned earlier. In line with these, the driver who is pressing or impatient may drive aggressively avoiding safety signs, that leads to upsurge traffic accidents constituting unsafety human life and concludes more aggravated travel time. Through these observations, it should be noted that the whole transportation system has to be simulated in a way such that all traffic conditions composing traffic process are considered added to any other factors may disturb the traffic motion.

Not long ago, governments, universities, researchers, institutions, consultants, and private industrial groups worldwide became truly multi-modal in the orientation concerning with transportation issues, and effective approaches are adopted in solving transportation problems. In this context, the researcher efforts exerted on traffic flow modelling, and traffic assignment was succeeded to perform analysis on the entire network system, starting with the static network loading models that continued until 1980 (Wu *et al.*, 1998b).

Later, it followed by the dynamic network loading (DNL) models that are used to perceive traffic characteristics in a dynamic form. DNL became obligatory in traffic dynamics; evaluating route flow, travel times, densities and other related parameters which could be necessary for traffic management through modelling. Obviously, the DNL problem is related to the dynamic traffic assignment (DTA) modelling; the focal point in transportation network optimization. DTA model, however, could not be generated without a solution for dynamic network loading problems.

In fact, the DNL problem has been investigated within many models. In accordance to (Wu *et al.*, 1998b) the variations in the model structure refer to the assumptions made to obtain a solution, the criteria that affect the computation of the link loads and finally, path link travel times. More precisely, the assumption used in constructing a model solves the DNL problem (equivalently a DTA), affects the mathematical properties of the solution (upstream and downstream link capacities). Simultaneously, considering the discretized dimensions, the resulted traffic flow of the DNL is being disturbed as well as its physical properties due to the effect of traffic congestion.

In addition to the aforementioned above, traffic simulation that considers the beneficial capabilities of the DNL models can be implemented assuming two compound models. These two sub-models interact dynamically to solve traffic dynamics in the outline of the boundary conditions. To clarify, link and node-based models interact to undertake DNL problem over a fixed time interval. The link-based model handles real-time link flows, while node based manipulates merging and diverging links occurring at intersections.

In technical literature, a limited number of dynamic node based loading models for flow propagation modelling, network assignment, and network loading have been proposed. This shortage perhaps attributable to the complexity of node-based models, which considers the entire transportation network with multiple nodes of both diverging and merging links; (Celikoglu *et al.*, 2009a; Wright *et al.*, 2017; Khelifi *et al.*, 2018), balanced compared to the link-based models; (Astarita, 1996; Ran and Boyce, 1996; Adamo *et al.*, 1999; Nie and Zhang, 2005; Celikoglu and Dell'Orco, 2007; He *et al.*, 2010; Han and Du, 2012; Xu *et al.*, 2017; Mirzaei *et al.*, 2018).

With eyes on more realistic traffic representation, many different conditions were included within the dynamic network loading problems: such these conditions, the multiclass property. For the sake of simplicity, a great number of researches dealt with the dynamic network loading problem assuming a flow with a single class condition such that, a captured traffic conditions were generalized. This approach could be found in (Dell'Orco, 2006; Celikoglu and Dell'Orco, 2007; Celikoglu *et al.*, 2009a; Ban *et al.*, 2012; Han *et al.*, 2013). On the other side, the simulation of traffic with more vehicle types generates different speeds, densities, and flows which is, of course, more realistic but much complicated.

Form these motivations, this thesis is expected to establish a novel mesoscopic dynamic network loading model that handles the DNL problems and considers multiclass conditions and dynamic queue spillback concurrently. The proposed model proposes a conceptual link-based model in which the flow is loaded as discrete packets.

## *1.2 OBJECTIVES*

This thesis aims, in general, to conclude a new multiclass network loading model, that is distinctively capable of handling traffic networks dynamically, through spotting traffic dynamics concurrently over a given time interval. Toward this end in view, the construction of a conceptual model is necessary, which keens to achieve the primary objective besides making the availability of the following:

- A constructed link-based model where the demand is propagated iteratively in the direction of capturing the time-varying congestion conditions from one side and capturing the free flow and partial congested flow parameters as well from another side, exploiting the advantages of employing mesoscopic simulation.
- Description of traffic dynamics considering multiclass condition based on vehicular type.
- Simulation of the dynamic queue spillback effects.
- Evaluation and validation of the proposed model to real observations and to a commercial simulator.

## *1.3 THESIS CONTRIBUTION*

The major contribution of this thesis is the development of a novel dynamic network loading model where both multiclass mesoscopic complications and queue spillback simulation are described in a realistic way.

The proposed model is formed to simulate the traffic network employing any of the following speed-density relations:

- Greenshields fundamental diagram.
- Triangular shaped fundamental diagram.

Other contributions include:

- Construction of a link-based DNL model, where the vehicles from each class aggregated by the network links using discretised time slices.

- Formulation of the proposed algorithm considering the discrete approach of the mesoscopic simulation.

- Development of nodes constraints where the density and capacity limits affect the flow.

- Demonstration of four practical feasibility simulations to evaluate the proposed model performance in under and in overcongestion conditions, using Greenshields and triangular shaped fundamental diagram relations.

- Simulating the same investigated networks by a commercial simulator (Aimsun), and carrying out comparisons to the proposed model outcomes.

## *1.4 THESIS STRUCTURE*

This thesis is organized as follows, in the next chapter; an overview of the existing models is reported, as well as their merits and problems. The proposed model is described in details in chapter 3. Chapter 4 presents model validation to real traffic observations for undersaturation conditions. Moreover, a numerical application of the model to a theoretical network for oversaturation conditions is developed, and the resulting comparison with a commercial traffic simulator is reported. Finally, conclusions are drawn, and future work directions are outlined in chapter 5.

# *CHAPTER 2. OVERVIEW OF EXISTING DYNAMIC TRAFFIC ASSIGNMENT MODELS AND DYNAMIC NETWORK LOADING APPROACHES*

In the direction of building a prominent value added to traffic modelling, towards a realistic simulation; this thesis puts forward a dynamic network loading model considering a physical, horizontal and dynamic queue that keen to capture real-time traffic dynamics explicitly. Furthermore, a multiclass based on vehicular type is also considered within the framework of the model. Subsequently, this model fits well to employ in the outline of dynamic network assignment models.

With a view of offering a brief about the proposed model together with its belongings, a concise state-of-the-art overview is devoted to the modelling approaches, with drawing attention to mesoscopic dynamic network loading models.

## *2.1 BACKGROUND*

In fact, the need to model the real traffic conditions with the complexity of their performance puts the computer at the top as an analysis tool for traffic engineering. As for, traffic flow propagation can be described by traffic flow models, with this in mind; planners became capable of simulating real situations in details. From here on, relying on the level of details, traffic flow models are distinguished as microscopic, macroscopic and mesoscopic simulation models. To be more specific, microscopic models view the traffic as individual vehicles and their interactions whereas the macroscopic one gives attention to traffic flow as a whole. However the mesoscopic falls in between them.

## *2.2 TRAFFIC SIMULATION-BASED MODELLING*

Actually, the existing methods for traffic modelling are four approaches i) neural networks ii) statistical iii) simulation based iv) analytical dynamic traffic assignment approach as categorized in (Yang, 1997). Others have clustered modelling as simulation-based, analytical and hybridisation between simulation-based and the analytical one as described in (Celikoglu and Dell'Orco, 2007).
However, simulation-based is one of different approaches models consist of methodologies that predict the real performance. Furthermore, they are designed for helping the planers to handle transportation problems under different conditions.

Simulation models became the pioneer tools for analysing the real world. Therefore, it is unavoidable, especially in traffic engineering. Of course, the mathematical or analytical solution is feasible, but sometimes they become not strong enough to solve problems due to their complex environment. Besides, the need for animated view for the traffic flow to study their behaviour. Notwithstanding, traffic simulation models still need to be updated for conveying the surplus demand with its various impacts, for example, the queue spillback.

### 2.2.1 MODELS CLASSIFICATION

Models can be categorized based on different criteria; they can be branded as stochastic or deterministic. The simulation is called stochastic whenever it includes a probabilistic input, as in the modelling time of the client service. Conversely, it can be deterministic when the simulation is free from any random content.

Generally, depending on the elements that change in their states to describe the system, models can also be categorized into continuous and discrete. In addition, continuous models simulate the system as changing continuously across time. Typically, it is described by a set of differential equations, while the discrete approach simulates the system considering discrete changing points in time. The latter again consists of discrete time-based and discrete event-based models. The time-based divides the simulation horizon time into fixed periods, and then it determines traffic characteristics at each interval.
In contrast, the event-based models detect the sharp changes in the system, and the computations can be performed further. However, the discrete time-based is preferred to be handled whenever the simulation is needed to be more described and realistic in representing the real world.

As I have said, simulation models are categorized into microscopic, macroscopic and mesoscopic according to the level of details. Accordingly, the approach is macroscopic, once vehicle movements are traced implicitly, and link performances are conveyed in an aggregated way. On the contrary, when vehicle movements are traced explicitly, two cases are promising, depending on whether link performances are expressed in an aggregated or disaggregated way. The latter approach is microscopic. Otherwise, it is mesoscopic (Celikoglu and Dell'Orco, 2007).

#### 2.2.1.1 MICROSCOPIC SIMULATION

Again, microscopic models view the traffic as individual objects concerning interactions with each other's and between vehicles themselves with the infrastructure. As for, many studies were carried out to simulate the driver behaviour in different situations, to give an example, when the driver exposed to an unexpected obstacle either static or dynamic. Some of these studies are described in (Jamialahmadi and Fallah, 2017; Morton *et al.*, 2017; Stankoulov, 2018; Xu *et al.*, 2018).

Indeed, these behaviours can be captured when one or more of the following actions achieved: vehicle acceleration, deceleration or lane change. However, the most famous models evolved to detect vehicles behaviour are illustrated as follows:

- **The car following model:** this model describes how one vehicle follows the other in the uninterrupted flow. Moreover, a set of mathematical equations has been employed to describe the behaviour of a leading vehicle and its follower as explained in (Yang and Zu, 2004), However Fig. 1 presents the follower and leader vehicles assumed in this model.

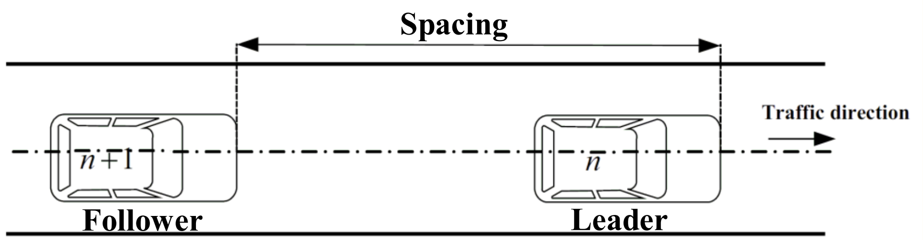


Fig. 1 - A presentation of leader-follower vehicles in the car following models

To sum up, car following model represents acceleration, deceleration and breaking as a consequence of the interaction between the driver and his follower with the infrastructure elements such as vertical highway curves, speed limit, etc.

Examples on car-following models are intelligent driver model (IDM), the Krauss car-following model, and the Wiedemann car following model as stated in (Pourabdollah *et al.*, 2017) and General Motor model (GM) as described by (Munigety *et al.*, 2018).

- **Lane changing model:** based on the driver preferences and the traffic stream situation in the current and the adjacent lanes such as a founded gap to occupy, lane changing model as depicted in Fig. 2 and developed to describe the decision of the driver.

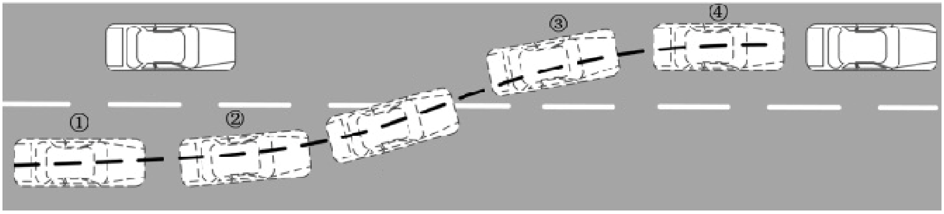


Fig. 2 - The demonstration of the lane changing process

Actually, modelling of the driver behaviour in the current lane is straightforward if compared with the one who is keen to change his lane, as the only consideration is devoted to the speed together with the position of the preceding vehicle. Therefore, the decision to change lane; however, relies on different objectives and doubtless, at a certain instant they may be in the face of each other.

Increasingly, models of lane changing action can be categorized to mandatory lane change models (MLC) as when the driver is obliged to change the lane to follow a wished route and discretionary lane change models (DLC) when the driver changes the lane seeking better traffic conditions, for instance when he changes to overtake other vehicles.

Examples of lane changing models are Netsim, Fresim, Mitsim and MRS model as mentioned in (Zhang *et al.*, 2017).

- **Route choice model:** The core of any traffic assignment method is the route choice model (Prashker and Bekhor, 2004), it has been developed to describe how people select a path from origin to destination, besides, how drivers react with the infrastructure elements such as traffic signs and signals.

  Generally, the estimation of the route choice model requires a subset of paths to be defined. Typically, path generation algorithms are used; they can be divided into deterministic when generalized cost function used to determine the shortest path for example. In addition, event approaches when the randomly distributed generalized cost function is used for paths generation (Frejinger, 2008).

To sum up, network loading in microscopic models can be described by simulating traffic that enters to network in line with the percentage of traffic turning right, left or going straight to each junction. Contrarily, the network can be divided into zones and then, the origin/destination matrix (OD matrix) can express how many vehicles travel from each zone to other.

The most well-known microscopic simulation packages are Vissim 10 (PTV, 2018a), Aimsun (Aimsun, 2018), TransModeller (TransModeler, 2018) and Paramics (Paramics, 2018).

#### *2.2.1.2 MACROSCOPIC SIMULATION*

In fact, it is hard to realize the simulation results at the network level; for example, the queue spillback impact on a purely microscopic basis. Therefore, despite the intense complexity of these systems, it is believed that the surveying of relations among averages of relevant variables in a macroscopic simulation level leads to a functional dependence as a product of collective effects.

With this in mind, macroscopic simulates entities, activities, and interactions with infrastructure at a low level of details. Following this, traffic stream is described in an aggregated representation; average speed, density and flow.

As described in (Cantarella *et al.*, 2014), two main types of models can be identified at the macroscopic simulation level: continuous and discrete models. The latter approach describes flow propagation in the link in terms of relations among variables such as inflow, outflow, and link travel time over a specified period. Comparatively, continuous models derive the homogeneity between the vehicular flow and the continuous traffic flow concurrently; this yields a number of flow models with partial equations which are very complicated to be solved and less capable of describing the link dynamics.

To take a case in point, Whitham (Whitham, 1955) and Richards (Richards, 1956) simultaneously developed the most straightforward continuous flow model assuming that the number of vehicles is conserved between two points if there are no entrances or exits (Cantarella *et al.*, 2014). The outcome model is known as the Lighthill-Whitham-Richards (LWR) model, which considered as a first-order model.

As the differential equations used in the LWR model are complicated to solve. Daganzo (Daganzo, 1994;1995) has discretized the continuity into homogeneous sections called cells through his model which is well-known as the cell transmission model (CTM). To illustrate, it simulates the traffic with a time scan process whereas the current traffic conditions are updated in every clock tick. Moreover, It based on a simplified trapezoidal or a triangular form which provides a constant free flow speed, at low densities, and backward shockwave speed for high densities as described in (Cantarella *et al.*, 2014).

Macroscopic simulation has an added value in terms of its characteristics, so it is capable of describing the dynamic network loading regarding the queues propagation, inflow, density..etc., as discrete packets. In spite of that, for a more representative description of traffic dynamics; it must be integrated with the microscope simultaneously, this hybrid is a well-known mesoscopic simulation as described in the following section.

In the following packages, macroscopic traffic flow modelling has been considered: Aimsun (Aimsun, 2018), Visum 16 (PTV, 2018b) and Synchro studio 10 (Trafficware, 2010).

#### *2.2.1.3 MESOSCOPIC SIMULATION*

As has been highlighted earlier, simulation models are categorized according to the level of details. With this in mind, mesoscopic simulates most of the entities at a high level, but activities and interactions at a low level of details. To differ from, microscopic which represents all at a high level and macroscopic which contrarily describes all on a low level as mentioned previously. Following this, the traffic stream in the mesoscopic simulation is described in an aggregated representation as in macroscopic.

In short, the selection of traffic variables, which may describe the dynamic queueing macroscopically, for example, is a significant comparatively to link dynamics once studied on a microscopic basis, likewise speed per every single vehicle, time headway and space headway among them. Conversely, once the simulation is macroscopic, traffic mean speed is concerned, time and space headway become traffic flow and density respectively.

This type of models takes the movement of a single or a series of vehicles entitled "packet" in the consideration as this group of vehicles routed to a link and behave as one entity. The speed of packet is defined from a speed density function derived for that link. (Cantarella *et al.*, 2014)

To be more specific, two approaches with their applications in the literature are distinguished: continuous packets (Di Gangi, 2011; Linares *et al.*, 2014; Di Gangi *et al.*, 2016; Di Gangi and Polimeni, 2017), differently from discrete packets approach where vehicles are simulated as distributed uniformly in time or space that is defined mostly by the tail or the head of each single packet; where employed in (Celikoglu and Dell'Orco, 2007; Dell'Orco *et al.*, 2016; Shafiei *et al.*, 2018).

From these motivations, network loading packets need to be described in terms of flow, density, together with speed per individual packet concurrently, the approach is built around the definition of the multiclass mesoscopic simulation based on vehicular type, adopting discrete packets flow as an upshot of all above.

## *2.3 OVERVIEW OF MESOSCOPIC SIMULATION MODELS*

Due to the trade-off between sufficient details level and modelling simplicity concurrently, the mesoscopic level is preferred in this thesis. In general, the solution of the dynamic network loading problem is clustered into three approaches; analytical, simulation-based or hybridisation of the two approaches (Celikoglu and Dell'Orco, 2007).

Analytical model relays on direct mathematical computations to determine system dynamics once it used to solve an assignment as in (Celikoglu *et al.*, 2015; Shafiei *et al.*, 2016; Tanvir *et al.*, 2016; Osorio, 2018). Additionally, analytical models can estimate density, speed, delay, capacity and queuing directly also with a variety of transportation facilities. Of course, these models are applicable for performance analysis of the link function or for the small-scale transportation facility; but, in the meantime their abilities to analyse networks are limited (FHWA, 2009).

Instead, the simulation-based approach utilizes various rules as a set of mathematical equations to simulate the movement of individual vehicles or packets in the system. As described by (Celikoglu and Dell'Orco, 2007), the simulation-based approach includes models which regenerate detailed flow dynamics which again become the input for specific phases of flow propagation and route choice. Moreover; these models simulate the initial solution results, assuming that the performance of the optimized model parameter set; estimates the expected performance of that set in the succeeding time span with the assistant of previous data. Some of the models adopted simulation-based approach are DYNAMEQ (Tian *et al.*, 2007; Mahut and Florian, 2010), DynaMIT (Ben-Akiva *et al.*, 2010), CONTRAM (Leonard *et al.*, 1989) and DYNASMART-X (Fei *et al.*, 2009).

It is important to realize that taking the advantages of analytical approach coupled with simulation-based at once; yields hybrid approach models that are capable of undertaking more accurate solutions and efficient optimizations. Another key point behind the idea of hybridisation is that it enables to work on large-scale traffic networks. In this thesis, a hybrid approach is employed on a mesoscopic level to simulate the transportation network dynamics including the queue spillback considering more than one vehicle class.

Last decades, the hybrid approach attracted the attention of many researchers to hire; (Daganzo, 1995; Burghout *et al.*, 2006; Celikoglu and Dell'Orco, 2007; Celikoglu *et al.*, 2009a).

Henceforth, in this section, a number of dynamic mesoscopic simulation-based models, which motivated the interest of developers are overviewed:

### *2.3.1 DynaCHINA*

DynaCHINA is a real-time simulation-based traffic prediction package developed by Lin Yong and Houbing Song in 2007. According to them; DynaCHINA is first and unique traffic in China. It has been produced and directed to the Chinese traffic networks (Lin and Song, 2007). Because of the local traffic characteristics, for example the unique driver behaviour in China besides the mixed traffic; the available traffic simulators such as DynaMIT (Ben-Akiva *et al.*, 2010), DYNASMART (Jayakrishnan *et al.*, 1994), and CONTRAM (Leonard *et al.*, 1989) were limited to describe the different traffic dynamics there.

Given these points, and although DynaCHINA is different from DynaMIT and DYNASMART, it employs DynaMIT basic framework in its implementation. Additionally, four main unique features are compounded in DynaCHINA to adapt the situation that it founded for; anisotropic mesoscopic supply simulator, availability of floating car data in urban networks, availability of true OD flows in freeway networks and Modelling mixed traffic flow including bicycles, motorcycles, and pedestrians (Lin and Song, 2007).

At the same time, it is important to realize that DynaCHINA customs two main simulator tools: the microscopic demand simulator which on the one hand designed to forecast time-dependent origin-destination flows, and on the other hand to get the demand data disaggregated to model the socio-economic characteristics of the driver. Hereafter, taking advantage of the embedded behavioural models; drivers decision concerning departure time coupled with route choice can be identified as described in (Li *et al.*, 2013).

Once more, DynaCHINA has also a mesoscopic supply simulator which simulates vehicular movements through queue length, travel time, speeds and destinations in all network positions. Accordantly, utilizing this data, traffic network performance can be indicated (Li *et al.*, 2013).

Consequently, DynaCHINA is pioneer know-how, since it is a model that developed to local traffic conditions. To this end, the experienced methodology can be procreated to any other country other than China when a unique simulator is needed. Until now, it has shown a significant role in estimating traffic conditions in China: (LIU *et al.*, 2007; Zhang *et al.*, 2008; Shubin *et al.*, 2009; XU *et al.*, 2009; Li *et al.*, 2016; Li *et al.*, 2017).

### *2.3.2 DynaMIT*

DynaMIT (Dynamic Network Assignment for the Management of Information to Travelers) is a simulation-based DTA model founded by (Ben-Akiva *et al.*, 2010). The framework of DynaMIT is designed to estimate and predict short-term future traffic network dynamics. Moreover; the system provides a real-time regular predictive information for users. Additionally, DynaMIT is a compound of two main engines: the demand simulator which describes the time-dependent OD flows, route choice as well as departure time. In this context, the hired demand simulation methodology obeys this equation:

$$D_{DynaMIT} = D_{Hist} + \Delta D_{Info} + \Delta D_{Fluct} + \varepsilon$$

Where,

$D_{DynaMIT}$ : Actual demand

$D_{Hist}$ : Historical demand portion, or the disaggregation for offline historical data where stored in the database. More accurately, the historical data can be the population or the feasible socio-economic factors generated by Monte Carlo approach based on their distribution over that population, coupled with the habitual departure times assigned to each traveller in the database and the travel time.

$\Delta D_{Info}$ : Portion of the response to the information received by drivers.

$\Delta D_{Fluct}$: Individuals activity patterns

$\varepsilon$: Random mean error.

The other engine is the supply simulator which is a mesoscopic traffic modeller, and the vehicles are aggregated as packets with speed derived by speed-density relation. At joints, traffic elements; signals, weaving sections, merging and diverging are modelled explicitly. In DynaMIT, the traffic network is modelled per link, section and lane. Likewise, each link is considered a combination of running and queuing part. In more details, there are two capacity concepts in DynaMIT; acceptance capacity which is a rate of availability for the physical space in the road section. Instead, output capacity is the rate of vehicles that exit the downstream. Typically, a deterministic queue approach is used to calculate delay time in queues, once acceptance capacity is equal to zero, no farther vehicle can be routed to the network and queue start to spillback. Congestion modelling in DynaMIT is difficult to implement since it is nontrivial to identify each of running and queuing part portions in general traffic conditions as noted by (Li *et al.*, 2013).

DynaMIT has been developed by the University of Texas in Austin. It has been selected as one of the candidate models for the Federal Highway Administration project FHWA's DTA (Dynamic Traffic Assignment) together with DYNASMART (FHWA, 2005). They have improved both of them for traffic information generation for Advanced Traveller Information Systems (ATIS).

DynaMIT, supports the operation of ATIS, this helps drivers to experience route and departure time choices, and to assist traffic departments in tasks such as emergency unit, and traffic management. DynaMIT is applicable to manage and control real-time independents, evaluate alternative traffic signals, ramp metering, and historical databases generation.

There are two versions of DynaMIT, online DynaMIT-R (Barceló, 2010; Kim *et al.*, 2014; Hu *et al.*, 2018) which estimates current traffic conditions and future states based on cooperated assignment system and offline planning version that called DynaMIT-P (Ben-Akiva *et al.*, 2001).

Instead, DynaMIT-P is a short-term planning tool that assists planners to evaluate intelligent transport system (ITS) strategies and short-term planning applications; these applications could be infrastructure related, information change and or related operational applications. As for, travellers may change their route based on dynamic information or congestion. Accordingly, this change certainly affects stream conditions. Therefore, DynaMIT-P was developed to handle these interactions and to assess network performance.

Structure of DynaMIT-P is well appropriate for the offline generation of libraries of incident diversion strategies as well as the evaluation of the advanced traveller information systems before their actual online deployment. This has been implemented by modelling in a wide range of generating information approaches and diversion strategies taking in the account the driver response to traffic information.

Each of both mentioned versions interacts between the supply and demand engine, toward extracting the driver behaviour consistently by the experienced traffic conditions.  DynaMIT-R has in its framework a method for network conditions prediction, whereas demand and supply simulators are calibrated to fit actual conditions grabbed from sensors concurrently. This leads to the estimation of OD matrices as well.

DynaMIT-R and DynaMIT-P have been extensively validated for many real traffic networks; (Sundaram, 2002; Chauhan, 2003; Balakrishna, 2006; Sundaram *et al.*, 2011; Ben-Akiva *et al.*, 2015).

### *2.3.3 CONTRAM*

Continuous Traffic Assignment Model (CONTRAM) is one of the few models that broke the barriers toward mesoscopic modelling ever, which developed by (Leonard *et al.*, 1989). The efforts to construct CONTRAM has started in the early of 1970s by Leonard, Grower and Taylor. CONTRAM, models time-varying demand between a set of origin-destination zones in urban and other road networks that are subjected to capacity constraints, to conclude network flows, travel times and to predict the variation over time slices of queues, delays and traffic assignments concurrently.

In addition, CONTRAM is structured as a link-node structure, where the traffic in links is described as discrete packets, each of packets consists of a number of vehicles (1-20 vehicles) for the same class that are distributed over links and obey capacity constraints. Once flow exceeds capacity, queues formed and the delay is determined based on timing plans at each node. Also, CONSTRAM adopts the Point-Queue approach. Moreover, First-in-First-out (FIFO) is not respected in links.

Since CONTRAM is a simulation-based DTA model, founders have designed it to work iteratively until the simulation of individual vehicles leads to achieve one equilibrium condition at least. Then, it is possible to simulate a response to ITS.

The model has been developed and improved continuously toward the more precise simulation of traffic networks. A good illustration of this is CONTRAM 5 by (Taylor, 1990); it contains many improvements to the original capabilities of CONTRAM (Leonard *et al.*, 1989) and it introduced some new facilities as stated by (Taylor, 2003). The queue models in the 5th version are based on time-dependent stochastic queueing theory. In spite of getting CONTRAM improved, the model hasn't applied in online context conversely to DYNASMART (Jayakrishnan *et al.*, 1994) and DynaMIT (Ben-Akiva *et al.*, 2010).

Putting a case in point, CONTRAM model has been hired as an ITS modeller in (Rilett *et al.*, 1994; Buisson *et al.*, 1998; Davidsson and Taylor, 2003; Waterson *et al.*, 2003; Kristoffersson and Engelson, 2008).

### *2.3.4 DYNASMART*

Dynamic network assignment simulation model for advanced road telematics (DYNASMART), is a mesoscopic simulation-based model developed with valued efforts of (Jayakrishnan *et al.*, 1994). To be specific, DYNASMART is a real-time model that adopts a time discrete approach once it runs for traffic pattern modelling and or to evaluate the network performance dynamically (UCI, 2018).

In DYNASMART, the origin-destination matrix is assumed to be specified together with paths flow and based on the assignment-defined rules. To this end, many rules are modelled: user equilibrium, system optimal, route switching and real-time best route choice. A solution to the traffic assignment is iteratively using the all-or-nothing method.

Node transfer modules are used to model nodes, based on the interaction between traffic flow at intersections or to use queue server approach; this helps to account for traffic lights and the delays that may be formed. Given inflows, outflows, and densities for each section, link densities are determined by solving for the finite difference form of the continuity equation at each time step:

$$q(x,t) = k(x,t).u(x,t)$$

Then after, modified Greenshield speed-density relationship (Greenshields *et al.*, 1935) is used to calculate each section speeds:

$$u_i^t = (u_f - u_0) - (1 - \frac{k_i^t}{k_j})^\alpha + u_0$$

Where, $u_i^t$ and $k_i^t$ are the mean speed and density in section $i$ at time step $t$, respectively, $u_f$ and $u_0$ are the free flow speed and the minimum speed, respectively, $k_j$ is the jam density, and $\alpha$ is a parameter that captures the sensitivity of speed.

The number of vehicles on each link is determined using the conservation equation, and a number of vehicles in each class are aggregated separately in each time step.

In DYNASMART, queuing and turning manoeuvres at intersections are modelled explicitly. Because of the capacity constraints, vehicles at the back of the stream are not allowed to spillback to the backward link, and they must wait until the others discharged from the head of the stream. Accordingly, this ensures satisfying of FIFO principle. Moreover, the physical size of the queue is presented explicitly in the simulation assuming the link splitting up to a queuing and a running part.

DYNASMART has been tested and evaluated in a Federal Highway Administration project (FHWA, 2005). As noted in (UCI, 2018); two versions of DYNASMART are available in the Dynamic Traffic Assignment project; DYNASMART-X for real-time analysis and DYNASMART-P for offline planning.

### *2.3.5 DYNASMART-X*

DYNASMART-X is Dynamic Traffic Assignment model developed by (Mahmassani *et al.*, 1998a; Mahmassani *et al.*, 1998b; Mahmassani *et al.*, 2004; Mahmassani *et al.*, 2005). The model is a system which provides an outline for estimation of current traffic condition. Furthermore, it helps in the prediction of future network demand patterns, route information and traffic conditions.

Taking advantage of historical demand data coupled with dynamic traffic observations, the model predicts time-varying demand patterns using Kalman filter supported by a polynomial trend model to estimate the deviation from the historical demand data. To predict the true demand with regular patterns as a prior estimation, DYNASMART-X uses structural deviations and random disturbances; following Gaussian distribution with zero means. The speed of single vehicles is calculated by modified Greenshield speed-density relationship (Greenshields *et al.*, 1935).

To evaluate DYNASMART-X, (Mahmassani *et al.*, 2005) have simulated and predicted densities, then they compared results of DYNASMART-X with observations on a link in the Orange County/Irvine region's network. They concluded that the simulator captured the time-dependent trend with acceptable prediction RMSEs (root-mean-square error) of densities and flows. However, more details can be found in (Mahmassani *et al.*, 2005).

### *2.3.6 DYNAMEQ*

DYNAMEQ is a dynamic simulation-based DTA model developed in the University of Montreal in Canada (Mahut *et al.*, 2002; Florian *et al.*, 2006; Mahut and Florian, 2010) including user equilibrium (UE) approach adopting link-node representation. Moreover, the model designed to simulate using a lesser input data than other models. Henceforth, inputs to DYNAMEQ are traffic demand which is presented for each vehicle's class by one time-based OD matrix, control plans, and network definition, to conclude; flows, speeds, densities, travel time, vehicles number and queues conditions per lane for each vehicle class depicted in animated plots. In addition to path results, for instance, the route choice decisions and path sets.

Traffic propagation in DYNAMEQ incorporates three components; car following, lane changing approach and gap acceptance. To this end, these factors generate queues over the traffic network. Moreover, simulation in DYNAMEQ is a discrete event-based that depends on the number of vehicles pass each link regardless of the travel time.

Routes are generated initially in the first iteration since no observed traffic conditions are experienced before the first iteration, the drivers are assumed to select the quickest routes and flows at the free flow speed of each link are supposed. Then, the travel time for links concluded at the end of the simulation is employed to identify the shortest routes in the network. Therefore, links can be updated with the new dynamic factors including the shortest route using the method of successive averages (MSA) to update routes between iterations. After a number of iterations, only routes, which used are retained, and no fresh routes can be updated.

In addition, DYNAMEQ employs free flow speed behaviour to detect link dynamics. Vehicles delay at intersections because of the interaction between them. Accordingly, this may occur because of lane changing action. Hence, this approach is assumed in the model. Additionally, vehicles are assumed to be impeded because of preceding ones that travel at the same speed or at intersections as mentioned earlier. Consequently, implementing the impedance mechanism, DYNAMEQ can describe the dynamic spillback of the queue.

As well as CONTRAM (Leonard *et al.*, 1989), DYNAMEQ neither applied as online traffic modeller nor validated on large networks conversely to DYNASMART (Jayakrishnan *et al.*, 1994) and DynaMIT (Ben-Akiva *et al.*, 2010).
A responsible role of DYNAMEQ has shown in (KETTNER, 2006; Tian *et al.*, 2007; Volet and Letarte, 2007; Mahut and Florian, 2010; Gori *et al.*, 2014; Alam and Habib, 2016; Mahut *et al.*, 2016).

### *2.3.7 MEZZO*

It is a hybrid mico-mesoscopic traffic simulator, developed by Wilco Burghout at the Royal Institute of Technology in Stockholm (KTH). As described in (Burghout *et al.*, 2004), the structure of MEZZO is a link-node representation as a mesoscopic system. In MEZZO, each link consists of a running and a queuing part. Besides, each roadway represented by two-way links; as one on each direction. In other words, each link comprehends lanes, which are not presented separately. In the Node model, multiple margining and diverging links present the stream.

As in DYNAMEQ (Mahut and Florian, 2010), the simulation is an event-based. To this end, the estimation of travel time and queuing phenomenon are simulated explicitly. MEZZO handles queue formation and dissipation over continuous time and space as a deterministic queue server approach.

Also, the route choice in MEZZO combines pre-trip route choice that exploits known routes and historical travel time for all links, and En-route switching (Burghout *et al.*, 2004). MEZZO has been validated and calibrated on small networks; it has shown a performance as good as a hybrid model according to (Burghout *et al.*, 2005). Consequently, MEZZO needs to be validated on a big network and speed-density functions is recommended to be more simple.

### *2.3.8 DISCUSSION AND CONCLUSIONS*

From the overview above, mesoscopic DNL models are generally varying in capturing traffic dynamics. As before, these models can be categorized in terms of flow propagation presentation. Under these circumstances, flow is presented either as discrete platoons; CONTRAM (Leonard *et al.*, 1989), DYNAMIT (Ben-Akiva *et al.*, 2010) and DYNASMART (Jayakrishnan *et al.*, 1994) or in a continues representation distributed in the space and time; MEZZO (Burghout *et al.*, 2005) and DYNAMEQ (Mahut and Florian, 2010) . Recently, researchers have paid a lot of efforts to practice the discrete approach with many vehicles compounded in each packet; computers were taken in the concern because of the capabilities of their limited resources, which would handle simulations. At present, it became possible to handle simulations with a single vehicle per packet because of current powerful computers offers. However, the continuous approach attracted only a limited number of researchers; this is related to the inherent complications in the numerical problems for the internal uniformity as soon as instantaneous density distinctions between neighbouring simulation phases take place.

Mesoscopic DNL models may be further categorized regarding the queue representation. CONTRAM model (Leonard *et al.*, 1989) adopts the time-dependent queue theory; the queue is a result of capacity constraints. In other words, once the capacity exceeded by the demand, then queue factors can be identified. Moreover, the model assumed Point-Queue process which didn't take in the account a real or physical queue over the link. This falls under what so-called travel time models; (Astarita, 1996; Adamo *et al.*, 1999; Taylor, 2003). This type of models considers the entire link so that the travel time is the result of queuing and running time as well as in DYNASMART (Jayakrishnan *et al.*, 1994). Consequently, travel time-based model generates incorrect densities.

In contrast to CONTRAM (Leonard *et al.*, 1989), DynaMIT (Ben-Akiva *et al.*, 2010) and DYNASMART (Jayakrishnan *et al.*, 1994) use flow-based models that load individual vehicles according to a modified Greenshield speed-density approach (Greenshields *et al.*, 1935). In addition, they adopted a physical queue over the network links, assuming that each link length is compounded by a running part and queuing part. In the queuing part, traffic conditions are assumed to be fixed. This yields a less realistic representation of traffic flow over links. These models are oriented in general to any network worldwide comparatively to DynaCHINA (Lin and Song, 2007) which is oriented to the Chinese traffic systems taking in the account a mixed traffic class, as a pioneer experience where can be transferred to any other country.

Unlike DynaMIT, each of DYNAMEQ, CONTRAM, MEZZO, and DYNASMART did not include in their framework a methodology for the online demand estimation and calibration or network state estimation. Moreover, Event-based simulation is handled in MEZZO and DYNAMEQ; queuing and travel time estimation are modelled explicitly.

This thesis proposes a mesoscopic dynamic network loading model that simulates the real-time spillback queuing whereas link consists of a length-varying running and queueing part in order to detect the effect of the dynamic queuing. Moreover, discrete packets represent the flow where each packet consists of one or more from different classes, so a more realistic output can be captured.

## *2.4 TRAFFIC ANALYTICAL MODELLING*

According to (Yang, 1997), the existing methods for traffic modelling can be classified to four approaches i) neural networks ii) statistical iii) simulation based iv) analytical dynamic traffic assignment approach. They also classified as a simulation-based, analytical or hybridisation between the both as noted by (Celikoglu and Dell'Orco, 2007). However, the latter is described by a system of mathematical equations set which usually retain analytical characteristics. Moreover, it focused on the system optimum objectives (SO) or the dynamic user equilibrium (DUE) purposes. Attaining a unique solution for SO or DUE is the ultimate objective, more details can be revealed in (Szeto, 2003).

Again, the analytical dynamic traffic assignment modelling problem has been solved for DUE and SO through a set of mathematical programming problem solution (MP) (Merchant and Nemhauser, 1978; Carey, 1987; Janson, 1991; Ziliaskopoulos, 2000), by an optimal control problem solution (OCT) (Friesz *et al.*, 1989; Wm, 1991; Ran *et al.*, 1993) or by a variational inequality problem answer (VI) (Friesz *et al.*, 1993; Ran and Boyce, 1996). In recent years, analytical dynamic traffic assignment has shifted toward variational inequalities (VI) approach to alter the optimal control theory (OCT) and the mathematical programming solution (MP) due to their limitations, however an extended comparison of VI, OCT and MP are illustrated in (Peeta and Ziliaskopoulos, 2001).

In the literature, the analytical DTA models were well-known based on the adopted function for detecting the traffic dynamics; link performance function models, exit function and cell transmission models:

- **Link performance modelling approach (LP)**

  In the link performance approach, travel time is a function of traffic flow. In other words, the link travel time is a function of vehicles number. Moreover, capacity limitations are not explicitly taken in the account. Further, FIFO is not respected, and the modelling of queue spillback is not applicable to this approach. Some of the studies employed a link performance approach; (Ran and Boyce, 1996; Chen and Hsueh, 1998; Bliemer and Bovy, 2003).

- **Link exit function modelling approach (LEF)**

  As well as the performance function approach, link exit function models also violated FIFO by assuming a dynamic density variation. Furthermore, they are helpless in modelling the queue spillback. Link outflows are determined as a function of the given number for vehicles that loaded to each link and the travel time depends on traffic conditions as described in (Carey, 1987). Hence, exit approach has been hired for traffic propagation in different DTA; (Merchant and Nemhauser, 1978; Carey, 1987; Friesz *et al.*, 1989; Ortigosa *et al.*, 2015).

- **Cell transmission modelling approach (CTM)**

  As illustrated former, the cell transmission model has been constructed by (Whitham, 1955; Richards, 1956), simultaneously they developed the most straightforward continuous flow model assuming that the number of vehicles is conserved between two points as long as there are no existing entrances or exits (Cantarella *et al.*, 2014). The resulting model is known as the Lighthill-Whitham-Richards (LWR) model, which is considered as a first-order model.

  In general, the differential equations used in the LWR model are complicated to solve. Daganzo (Daganzo, 1994;1995) has discretized the continuity into homogeneous sections called cells through his model which is well-known as the cell transmission model (CTM). Conversely to LP and LEF, Th cell transmission model was able to describe the traffic conditions including queue spillback.

Furthermore, it simulates the traffic with a time scan process whereas the current traffic conditions are updated in every clock tick. In addition, CTM is based on a simplified trapezoidal or a triangular form which provides a constant free flow speed, at low densities, and backward shockwave speed for high densities as described in (Cantarella *et al.*, 2014). To take a case in point, CTM was used in some assignment problems (Lo, 1999; Szeto and Lo, 2004).

## DISCUSSION AND CONCLUSIONS

The analytical approach is easy to implement compared to the simulation-based; it relies on direct mathematical computations to determine the dynamics of the system when it used to solve an assignment. Additionally, the analytical approach is capable of predicting traffic dynamics in the presence of a variety of transportation facilities. Most analytical models rely on a method of successive averages (MSA) that includes an iterative mechanism to approximate the solution.
Of course, they are applicable for analyzing link performance function or small-scale transportation facility; but in the meantime, their abilities to analyse a network are limited.

## *2.5 DYNAMIC NETWORK LOADING (DNL) FRAMEWORK*

### *2.5.1 BACKGROUND*

Modelling the network loading for traffic dynamics is at the heart of any modelling process for dynamic traffic assignment (DTA). Basically, the DTA model was proposed to perceive the choice of driver route; this can be made available by identifying the set of possible paths for users and evaluating the various alternatives in some criterion. Eventually describing the driver's choice. Modelling of this choice selection is a special case of the discrete choice modelling theory (Ben-Akiva *et al.*, 1985; Ben-Akiva and Bierlaire, 1999; Garrow, 2016). However, this type of models has shown a crucial role as a tool in analyzing transportation networks in the last three decades, given that static models are still used.

Researches to achieve concerned progress using static network loading models until 1980 (Wu *et al.*, 1998b). Accordingly, the limited ability in perceiving the real-time traffic characteristics has led to shift to the dynamic network load models (DNL). In addition, the DNL approach presents a nonlinear relationship between link dynamics and path flows, unlike the static network loading that is linear and easy to solve.

### *2.5.2 CONTINUOUS MULTICLASS DYNAMIC NETWORK LOADING PROBLEM*

In fact, solving for flow dynamics, for example; travel time, a number of vehicles and flows from each class, requires determining of the continuous multiclass dynamic network loading problem. With eyes on applying the DNL method for the multiple types of vehicles, a successive dynamic network loading must be performed as a continuous-time regime of non-linear equations in the framework of boundary conditions, link dynamics, flow propagation and flow conservation constraints as well. This requires the construction of a model with a discretized time slices on a mesoscopic basis, with support of applicable algorithms.

On the one hand, a real-time simulation with consideration of different vehicle classes would increase modelling accuracy to represent traffic conditions. On the other hand, it is not trivial, because the system has to be able to handle different speeds, dynamic lengths, overtaking and so on. Moreover, handling more than one class motivates users of passenger cars  to overtake heavy ones acting in contrast to FIFO in the running part, conversely to the queuing part when the queue formed; no overtaking is possible. However, the challenge becomes surplus complicated in the direction of a promising solution. Passing through existing DNL methods; (Daganzo, 1994; Nie and Zhang, 2005; Dell'Orco, 2006; Celikoglu and Dell'Orco, 2007; Celikoglu *et al.*, 2009a; Castillo *et al.*, 2012), link travel time has been assumed equivalent for all users, and FIFO has been obeyed too. On the contrary, pretty modifications recommended by a number of authors led to models that recognize overtaking seeing congestion as a ratio as in (Castillo *et al.*, 2013) or a physical queue in macroscopic simulation as in (Bliemer, 2007).

### *2.5.3 CONTINUOUS MULTICLASS DYNAMIC NETWORK LOADING SOLUTION*

Generally, the solution of the dynamic network loading problem can be analytical, simulation-based or hybridization of the two approaches. In sections 2.2 and 2.3, these approaches have been taken in details, so it is worth to discuss them in short. The analytical model adopts direct mathematical computations to determine system dynamics. On the contrary, a simulation-based approach utilizes an algorithm to propagate flow dynamics that reused again for specific phases of flow propagation and traffic assignment. Moreover; this type of models is capable of initial modelling solutions, assuming that the performance of the optimized model parameter set; estimates the expected performance of that set in the succeeding time span with the assistance of antecedent data: DYNAMEQ (Tian *et al.*, 2007; Mahut and Florian, 2010), DynaMIT (Ben-Akiva *et al.*, 2010), CONTRAM (Leonard *et al.*, 1989) and DYNASMART-X (Fei *et al.*, 2009).

In this study, the hybrid approach is employed on a mesoscopic level to simulate the spillback of the queue concurrently with the support of link dynamics. In the literature, the hybrid approach has been used extensively, such as the models provided by (Daganzo, 1995; Burghout *et al.*, 2006; Celikoglu and Dell'Orco, 2007; Celikoglu *et al.*, 2009a).

One of the few studies that broke the barriers of dynamic network loading is the one by (Friesz *et al.*, 1993). Hence, CDNLP has been formulated for the first time as a fundamental component of the dynamic equilibrium problem. Of course, they did not exclude a proposed solution, but FIFO condition holds at whatever the path travel time function presents.

By the time, (Astarita, 1995;1996) has proposed a CDNLP model which is based on the interaction of link outflow function and travel time concurrently. Indeed, the relationship confers outflow dynamically as soon as inflow together with travel time functions are given, under the assumption of FIFO rule respecting. Thereafter, CDNLP has been described by a system of functional equations on the hands of (Wu *et al.*, 1998b). An approximated solution was achieved by solving a system of polynomial and finite dimensional estimation functions.

By efforts to decrease the discretization errors by (Wu *et al.*, 1998b), through reducing control variables together with the utilization of inexplicit continuous functional form, an improved solution for CDNLP has been evolved by (Xu *et al.*, 1999). In more details, a discretized version of a finite-step algorithm through a system of non-linear equations formulated; to solve for route travel times coupled with time-based path volumes dynamically.

These considered determinations were preceding the one by (Chabini, 2001), where the DNL analytical problem was considered in the discrete-time presentation, through two simulation-based and analytical models called C-load, I-load respectively. The latter is easy to implement, but at the same time, it is slow in approximating solutions since it adopts the method of successive averages (MSA) in its methodology; the model iterates to solve the DNL problem as a fixed point problem. Further, it is not guaranteed to give simulation outcomes that can be considered as an exact solution, but they would be close enough to it, for that I-load is concerned as an empirical model. On the contrary, C-load is an exact algorithm that adopts time-based simulation methods. Consequently, C-load solves for the DNL problem by the induction of the discretized intervals in sequential order.

In this context, two improved numerical algorithms for the CDNL problems offered by (Rubio-Ardanaz *et al.*, 2003). They performed those improvements on the functional approach which was given by (Wu *et al.*, 1998b) and the solution scheme assumed by (Xu *et al.*, 1999). The latter is a method in which based on link exit time functions and their inverses which known as DYNALOAD. To be more precise, DYNALOAD was the first improved algorithm by (Rubio-Ardanaz *et al.*, 2003) through assuming a third order Langrage polynomial approximation for the effective discretization of time slices for the given by (Wu *et al.*, 1998b). After then, the second improved algorithm developed by reformulating the DYNALOAD of (Xu *et al.*, 1999) problem by involving only the cumulative flow functions which require inexplicit exit functions and explicit consideration of capacity constraints. The computational results obtained have considered as an improvement on the results reported by (Wu *et al.*, 1998a).

A time later, (Dell'Orco, 2006) uncovered a new study where the accelerations of the vehicle have been taken in the account, assuming a mesoscopic discrete single node model that showed responsible results. Directly, the approach has been extended to a dynamic link loading process (Celikoglu and Dell'Orco, 2007); by employing a system of non-linear equations set. In more details, they assumed that vehicles of each packet are allocated on the link where the head of that packet is.

Further, the speed has assumed equal for all packets over the link and accelerated uniformly. Moreover, the speed variable has been assumed as a function of the average density. This study was as a part of a wider study, where travel time function for link performance considering the constraints of flow conservation, flow propagation, boundary conditions and capacity constraints is adopted (Celikoglu *et al.*, 2009a). In other words, they assumed that the discrete mesoscopic model consists of link and node models, that interact to capture traffic dynamics. By means of link exit function (LEF), the link outflow is a function of the number of crossed vehicles to the network regardless of their position.

Instead of starting with an exit flow function, their proposed methodology differed from the LEF approach by employing a mesoscopic simulation solution and matches the LEF approach by requiring link travel times to be defined from the inflows and outflows. At this point, link loads are the input to the node model, and the outflow yields by maximizing the total traversal flow through the node. A buffer area for the exceeding flow has been assumed at the nodes of links as a consideration of capacity constraints. Consequently, adding these delays to link travel times gives the total link travel time, more details can be explored in (Celikoglu *et al.*, 2009a).

Later on, (Di Gangi *et al.*, 2016) proposed a DNL model to simulate a multi transportation mode, considering varying en-route transportation modes. Further, outflow conditions have been assumed to be captured of at the beginning of each sliced time interval regardless to packet order. Additionally, they assumed that link consists of a moving and queuing segments. Tracking each packet movements, where a point situated at abscissa of the link represents its position, allows detecting the real-time length of the assumed physical queue. Accordingly, travel time is assumed as a function of link flow.

### *2.5.4 SOLUTION ALGORITHM OUTLINE*

For a better description of the proposed algorithm outline, the following well-known terms are worthy of clarifying:

- **FIRST-IN-FIRST-OUT (FIFO) condition**

  In continuous dynamic network loading, FIFO performance is preferred in DNL mesoscopic simulation. Having FIFO conditions satisfied gives correct flow propagation aggregation and correct link travel times accordingly. To achieve so, a user who loaded to such link earlier is required to leave that link earlier. Mathematically;

  $$\forall(t_1, t_2) \in [0, T] \quad if\ t_1 < t_2,\ then\ t_1 + \tau_i(t_1) < t_2 + \tau_i(t_2) \qquad (2.1)$$

  This expression can be interpreted as, once a packet is loaded to a given link at a certain time; this inequality disallows to that packet to catch the packets that loaded before.

  Furthermore, link traversal time in the direction of exiting has to be non-decreasing. In more details, this condition has to be guaranteed in the running segment on the link, naturally in the queuing link segment the overtaking is impossible, as expressed mathematically;

  $$\forall(t_1, t_2) \in [0, T] \quad if\ t_1 \leq t_2,\ then\ t_1 + \tau_i(t_1) \leq\ t_2 + \tau_i(t_2) \qquad (2.2)$$

  In this thesis, the running part where multiclass property based on vehicle types is applicable, the overtaking is allowed among different classes. Moreover, FIFO holds per each vehicle class, and no overtaking in the same class is allowed.

- **Queuing approach**

  Traffic congestion is a daily problem in most urban areas. Usually, during peak periods; capacity becomes deficient in handling traffic demand which known as a capacity drop. Moreover, traffic delays aggravated when congestion sets in.

In fact, two main facts are caused by oversaturation: queue spillback and capacity drop. Spillback of the queue takes place when queued vehicles occupy link storage. In most cases, the queues form at the bottleneck expand reaching starting node at the link entrance; this generates a blockage against traversing the bottleneck as depicted in Fig. 3:

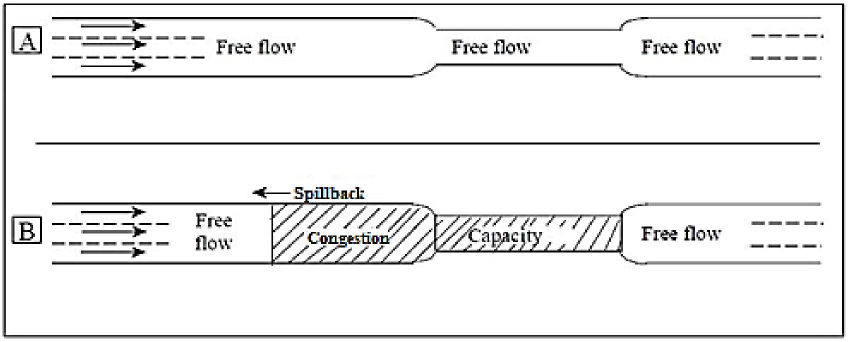


Fig. 3 - The traffic flow on road section with a bottleneck

Accordingly, the spillback discharges the flow to other network links, potentially resulting a gridlock phenomenon.

In the literature, delay represented in many DNL models as link travel time functions. Furthermore, travel time was aggregated as a function of the number of vehicles over the link at the time of loading, a good illustration of this; (Astarita, 1996; Wu *et al.*, 1998b; Chabini, 2001; Bliemer *et al.*, 2004). However, adopting such assumption violates the realism in the sense of travel time reliability. In other words, the real travel time is the traversal time that the packet consumes crossing the concerned link and this time gained only until the packet leaves that link.

Moreover, these travel time functions assume fixed travel times, which act contrary to the real-time representation of traffic dynamics; capacity, queuing and outflow where they are products of these travel times.

Instead, some DNL models represent delay as unrealistic vertical queues or point queues, where the flow surpassing capacity is assumed to be stored in virtual buffer areas. However, they take place at the initial node of the link; (Celikoglu *et al.*, 2009a; Ban *et al.*, 2012; Zhengbing *et al.*, 2015). Then, the delay in assuming buffer areas is added to the travel time.

Conversely, realistic horizontal queue approach is preciously dividing links into running and queuing parts, where these segments behave dynamically regarding their length in the one hand and flows and capacity on the other hand. The vehicles in the queuing part are delayed due to the capacity limits of the downstream for such link. The nodes are modelled by means of transferring from the upstream flows to downstream govern by the vehicles exiting process.

However, in this thesis, the proposed model assumed the link as a combination of running and queueing segment where a horizontal queue formed as soon as congestion occurs.

- **Multiclass simulation based on the vehicular type**

  For modest simulation efforts, a limited number of studies have taken in the account different dynamics during flow propagation. A good illustration of those simple efforts is the simulation considering assuming single class flow. The number of assumptions is in some way inversely proportional to the closeness of modelling to the reality.

  Unlink single class models, where DNL has been studied assuming that the traffic network is accessed by one type of vehicle (passenger car in most cases); (Dell'Orco, 2006; Celikoglu and Dell'Orco, 2007; Celikoglu *et al.*, 2009a; Ban *et al.*, 2012; Han *et al.*, 2013), a multiclass, based on the type of car, has an significant role in scheming of the travel time in particular; in the link moving part.

  Actually, passenger cars compete to overtake heavy vehicles; this impacts link travel times because each vehicle class has its own link travel time function. Accordingly, not all traffic classes move at the same speed over the link.

As mentioned before the simulation of traffic with more vehicle types generates different speeds, densities, and flows. Of course, vehicle types on the same link at the same time influence each others (i.e. a vehicle type can have a certain impact on the link travel times of other vehicle types), possibly in an asymmetric way, yields an increased complicated challenge in the direction of a promising solution, but multiclass cannot be disregarded in the traffic modelling for better representation of the real world situation on the network.

- **Discrete time-based solution framework**

  As mentioned before, models can be considered as continuous and discrete with an eye on the elements properties variation to describe the system; To be specific, continuous models simulate the system as fluctuating continuously across time. Typically, it is described by a set of complex differential equations that are difficult to solve, despite the fact that the discrete is the one of which simulates systems as discrete changing points over time.

  The discrete approach consists of discrete time-based and discrete event-based models. The time-based splits the time horizon of analysis into fixed time slices, and subsequently, it determines the traffic characteristics at each slice. Conversely, the event-based models detect the sharp variations in the system and then undertake calculations. However, the discrete time-based is preferred to employ when the simulation is needed to be more described and realistic.

  In this thesis, the discrete time-based approach is selected to represent the continuous simulation time. In other words, the algorithm handles discretized time periods as a product of horizon length $[0 - T_\infty]$ divided by the number of wished periods. In this context, more number of periods consequences more precise simulation outcomes and more computational efforts. On the contrary, a less number of periods yields an approximate solution with humble computational needs.

From these motivations, the planned continuous simulation is divided into time slices:

$$\text{Time slice length } (\sigma) = \frac{T_\infty}{N_\infty} \tag{2.3}$$

Where, $[0, T_\infty]$, donates a continuous simulation time for such a network. And $N_\infty$, is the selected number of time slices. As for intervals, they are indexed by a positive integer number incremented as follows;

$$n_\infty = [0,1,2,3, \ldots \ldots, N_\infty]$$

Time intervals are subjected to the interval $[n_\infty . \sigma,\ (n_\infty + 1). \sigma]$. However, the algorithm iterates in each time slice for capturing traffic dynamics.

- **THE FUNDAMENTAL DIAGRAM**

In fact, the mathematical relation between different traffic dynamics (flow, density and speed) is represented as a set of simulation results in a diagram called the fundamental diagram. This diagram is considered as a primary function of transportation engineering to capture mobility flow-based variables (Mannering *et al.*, 2012). To be specific, analyzing traffic reflects a glance in terms of the measurement of the operational performance on the road.

The correlation between the density and the flow is the most inherent focal point in the way of constructing a consistent and comprehensive mesoscopic traffic model, assuming a road section with a single packet. Accordingly, the density, in this case, would be very low which allows the drivers to freely travel approaching a speed close enough to the design speed. Hence, this speed is known as the free flow speed. In turn, while more and more packets enter the section, the density would upsurge in such way other packets will likely drop from free flow speed to the average operational speed as drivers slow to permit others to manoeuvre as well.

The section will turn out to be congested characterized by a high value of density, and the speed would drop to zero, this density is called the jam density. Typically, density is dependent on the length of packets or vehicles coupled with the gaps among them in one hand, and to the number of them on the other hand. The interpretation is the linear relation depicted in Fig. 4.

However, the relationship between section speed and its density exists and presented in the Greenshield model (Greenshields *et al.*, 1935). Mathematically can be expressed as;

$$v = v_f \left(1 - \frac{k}{k_j}\right) \tag{2.3}$$

Where,

$v$: Space-mean speed

$v_f$: Free flow speed

$k$: Density

$k_j$: Jam density

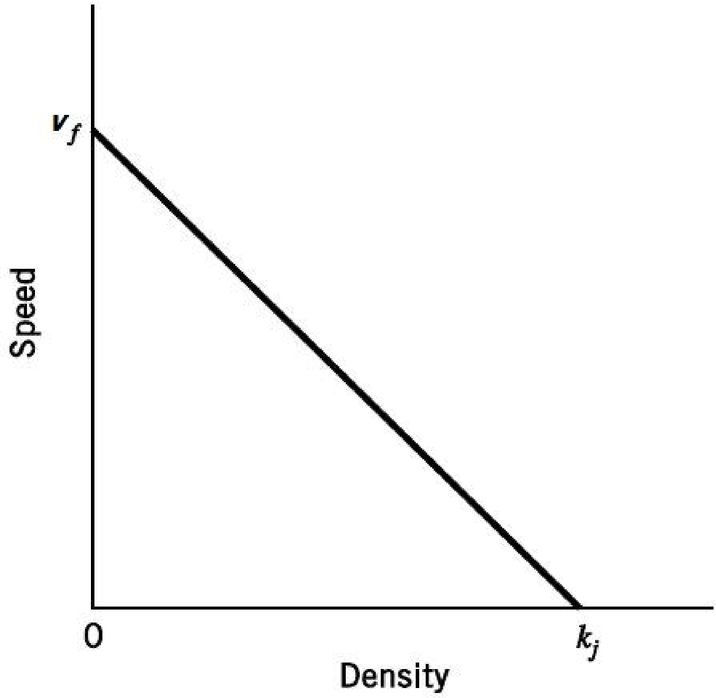


Fig. 4 - the linear relationship between density and speed.

In fact, the linear demonstration of the speed-density relationship makes available of a simplified understanding of the relationships among traffic dynamics, avoiding of confusing these variables by the surplus complexity that a nonlinear speed-density relationship presents. Of course, it is basic and easy, but it also worthy to note that field studies have shown that it is rational to give a picture of non-linear relationship at low and high densities to better describe the jam density and free flow speed as well (Mannering *et al.*, 2012).

Basically, flow, density and average speed are factors that describe the traffic dynamics at the macro and mesoscopic level. A good illustration of their correlation is presented in this basic formula:

$$q = v.k \tag{2.4}$$

Where,

$q$: Flow

By substituting Eq. 2.3 in Eq. 2.4. The parabolic (non-linear) flow-density relationship can be formulated:

$$q = v_f \left( k - \frac{k^2}{k_j} \right) \tag{2.5}$$

Graphically,

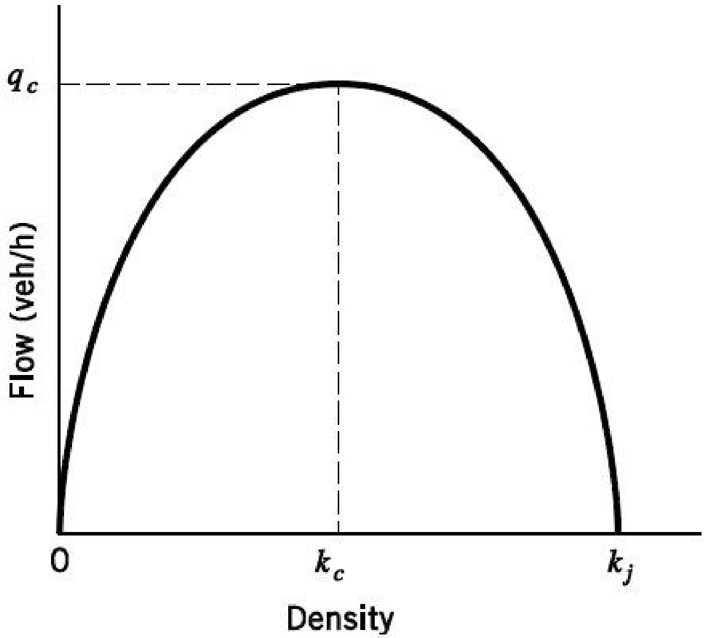


Fig. 5 - The non-linear relationship between density and flow

The maximum flow at the point $(k_c, q_c)$ where$(dq/dk) = 0$ , is capable of manipulating before congestion occurs.
As illustrated in Fig. 5, link capacity corresponds to the maximum flow ($q_c$), critical density ($k_c$ and critical speed ($v_c$). Mathematically;

$$\frac{dq}{dk} = v_f \left( 1 - \frac{2k_c}{k_j} \right) = 0 \tag{2.6}$$

At the maximum flow, where $k = k_c$ and $= k_c$ , since $v_f \neq 0$ ;

$$k_c = \frac{k_j}{2} \tag{2.7}$$

Subsequently, substituting Eq. 2.7 in Eq. 2.3, provides:

$$v_c = k_j\left(1 - \frac{k_j}{2k_j}\right) = \frac{v_f}{2} \tag{2.8}$$

Calling Eq. 2.4, and substituting Eq. 2.7 and Eq. 2.8, the maximum flow ($q_c$) or the capacity ($C$) of a generic traffic link:

$$q_c = v_c.k_c \tag{2.9}$$

Then,

$$C = \frac{v_f\,.k_j}{4} \tag{2.10}$$

Calling the linear density-speed relationship to develop a flow-speed correlation. The Eq. 2.3 can be rearranged as follows:

$$k = k_j\left(1 - \frac{v}{v_f}\right) \tag{2.11}$$

Now, by substituting Eq. 2.11 in the fundamental equation (Eq. 2.11), the flow can be formulated as follows:

$$q = k_j\left(v - \frac{v^2}{v_f}\right) \tag{2.12}$$

This has led to a parabolic function, as illustrated in Fig. 6. To be more precise, there are two speeds are available for flow; critical speed ($v_c$) which corresponds to the maximum flow (capacity), and the free flow speed which corresponds to a tiny density and flow ($q \cong 0$).

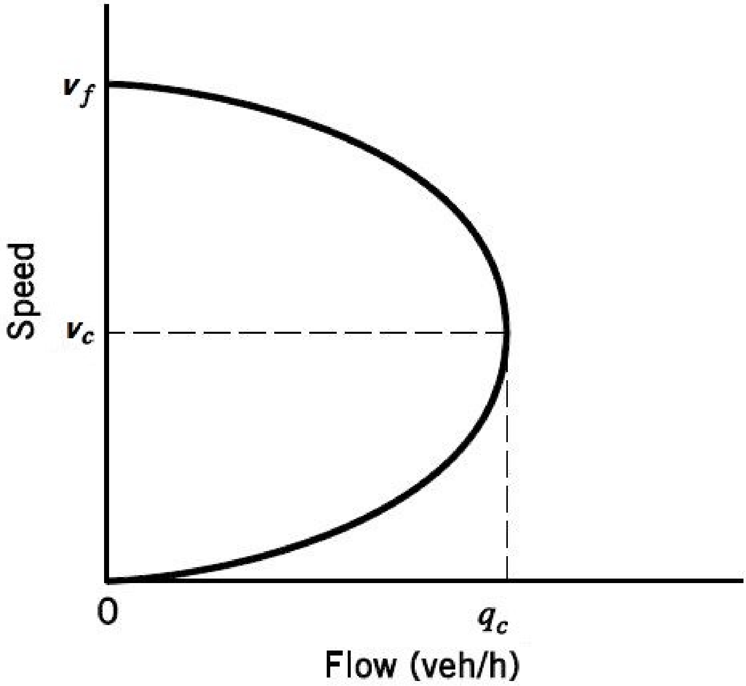


Fig. 6 - The non-linear relationship between speed and flow

It is worthy to note that, the higher portion of the parabolic (above $v_c$) is related to the average space-mean speed. However, once the speed falls in the lower area, it will start to correspond to unstable conditions. In other words, traffic tends to be highly congested gradually and the spillback holds.

The upshot of all is depicted in Fig. 7 where the interactions among flows, densities, and speeds are represented at once.

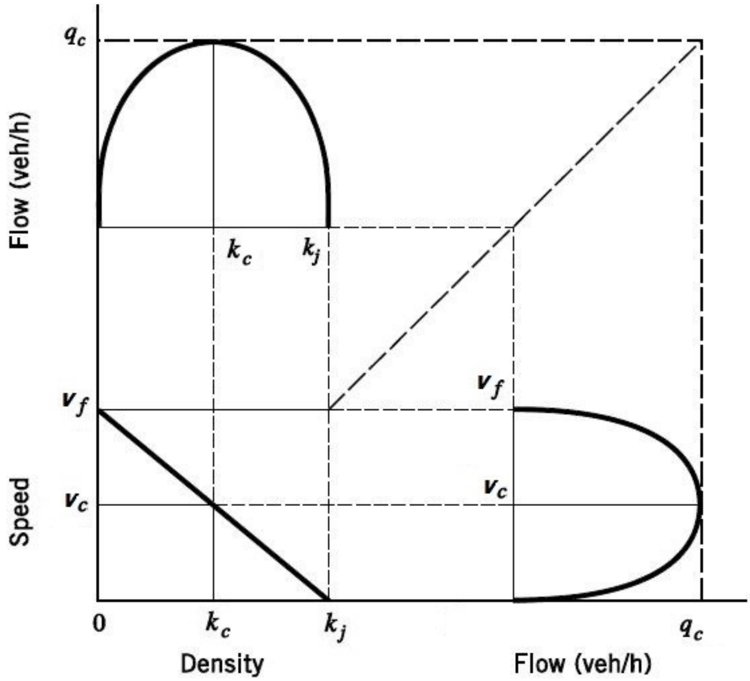


Fig. 7 - Illustration of non-linear speed-flow, density-flow relationships and linear speed density relationships

In conclusion, last significant relationships have been reproduced by Greenshield (Greenshields *et al.*, 1935) as pointed out before. Additionally, they were employed widely in the literature in many considered studies that adopt macro and mesoscopic stream models, to represent the performance of traffic flow changes and how one parameter affects the other.

## *2.6 TRAVEL TIME IN TRAFFIC AND LOGISTICS MODELLING*

Travel time data is essential for many purposes. In traffic, information is needed to guide the drivers for selecting the right path for little time and cost accordingly. In other words, more reliability can be achieved by selecting travel en-route and pre-trip. To improve the level of service, travel time is an index for traffic managers to understand transportation system operations

A significant number of research studies (Buisson *et al.*, 1998; Wu *et al.*, 2004; Oh *et al.*, 2015; Jenelius and Koutsopoulos, 2018; Moonam *et al.*, 2019), interested in travel time estimation and confirmed the role of travel time data in the practical applications in transportation and logistics. In the meantime, these data used in many fields and applications, it gives information to the driver to understand the traffic conditions. Consequently, drivers can avoid congested links, which improve the level of service for commercial delivery to distribute goods by the expected time.

In particular, the methodology of predicting travel time in terms of data quality depends on two principles; the simplicity of the methodology is weighted in contrast to the quality. In turn, the data quality relays on the traffic conditions; in the area, with stable traffic characteristics a simple estimation may be used, but in the areas where the traffic conditions change the travel time prediction model rapidly is essential (Van Grol *et al.*, 1999). Because the travel time is a sensitive factor which impacted by many elements, and a single incident could generate valued congestion during the trip.

In particular, the method of predicting travel time depends on two principles; the simplicity of the method and the data quality. Data quality relays on the traffic conditions, for example, a simple estimation can be used in the area which has stable traffic characteristics. Likewise, the areas where the traffic conditions change, travel time prediction model is essential (Van Grol et al., 1999).

### *2.6.1 TRAVEL TIME VARIABLES*

At present, the travel time data plays a valued role in traffic simulation and logistics. It used in ITS and advanced systems for traffic control. As for, travel time is impacted by many traffic factors; the accurate estimation needs too many traffic data. The data which influencing travel time is rational for increasing the estimation accuracy.

Users, vehicles and infrastructure elements are the main components of the transport system. Many factors influence these elements also influence the final travel time. For example, many types of vehicles with other traffic conditions can achieve diversity in time. Furthermore, different travel times can be detected even though they use the same route in the same time period (Li and McDonald, 2002).

In general, free flow speed is the main factor that affects travel time. Therefore, the link speed depends not only on the road geometry but also on the traffic flow conditions with signals coordination (Lum *et al.*, 1998). Other significant factors that influence travel time estimations are a signal delay (Wu, 2001), holidays and special incidence (Karl and Trayford, 2000) and weather conditions (Chien and Kuchipudi, 2003). The greater length of the simulation period results a greater prediction error (Kisgyörgy and Rilett, 2002). However, the accuracy and efficiency of prediction models depend on the adapted variables during the estimation process.

### *2.6.2 TRAVEL TIME MEASUREMENT*

There are many methods used to perceive travel time; the driver can record his travel time using a stopwatch. Other methods like toll-gates (Martí, 2016; Fan *et al.*, 2018) and plate recognition (Liu *et al.*, 2011) can detect travel time automatically. However, the measurement of travel time can be achieved by tracking vehicles from fixed points along the link section to another selected point. Alternatively, by using moving observation platforms routing in the traffic stream and tracking the progress of travel time.

The most used method for measurement is site-based. It includes registration plate matching, indirect or remote tracking and input-output methods and so on. In addition, the stationary observing systems where the loop detectors, radio beacons video surveillance and transponders employed to get the travel time detected (D'Este *et al.*, 1999). On the contrary, the moving observer procedures include the floating car, volunteer driver and probe vehicle techniques. The succeeding sections bring together the main methods to measure the travel time:

-**Site-based travel time measurement techniques:**

As for, the site-based includes a variety of methods as follows:

- **Registration plate matching** methods are made up of collecting departing vehicle license plate characters and arriving ones, then by matching both plates, the arrival times at various consecutive checkpoints can be aggregated. This method of the survey can be manual, or by tape records, these days, the license plate can be captured as a video or a speech, and then they can be transformed to a digital data using recognition techniques like the dynamic image processing (Joseph and Singh, 2016).

- **Remote tracking** is a technique that use the vantage point to detect vehicle movements progress. According (Shailes, 2001; Taylor and Bonsall, 2017), the travel time data of individual vehicles along the short section of the roads can be gained by tracking them from a vantage point that has a view of the start and the end of the path.

- **Input-output and hybrid techniques,** this method can predict the average travel time for crowds of vehicles and the travel between aimed survey sites. Nowadays, technological advancement in the area of traffic and sensors controllers achieved an effective travel time measurement (Sharma *et al.*, 2007).

- **The cellular telephone system** is one of the advanced possible today techniques to provide travel time data. The technique uses local operators and location devices to aggregate travel time and other traffic data. In the foreseen years, it is possible that the vehicles are likely to communicate with each other's with support of some control centres, this leads to more enhanced traffic estimation gained from the cellular system techniques (Gundlegård and Karlsson, 2009).

- **Vehicle-based measurement techniques:**

  the traffic data estimation methods are the site-based using fixed sensors on the sides of the road section as the highway cameras (Shan and Zhu, 2015) or magnetometer detectors (Kwong *et al.*, 2009). Besides the second technique which is the floating vehicle data (FVD). Floating vehicle data is a data accumulation of vehicles routing city roads during the day. Taxies and express delivery vehicles are the absolute examples of the FVD data collection method, as they are traversing most of the city road daily.

  Of course, FVD not only the cheapest data gathering performance, as many express corporations and taxi agencies are automatically aggregating these data for logistics and management purposes, but also the position data are very accurate because of the global positioning system (GPS) is used onboard. On the contrary, FVD has the drawback of processing needs. The used service vehicles as before are order vehicles, and they generate big data, which needs a machine learning/productive algorithm in order to manipulate these data toward getting meaningful travel time estimations.

### *2.6.3 TRAVEL TIME SIMULATION MODELS*

Congestion is growing with alarming rapidity and continually posing a threat to life quality in many countries worldwide over the last decades. The surplus travel time using public transportation modes, for example, pushed people to own private cars farther; this leads to more fuel usage, air pollution and more traffic demand, therefore less accessibility and mobility. However, this motivated managers to reduce the challenge of traffic jam through different techniques days; supporting the supply side by constructing more roads, bridges and adding more lanes, and adjusting the demand side (traffic management and congestion pricing) and their integration.

Dynamic travel time data cannot be easily measured nor provided directly. Hence, mathematical models can obtain a promising prediction with reasonable accuracy, which is necessary. There are many traffic flow models, which developed for travel time prediction; however, some of them are discussed -in general- as follows:

- **Historical average models**

  This classification of models provides current and future travel time using observed historical data for former trips assuming that the present traffic circumstances unchanged. Therefore, historical average models could be suitable for dynamic travel time data since the algorithms required to be simple with relatively short simulation time.

  Nevertheless, the performance of this type of models is small, excluding the case when the traffic pattern in the area of interest is moderately stable over time or where the congestion is negligible. In short, historical average models assume that the historical observations are similar to the current dynamic data and then they estimate the time of a particular journey based on different previous journeys travel times (Yu *et al.*, 2018). Many research efforts directed to the bus travel time estimation using this type of models, some of these studies are described in (Jeong and Rilett, 2004; Ramakrishna *et al.*, 2006).

- **Kalman Filtering models**

  This category of models can be employed for predicting the dependent variable, taking advantage of their elegant demonstration, for instance, the linear state-space equation, where the traffic fluctuations can be sufficiently accumulated with their time-dependent parameters (Chien *et al.*, 2002). However, the basic purpose of these models is to provide a current estimation from prior time steps.

  Kalman filtering models can be used for providing a prediction for future data or improving the estimations of variables at earlier times exploiting their capacity to filter noise (Kalman, 1960). Furthermore, Kalman models were used by many authors particularly for bus travel time estimation; (Chien *et al.*, 2002; Shalaby and Farhan, 2003; Chen *et al.*, 2004; Vanajakshi *et al.*, 2009).

- **Regression models**

  Regression models (Chen *et al.*, 2004; Jeong and Rilett, 2004; Patnaik *et al.*, 2004) involve a linear mathematical function to describe a dependent variable with a trend of independent variables. The dependent variable can be the total of operations, trips or passengers. To differ from other models, regression models are competent to offer satisfactory outcomes in terms of travel time data even though traffic conditions could be unstable.

  Typically, they measure the concurrent impact of many factors that affect a dependent variable. To exemplify, (Patnaik *et al.*, 2004) have developed multiple linear regression models where the bus travel time has been predicted using the information of position, dwell times, stops number, alighting passengers data and weather information as independent variables. In addition, they found that the regression models are capable of using for bus arrival time prediction at downstream stops. Also, Ramakrishna (Ramakrishna *et al.*, 2006), Jeong and Rilett (Jeong and Rilett, 2004) have also developed multiple linear regression models using many sets of independent variables

- **Machine learning models**

  When the one thinks in travel time prediction using machine-learning techniques, with a possibility to handle noise and complex data, the rationale is the artificial neural networks (ANN) modelling (Jeong and Rilett, 2004; Ki *et al.*, 2018; Pang *et al.*, 2018). According to (Penm *et al.*, 2013), neural networks modelling are a non-linear statistical data tool that includes highly unified joints which are capable to model complex relations among input and output data.

Additionally, ANN was first established for the traffic through the inspiration of biological neural networks, which constructed with several layers of processing divisions, called the artificial neurons. The latest contains activation functions (Vamvoudakis and Jagannathan, 2016) that are greatly unified with each other by synaptic weights (Omidvar and Dayhoff, 1997). However, the synaptic weights are adjusted automatically to map the input-output relationships through the learning process (Hagan *et al.*, 1996).

Recently, artificial neural networks have expanded attractiveness in predicting travel time thanks to their ability to handle complex non-linear interactions as can be explored in many studies as cited before. Hence, the outcomes of these models cannot be generalized from one location to another because of the geometry, traffic flow and control differences of each location.

# *CHAPTER 3. FRAMEWORK OF THE PROPOSED MULTICLASS SIMULATION MODEL*

## *3.1. BACKGROUND*

Dynamic network loading (DNL) designates a non-linear relationship between each link flow with path flows, on the contrary to the static network loading. Accordingly, path demand and link travel time in DNL problem-solving require disassembling of the dynamic path flow demand to links to find the traffic flow variables. Therefore, the traffic assignment uses the DNL model for modelling the traffic flow propagation and for calibrating the network performance in terms of travel time in the outline of flow conservation, propagation, link dynamics and boundary conditions constraints.

To demonstrate, the solution of the DTA problems is obtained iteratively, or by utilizing a feedback mechanism within a single iteration as performed by various simulation software packages. Successful simulation implementations of DTA such as DYNASMART(Jayakrishnan *et al.*, 1994), DynaMIT (Ben-Akiva *et al.*, 2010) and VISTA (Ziliaskopoulos and Waller, 2000) exists and definitely useful for the dynamic path flow generation and for the variable link performance computation as well as cited in (Celikoglu *et al.*, 2009b).

As clarified in the last chapter, in general, the dynamic network loading models were used in the literature had been intended through the following level of details:

Microscopic simulation fits the small scale planning determinations, in the light of a rich background about the entities interactions. In other words, the interaction between driver-driver and driver-infrastructure is handled by means of individual vehicle speed, time headway and space headway to represent the traffic conditions.

To differ from the microscopic, macroscopic models are capable of the general planning purposes adopting large-scale simulations. Furthermore, they assume the traffic as continuous fluid flow. The latter is subjected to the congruency and to the continuity constraints. With this in mind, the relation between the outflow and density on a link at time $t$ (exit link function) or the speed and density on the same link at the inflow time (travel time functions) is exist.

In both cases, there are other additional relations must guarantee that a portion of the vehicles which are running on this link at time $t$, will exit before new vehicles entering that link at the same time which is familiar as FIFO rule (Dell'Orco, 2006). In short, macroscopic characterizes the traffic stream inflow, density and average speed conversely to the micro where these parameters are time headway, space headway and vehicle speed respectively.

In this context, and due to the need of a reasonable level of details, coupled with entities interaction information at once, the mesoscopic models each link considering the traffic as a set of continuous or discrete packets. According to (Dell'Orco, 2006), each continuous packet is defined by its head and tail, while in the discrete case, the packet is defined by the head of the packet, regardless to the tail position. However, this study puts forward a dynamic multiclass mesoscopic model where the dynamic spillback of the queues is explicitly considered.

## 3.2. THE PROPOSED MULTICLASS MODEL

In general, the proposed DNL model represents a link-based model, which is capable of capturing the different traffic dynamics in the margins of boundary conditions. To be more definite, link model propagates demand on the traffic links as supposed in the kinematic wave theory.

Actually, the model defines flow propagation for each link in the origin-destination (O-D) route. Moreover, the mesoscopic link demand determined concerning a bulk of vehicles as accumulated into discrete packets. During the interval $[t, \Delta \mathrm{t}]$; all vehicles in each packet are assumed to be on the link once the head of that packet is on this link. However, in this study, the multiclass property based on the vehicular type is assumed, adopting the discrete mesoscopic simulation where each packet is made of one vehicle or more.

Assume $i$ to be a generic link in route the $p$. Following this, the group of vehicles, which depart at the same time interval and following the same path $p$ is noted as a packet $(\omega)$. Again, the packets are also simulated based on discrete intervals of time $[t-\Delta t],[t+\Delta t]$ . In the opposite side, the speed of each packet – in general – is a function of packet position and time.

Initially, by considering a generic link in the mesoscopic path where, $i \in p$, some notations are worth to clarify:

| | | |
|---|---|---|
| $i$ | : | Order of link $i$ , $i=[1,2,3, \ldots ., (I-1), I]$ |
| $p$ | : | The route between origin-destination (O, D) |
| $m$ | : | Vehicle class , $m=[1,2,3, \ldots ., (M-1), M]$ |
| $t$ | : | Index for continuous time |
| $\tau^i(t)$ | : | Travel time for link $i$ at time $t$ |
| $L^i$ | : | Length of link $i$ |
| $L_f^i$ | : | Running part $L_f^i \in L^i$ |
| $L_q^i$ | : | Queuing part $L_q^i \in L^i$ |
| $C^i$ | : | Capacity of link $i$ |
| $k^i(t)$ | : | Density of link $i$ at time $t$ |
| $kj^i$ | : | Jam density of link $i \in L$ |
| $k_f^i(t)$ | : | Density of the running part $k_f^i \in k^i$ at time $t$ |

| | | |
|---|---|---|
| $k_q^i(t)$ | : | Density of the queuing part $k_q^i \in k^i$ at time $t$ |
| $n_{\omega,m}^i(t)$ | : | Number of vehicles from class $m$ in the packet $\omega$ on link $i$ at time $t$. |
| $n_\omega^i(t)$ | : | Total number of vehicles in the packet $\omega$ on link $i$ at time $t$ |
| $N^i(t)$ | : | Total number of vehicles on link $i$ at time $t$ |
| $CN^i(t)$ | : | The total number of vehicles on link $i$ at time $t$ which couldn't exit |
| $[0,T]$ | : | Reference period of traffic demand simulation; |
| $V_\omega^i(t)$ | : | Packet speed on link $i$ at time $t$ |
| $V_f^i(t)$ | : | Free flow speed of link $i$ at time $t$ |
| $VC^i(t)$ | : | Creeping speed on link $i$ at time $t$ |
| $a_\omega^i(t)$ | : | Packet acceleration on link $i$ at time $t$ |
| $s_\omega^i(t)$ | : | Packet position on link $i$ at time $t$ |
| $f^p(t)$ | : | Total initial departure flow for route $p$ at time $t$ |
| $FC^p(t)$ | : | Total initial departure flow based on capacity constraint for route $p$ at time $t$ |
| $fc_m^p(t)$ | : | Initial departure flow for class $m$ based on capacity constraint for route $p$ at time $t$ |
| $FD^p(t)$ | : | Total initial departure flow based on density constraint for route $p$ at time $t$ |
| $fd_m^p(t)$ | : | Initial departure flow for class $m$ based on density constraint for route $p$ at time $t$ |
| $f_m^p(t)$ | : | Initial departure flow for class $m$ in route $p$ at time $t$ |
| $F_m^p(t)$ | : | Real departure flow for class $m$ in route $p$ at time $t$ |
| $F^p(t)$ | : | Real departure flow for route $p$ at time $t$ |
| $BF^p(t)$ | : | Total buffer flow at the initial node of route $p$ at time $t$ |
| $BF_m^p(t)$ | : | Buffer flow for class $m$ at the initial node of route $p$ at time $t$ |
| $W^i(t)$ | : | Real outflow of link $i$ at time $t$ |
| $w^i(t)$ | : | Initial outflow of link $i$ at time $t$ |
| $U^i(t)$ | : | Real Inflow of link $i$ at time $t$ |
| $Q^i(t)$ | : | Real queuing flow on link $i$ at time $t$ |
| $u_m^i(t)$ | : | Real inflow for class $m$, on link $i$ at time $t$ |
| $w_m^i(t)$ | : | Real outflow for class $m$, on link $i$ at time $t$ |
| $q_m^i(t)$ | : | Real queuing flow for class $m$, on link $i$ at time $t$ |
| $WC^i(t)$ | : | Total initial outflow based on capacity constraint on link $i$ at time $t$ |
| $wc_m^i(t)$ | : | Initial outflow for class $m$ based on capacity constraint on link $i$ at time $t$ |
| $WD^i(t)$ | : | Total initial outflow based on density constraint on link $i$ at time $t$ |
| $wd_m^i(t)$ | : | Initial outflow for class $m$ based on density constraint on link $i$ at time $t$ |
| $QC^i(t)$ | : | Initial queue flow based on capacity violation on link $i$ at time $t$ |
| $qc_m^i(t)$ | : | Initial queue flow for class $m$ based on capacity constraint on link $i$ at time $t$ |
| $QD^i(t)$ | : | Initial queue flow based on density violation on link $i$ at time $t$ |
| $qd_m^i(t)$ | : | Initial queue flow for class $m$ based on density constraint on link $i$ at time $t$ |
| $SP^i(t)$ | : | Queue spillback on link $i$ at time $t$ |

In our model, only one route is assumed $(p)$. Moreover, each link is made up of a running part $L_f^i$ and a queuing part $L_q^i$ as well as depicted in Fig. 8 , these lengths are variables in the proposed model. If the queue is not present, then $L_f^i = L^i$. likewise, when the traffic occupies the link, then again $L_q^i = L^i$ . In other words, once the queuing density $k_q^i$ reaches the maximum link density $kj^i$ , then $L_q^i = L^i$ and $k_q^i = kj^i$ at the same time. Under these circumstances, spillback of the queue certainly present from link $i$ to the preceding link $(i-1)$.

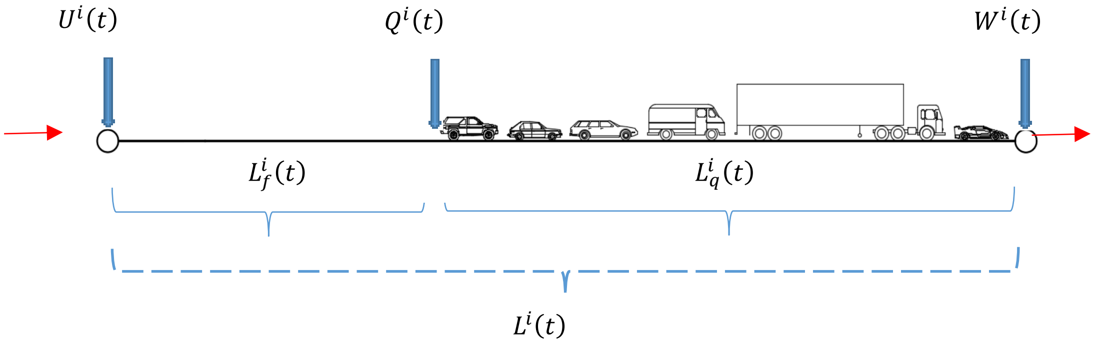


Fig. 8 - Multiclass queuing mesoscopic DNL link dynamics

In the light on the running part, where the multiclass is existing, FIFO holds per each vehicle class. Additionally, vehicles speed in each packet is common. Moreover, the stream packets are assumed to accelerate and decelerate uniformly. Therefore, any vehicle from any class is allowed to overtake others from other classes one in the running part (see sections 2.4.4.1, 2.4.4.3). Conversely to the queuing part where the speed is constant (creeping speed) for all vehicles and no overtaking can occur.

As for, with the hypothesis that:

- The location of all vehicles in the same packet situates at the position of the head of that packet.
- The speed is equal for all vehicles in the same packet and accelerated uniformly.
- A valid relationship between speed and density of the stream over the link in the reference period $[0, T]$ is exist.

From these motivations and relying on the correlation between density and speed on the link, the variables of packet position and speed can be accumulated, mathematically:

$$k^i(t) = \frac{N^i(t)}{L^i} \tag{3.1}$$

Following that, the speed of each packet in the stream is a function of the link density:

$$V_\omega^i(t) = f(k^i(t)) \tag{3.2}$$

In addition, as the simulation is mesoscopic, the packets are taken in the account in the following equation, which estimates the total number of vehicles on the link-based on the discrete approach:

$$N^i(t) = \sum_{\omega=1} n_\omega^i(t) + n_{(\omega+1)}^i(t) + \cdots \ldots \ldots .. + n_{(\Omega-1)}^i(t) + n_\Omega^i(t) \tag{3.3}$$

In the same way, the total number of vehicles in each packet equal to the summation of the number of vehicles from each class:

$$n_\omega^i(t) = \sum_{m=1} \psi_m . n_{\omega,m}^i(t) + \psi_{(m+1)} . n_{\omega,(m+1)}^i(t) + \cdots + \psi_{(M-1)} . n_{\omega,(\mathrm{M}-1)}^i(t) + \psi_M . n_{\omega,\mathrm{M}}^i(t) \tag{3.4}$$

Where,

$\psi$ : Conversion equivalent to the passenger car unit (pcu)

$m$ : Vehicle class order $m = [1,2,3, \ldots ., M]$

However, when the entry time of the packet (β) $> t$, and the position of that packet ($s_\omega^i$), speed ($V_\omega^i$) and the number of vehicles in the packet ($n_\omega^i$) are continuous functions; then, this implies that the packet is out of the link.

Accordingly, the number of packet –or vehicles – at the time $t$, ($n_\omega^i(t)$) equal to zero. Moreover, the speed is consigned to each packet at the link inflow time. In general, it depends on the packet order in the stream.

Henceforth, The total number of vehicles in the packet at time $t$ $\left(n_{\omega}^{i}(t)\right)$, is expected to have two values depending on the functionality of the position of that packet $s_{\omega}^{i}(t)$:

$$s_{\omega}^{i}(t) = f\left(s_{\omega}^{i}(t-\Delta t), V_{\omega}^{i}(t-\Delta t,), a_{\omega}^{i}(t-\Delta t,)\right) \tag{3.5}$$

With this intention, $n_{\omega}^{i}(t)$ :

$$n_{\omega}^{i}(t) = \begin{cases} 0 & , \quad if\ s_{\omega}^{i}(t) = 0 \\ \sum_{m=1}^{\mathrm{M}} \psi_{m}.\, n_{\omega,m}^{i}(t) & , if\ s_{\omega}^{i}(t) > 0 \end{cases} \tag{3.6}$$

The total number of vehicles on the link at time $t$ $\left(N^{i}(t)\right)$ is a function of the total number of packets at time $t$ $\left(n_{\omega}^{i}(t)\right)$ and the current number of vehicles on the link, which could not exit from that link $CN^{i}(t)$:

$$N^{i}(t) = f\left(CN^{i}(t), n_{\omega}^{i}(t)\right) \tag{3.7}$$

The initial link outflow can be aggregated in the outline of the boundary conditions as follows:

$$w_{m}^{i}(t) = f\left(n_{\omega,m}^{i}(t), s_{\omega}^{i}(t, t-\Delta t)\right) \tag{3.8}$$

$$\begin{aligned} w^{i}(t) = \sum_{m=1} \psi_{m}.\, w_{m}^{i}(t) + \psi_{(m+1)}^{i}.\, w_{(m+1)}^{i}(t) + \cdots \\ + \psi_{(M-1)}.\, w_{(M-1)}^{i}(t) \ + \psi_{(M)}.\, w_{(M)}^{i}(t) \end{aligned} \tag{3.9}$$

Here, the initial outflow for all classes is constrained by the receiving link $(i+1)$ capabilities. Consequently, this initial outflow is required to be evaluated in terms of jam density and capacity constraints:

$$WC^i(t) = \begin{cases} w^i(t), & if\ w^i(t) \le C^{(i+1)}.\Delta t \\ C^{(i+1)}.\Delta t, & if\ w^i(t) > C^{(i+1)}.\Delta t \end{cases} \tag{3.10}$$

Simultaneously, initial outflow for each class based on capacity constraint violation in the pcu unit:

$$\begin{gathered} wc^i_m(t) = WC^i(t) * [w^i_m(t)/w^i(t)] \\ wc^i_{(m+1)}(t) = WC^i(t) * [w^i_{(m+1)}(t)/w^i(t)] \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ wc^i_{(M-1)}(t) = WC^i(t) * [w^i_{(M-1)}(t)/w^i(t)] \\ wc^i_M(t) = WC^i(t) * [w^i_M(t)/w^i(t)] \end{gathered} \tag{3.11}$$

However,

$$WC^i(t) = \sum_{m=1}^{M} wc^i_m \tag{3.12}$$

The total number of vehicles that exceeded the capacity of the receiving link $(i+1)$ is the key point to perceive the total initial queue flow developed in the link $i$ because of capacity violation for all classes:

$$QC^i(t) = f\left(w^i(t), C^i\right) \tag{3.13}$$

As for, the initial queue flow that developed in the link $i$ based on capacity violation for each class:

$$qc_m^i(t) = QC^i(t) * [w_m^i(t)/w^i(t)]$$
$$qc_{(m+1)}^i(t) = QC^i(t) * [w_{(m+1)}^i(t)/w^i(t)]$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{3.14}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$qc_{(M-1)}^i(t) = QC^i(t) * [w_{(M-1)}^i(t)/w^i(t)]$$
$$qc_M^i(t) = QC^i(t) * [w_M^i(t)/w^i(t)]$$

And of course,

$$QC^i(t) = \sum_{m=1}^{M} qc_m^i \tag{3.15}$$

Likewise, the maximum density limitation for the receiving link $(i+1)$ is also required for the packets to enter, however,

$$WD^i(t) = \begin{cases} w^i(t) & , if\ [w^i(t) + N^{(i+1)}(t-\Delta t)] \le kj^{(i+1)}.L^{(i+1)} \\ kj^{(i+1)}.L^{(i+1)} & , \quad if\ [w^i(t) + N^{(i+1)}(t-\Delta t)] > kj^{(i+1)}.L^{(i+1)} \end{cases} \tag{3.16}$$

Concurrently, the initial outflow per each class based on density constraint violation in the pcu unit can be aggregated as follows:

$$wd_m^i(t) = WD^i(t) * [w_m^i(t)/w^i(t)]$$
$$wd_{(m+1)}^i(t) = WD^i(t) * [w_{(m+1)}^i(t)/w^i(t)]$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{3.17}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$wd^i_{(M-1)}(t) = WD^i(t) * [w^i_{(M-1)}(t)/w^i(t)]$$
$$wd^i_M(t) = WD^i(t) * [w^i_M(t)/w^i(t)]$$

Where,

$$WD^i(t) = \sum_{m=1}^{M} wd^i_m \tag{3.18}$$

Notably, the quantity of flow, which violated the density constraints for the receiving link $(i+1)$ would conclude the initial queue flow developed in the link $i$ based on maximum density violation:

$$QD^i(t) = f\left(w^i(t), N^{(i+1)}(t-\Delta t)\right) \tag{3.19}$$

With a little difference, the initial queue flow developed in the link $i$ on the basis of density violation for each class:

$$qd^i_m(t) = QD^i(t) * [w^i_m(t)/w^i(t)]$$
$$qd^i_{(m+1)}(t) = QD^i(t) * [w^i_{(m+1)}(t)/w^i(t)]$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{3.20}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$qd^i_{(M-1)}(t) = QD^i(t) * [w^i_{(M-1)}(t)/w^i(t)]$$
$$qd^i_M(t) = QD^i(t) * [w^i_M(t)/w^i(t)]$$

With this in mind, the real flow for the queue that developed on the link $(i)$ at the time $(t)$ for each class can be aggregated by selecting the maximum between the initial queue flow developed in the link $(i)$ based on the capacity violation and density violation at the time $(t)$ as well;

In the pcu unit:

$$q_m^i(t) = max\left(qc_m^i(t), qd_m^i(t)\right) \quad (3.21)$$

And in the unit of the original class:

$$q_m^i(t) = max\left(qc_m^i(t), qd_m^i(t)\right) / \psi_m^i \quad (3.22)$$

Likewise, the real outflow exits from the link $(i)$ at the time $(t)$ for class $(m)$ in pcu unit can be accumulated through taking the maximum between initial outflows concluded by capacity and density constraints;

In the pcu unit:

$$w_m^i(t) = max\left(wc_m^i(t), wd_m^i(t)\right) \quad (3.23)$$

In the original class unit:

$$w_m^i(t) = max\left(wc_m^i(t), wd_m^i(t)\right) / \psi_m \quad (3.24)$$

To this end, the real total outflow for the link $(i)$ at the time $(t)$ in pcu unit:

$$W^i(t) = \sum_{m=1}^{M} w_m^i \quad (3.25)$$

*Where, $w_m^i$ is in the pcu unit for class $m$.*

Again, the total real queue flow for the link $(i)$ at the time $(t)$ in pcu unit:

$$Q^i(t) = \sum_{m=1}^{M} q_m^i \tag{3.26}$$

*Where, $q_m^i$ is in the pcu unit for class $m$.*

Assuming that all traffic exits from the link $(i)$ at the time $(i)$ equal to the traffic which enters to the next link $(i + 1)$ at time $(t + \Delta t)$, mathematically:

$$w_m^i\,(t) = u_m^{(i+1)}(t + \Delta t). \tag{3.27}$$

As before, the total real inflow for the link $(i + 1)$ in pcu obeys the following formula:

$$U^{(i+1)}(t + \Delta t) = \sum_{m=1}^{M} w_m^i\,(t) \tag{3.28}$$

*Where, $w_m^i$ is in the pcu unit for class $m$.*

Queue length is the streamline of accumulated traffic from all classes waiting to be served by the transportation system where the head of the queue propagated over the link $(i)$ travels and complies with the creeping speed $(VC_m^i)$. However, the queuing part length is formulated as follows:

$$L_q^i(t) = Q^i(t).\frac{1}{kj^i} \tag{3.29}$$

Where,

$\frac{1}{kj^i}$ : space headway for total queued traffic on link $(i)$

Consequently, the queue density for the link $(i)$ at the time $(t), (k_q^i(t))$ can be determined by using the following equation:

$$k_q^i(t) = kj^i.\left(\frac{L_q^i(t)}{L^i}\right) \tag{3.30}$$

With,

$$\frac{k_q^i(t)}{kj^i} \leq 1 \qquad (3.31)$$

It follows that, the dynamic running part of the link $(i)$ at the time $(t)$, $(L_f^i(t))$:

$$L_f^i(t) = L^i - L_q^i(t) \qquad (3.32)$$

In general, congestion occurs when demand surpasses the availability in the network. The main challenging index caused by oversaturation is the queue spillback. It holds precisely once the traffic blockage holds in the receiving link $(i + 1)$ in such a way that prevents any progress at the head of the link $(i)$.

Moreover, a queue is developed at the bottleneck, which could be propagated until the initial node of the path, which results a shortage in the possibility of passing the bottleneck. Besides, the spillback is likely to discharge the flow to other network's links which potentially resulting the gridlock phenomenon, more details about gridlock can be found in (Mahmassani and Saberi, 2013). Under these circumstances, in order to account the existence of the spillback in the link $(i)$ at the time $(t)$, the following equation is formulated:

$$SP^i(t) = L_q^i(t) + \sum_{i+1}^{I} SP^{(i+1)}(t) \qquad (3.33)$$

Where, $SP^{(i+1)}(t)$ is the total length of next links queues in the oversaturation conditions at the time $(t)$.

However, the computations of link dynamics can be expressed in the following set of equations:

$$s_\omega^i\,(t + \Delta t) = s_\omega^i\,(t) + V_\omega^i . \Delta t + 0.5\, a_\omega^i\,(\Delta \mathrm{t})^2 \qquad (3.34)$$

With,

$$n_{\omega}^{i}(t+\Delta t)=\begin{cases}0 & , \quad if\ s_{\omega}^{i}\,(t+\Delta t)=0\\ \sum_{m=1}^{\mathrm{M}}\psi_{(m)}^{i}.\,n_{\omega,m}^{i}(t+\Delta t) & ,if\ s_{\omega}^{i}\,(t+\Delta t)>0\end{cases} \tag{3.35}$$

In fact, applying these equations is essential for mapping the dynamic outflow from the link $(i)$ at the time $(t+\Delta t)$ . As shown earlier, $w_{m}^{i}\,(t)=f\left(n_{\omega,m}^{i}(t), s_{\omega}^{i}\,(t,t-\Delta t)\right)$ subjected to capacity and density constraints.

Accordingly, to include the role of acceleration and deceleration variations in modelling the traffic dynamics, speed can be determined using the following equation:

$$V_{\omega}^{i}(t+\Delta t)=V_{\omega}^{i}(t)+a_{\omega}^{i}\,.\,\Delta \mathrm{t} \tag{3.36}$$

Consequently, the speed in the former equations set; is given by means of the variable $V_{\omega}^{i}(t+\Delta t)$. Following that, the proposed model uses the method of successive averages (MSA) to determine that variable in such a way achieving a convergence among the propagated discrete packets speed values to satisfy the mesoscopic simulation conditions. Subsequently, an iterative sequential averages cycle is demonstrated in the following relation:

$$V_{\omega,(y+1)}^{i}(t+\Delta t)=\left(\frac{1}{y}\,.\,V_{\omega}^{i}\left(N^{i}\left(n_{\omega}^{i}\left(s_{\omega}^{i}\,\left(V_{\omega,y}^{i}(t+\Delta t)\right)\right)\right)\right)+\left(\left(1-\frac{1}{y}\right).\left(V_{\omega,y}^{i}(t+\Delta t)\right)\right) \tag{3.37}$$

Where,

$V_{\omega,y}^{i}(t+\Delta t)$ : Speed of link $(i)$ at time $(t+\Delta t)$ in iteration $y$.

To this end, cycle terminates when a convergence of successive speed values is achieved. In other words, when the difference between two consecutive values reaches a fixed threshold. Additionally, in order to avoid the circulation blockage, a creeping speed is considered, when the density of the link exceeding its maximum one, i.e. in the oversaturation conditions.

Instead, in under saturation conditions, the proposed model is developed to employ both speed-density formula by Greenshields (Greenshields *et al.*, 1935) and speed-density relationship inspired from the triangular shaped fundamental diagram. In other words, the model is capable of running with hiring one of these relations in each simulation, not by employing both relations in the same simulation.

### 3.2.1 GREENSHIELDS FUNDAMENTAL DIAGRAM

Using empirical data, Greenshields (Greenshields *et al.*, 1935) was the first founder of a relationship between traffic density and flow.

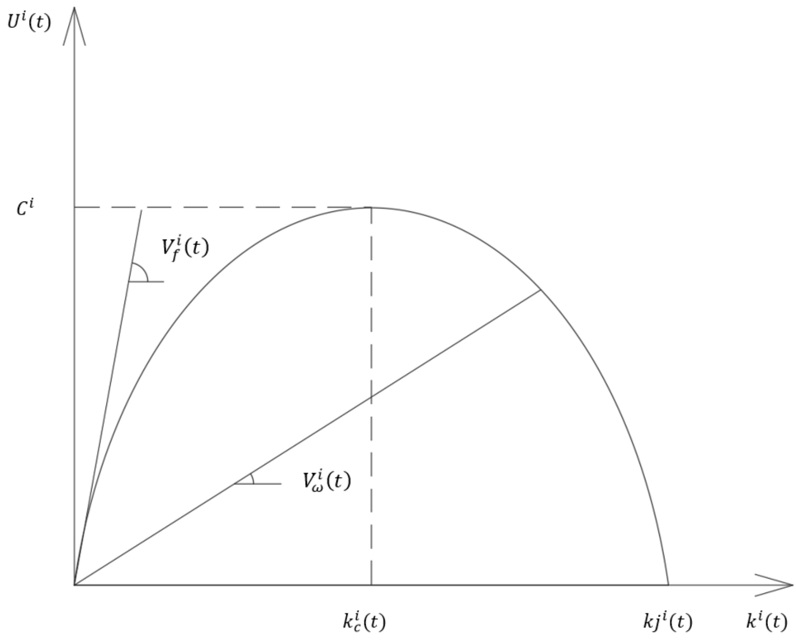


Fig. 9 - Greenshields fundamental diagram

Where,

$k_c^i(t)$: Critical density (density at maximum flow).

As indicated in Fig. 9, the average packet speed is represented by the slope of the straight line connecting the origin with the traffic state. The increasing part of the curve corresponds to the undersaturation conditions$[k_c^i(t) > k^i(t)]$. Likewise, the descending part represents the congested traffic conditions $[k_c^i(t) < k^i(t)]$. The maximum possible speed takes place for $[k^i(t) = 0]$.

However, the following relation provides the speed at any time:

$$V_\omega^i(t) = V_f^i(t)\left(1 - \frac{k^i(t)}{kj^i}\right) \tag{3.38}$$

With,

$$V_f^i(t) = \left(\frac{4C^i}{kj^i}\right) \tag{3.39}$$

### *3.2.2 TRIANGULAR SHAPED FUNDAMENTAL DIAGRAM*

This type of fundamental diagram illustrates the traffic flow and density relationship in a triangular shape as depicted in Fig. 10:

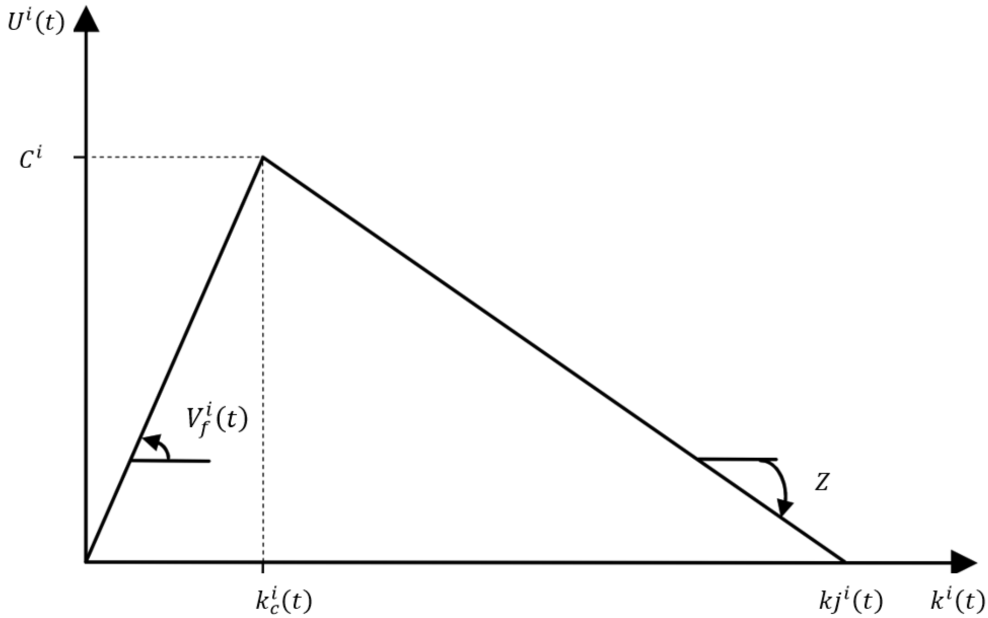


Fig. 10 - Triangular shaped fundamental diagram

Traffic conditions represented in the increasing branch of the triangular shaped fundamental diagram obey the free flow speed $V_f$ and the density $[k_c^i(t) > k^i(t)]$. Instead, decreasing branch represents the congested traffic states$[k_c^i(t) < k^i(t)]$ until jam density holds which corresponds to zero flow.

However, the speed-density relationship is illustrated as follows:

$$V_\omega^i(t) = min\left[V_f^i(t)\,, W^i(t)\left(\frac{kj^i}{k^i(t)} - 1\right)\right] \tag{3.40}$$

Where,

$Z$: Speed in oversaturation conditions.

Other parameters have been noted already, the density of link $(i)$ at any time is:

$$k^i(t) = \frac{N^i(t)}{L^i} \tag{3.41}$$

To this end, the acceleration of packet $(\omega)$ on the link $(i)$ at the time $(t + \Delta t)$ is the outcome of the following formula, and then it will be substituted in the next iteration:

$$a_\omega^i(t + \Delta t) = \frac{\left(V_\omega^i(t + \Delta t) - V_\omega^i(t)\right)}{\Delta t} \tag{3.42}$$

In the oversaturation case, the initial departure flow route $(p)$, $f^p(t)$ is constrained by the availability of the capacity on the one hand and the density on the other hand for the first link in the route. However, the proposed model assumes a presence of a buffer area at the initial node in the route for the aim of storing the surpassed value of the inflow that exceeded the availability of link $(i)$ in terms of capacity coupled with density. By the way, departure flow represents the inflow of the first link as illustrated below:

$$f^p(t) \ = U^1(t) \tag{3.43}$$

$$f_m^p\,(t) = u_m^1\,(t) \tag{3.44}$$

Consequently, the departure flow at the initial node is required to be evaluated according to the formula below:

$$FC^p(t) = \begin{cases} f^p(t), & if\ f^p(t) \leq C^i.\Delta t \\ C^i.\Delta t, & if\ f^p(t) > C^i.\Delta t \end{cases} \tag{3.45}$$

At the same time, the initial departure flow for each class based on capacity constraint violation in the pcu unit can be obtained as follows:

$$fc_m^p\,(t) = \ FC^p(t) * [f_m^p\,(t)/f^p(t)]$$
$$fc_{(m+1)}^p\,(t) = \ FC^p(t) * [f_{(m+1)}^p\,(t)/f^p(t)]$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.46)$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$fc^p_{(M-1)}(t) = FC^p(t) * [f^p_{(M-1)}(t)/f^p(t)]$$
$$fc^p_M(t) = FC^p(t) * [f^p_M(t)/f^p(t)]$$

And for sure,

$$FC^p(t) = \sum_{m=1}^{M} fc^p_m \quad (3.47)$$

The departure flow, which violated the density constraint at the initial node of the route $(p)$ can be aggregated as well by the following set of equations:

$$FD^p(t) = f\left(f^p(t), N^i(t-\Delta t)\right) \quad (3.48)$$

Likewise, initial departure flow for each class based on density constraint violation in the pcu unit:

$$fd^p_m(t) = FD^p(t) * [f^p_m(t)/f^p(t)]$$
$$fd^p_{(m+1)}(t) = FD^p(t) * [f^p_{(m+1)}(t)/f^p(t)]$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.49)$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$fd^p_{(M-1)}(t) = FD^p(t) * [f^p_{(M-1)}(t)/f^p(t)]$$
$$fd^p_M(t) = FD^p(t) * [f^p_M(t)/f^p(t)]$$

With,

$$FD^p(t) = \sum_{m=1}^{M} fd_m^p \tag{3.50}$$

To this end, the real departure flow route for class$(m)$ in the route $(p)$ at the time $(t)$, $F_m^p$ can be identified in (pcu) unit by taking the minimum as follows:

In the pcu unit:

$$F_m^p = min(fc_m^p, fd_m^p) \tag{3.51}$$

In original class unit:

$$F_m^p = max(fc_m^p, fd_m^p)\psi_m \tag{3.52}$$

In addition, the total real departure flow for the route $(p)$ at the time$(t)$, in pcu unit:

$$F^p(t) = \sum_{m=1}^{M} F_m^p \tag{3.53}$$

This follows that the total flow in the buffer area for the route $(p)$ at the time$(t)$ is determined by the set of equations as follows:

$$BF^p(t) = f^p(t) - F^p(t) \tag{3.54}$$

And for class $(m)$ at the time$(t)$ :

$$BF_m^p(t) = f_m^p(t)\text{-}F_m^p(t) \tag{3.55}$$

For class $(m)$ at the time$(t)$, but in pcu unit:

$$BF_m^p(t) = ((f_m^p(t) - F_m^p(t))/\psi_m \tag{3.56}$$

The dynamic travel time for the link $(i)$, at the time$(t)$ :

$$\tau^i(t) = L^i / V_\omega^i(t) \tag{3.57}$$

# CHAPTER 4. MODEL VALIDATION, RESULTS AND DISCUSSION

## 4.1. STATISTICAL ANALYSIS AND MODEL VALIDATION

Nowadays, the availability of computers has extended the analysis capabilities to include much bigger areas of cities or countries. In the meantime, traffic modelling is a cost-effective and reliable approach for evaluating the transportation networks to prevent possible gridlocks and excessive delays in the one hand and for the future planning purposes on the other hand. Therefore, these models need to be tested in terms of modelling accuracy to simulate the real world situation, which they have been found for.

In the field of traffic engineering, root mean square error (RMSE) is a very famous statistical formula, which is used to validate the proposed model output in contrast to real traffic data collected by the Automatic Traffic Counting (ATC) technique. The aim of this approach is to provide the bias of the simulated output from the observed one in each time step for each vehicle class. However, RMSE is calculated using the following relationship:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N}(\emptyset_{Sim} - \emptyset_{Real})^2}{N}} \quad (4.1)$$

Where,

$\emptyset_{Sim}$: Simulated flow

$\emptyset_{Real}$: Real flow observed by the ATC

N: Total number of values

## *4.2. LIMITATIONS OF THE AVAILABLE REAL DATA*

In fact, the proposed model is designed to estimate traffic dynamics and their behaviours along the transportation route. Moreover, the model aims to simulate the real-time spillback queuing considering multiclass mesoscopic simulation, which means various vehicle types, sizes and speeds interacting in the same route.

Many attempts paid by the thesis's author to acquire a data set, which observed in oversaturated conditions to validate the model output in terms of real-time links speed, densities, counts and queue spillback effects.

Consequently, due to the availability of real flow data in undersaturation conditions which measured by ATC, with an absence of other dynamics observations (Speeds, Densities …etc.). Therefore, the model is validated in the undersaturation conditions by real data set as reported in the next sections. In addition, a simulation with numerical data in oversaturation conditions is provided as well in the next sections. Moreover, comparisons for different traffic dynamics using a commercial package (Aimsun Next 8.2.3 (R54491)) are also presented.

## *4.3. SIMULATION CASE STUDY I: ASSESSING THE MODEL IN THE UNDERSATURATION CONDITIONS USING REAL DATA*

In order to assess the performance of the proposed model, it is necessary to apply the algorithm on a real data set from sensors observation.

### *4.3.1. INVESTIGATED NETWORK*

There are different key points to consider before making a choice for the investigated traffic network. As this thesis aims to capture the dynamic network loading in each time step for every vehicle class, assuming discrete mesoscopic simulation. It is rational to select multiclass flow data distributed on time steps where each slice includes flow observations from each vehicular class.

Furthermore, the observed traffic data are required to have as many varieties of traffic states as possible so the model can be validated more effectively.

Maliha highway (Fig. 11) matches the desired criteria and selected as an investigated network.

Table.1 - Investigated network location

| **Maliha Highway-West Bound** | | |
|---|---|---|
| **Location** | **Latitude** | **Longitude** |
| **Sharjah, United Arab Emirates** | N 25.27095° | E 55.48057° |

The proposed model is developed not only to capture the traffic dynamics employing the Greenshields speed-density relation but also applying the triangular fundamental diagram. To this end, the selected network is simulated by both approaches, and the results are provided separately.

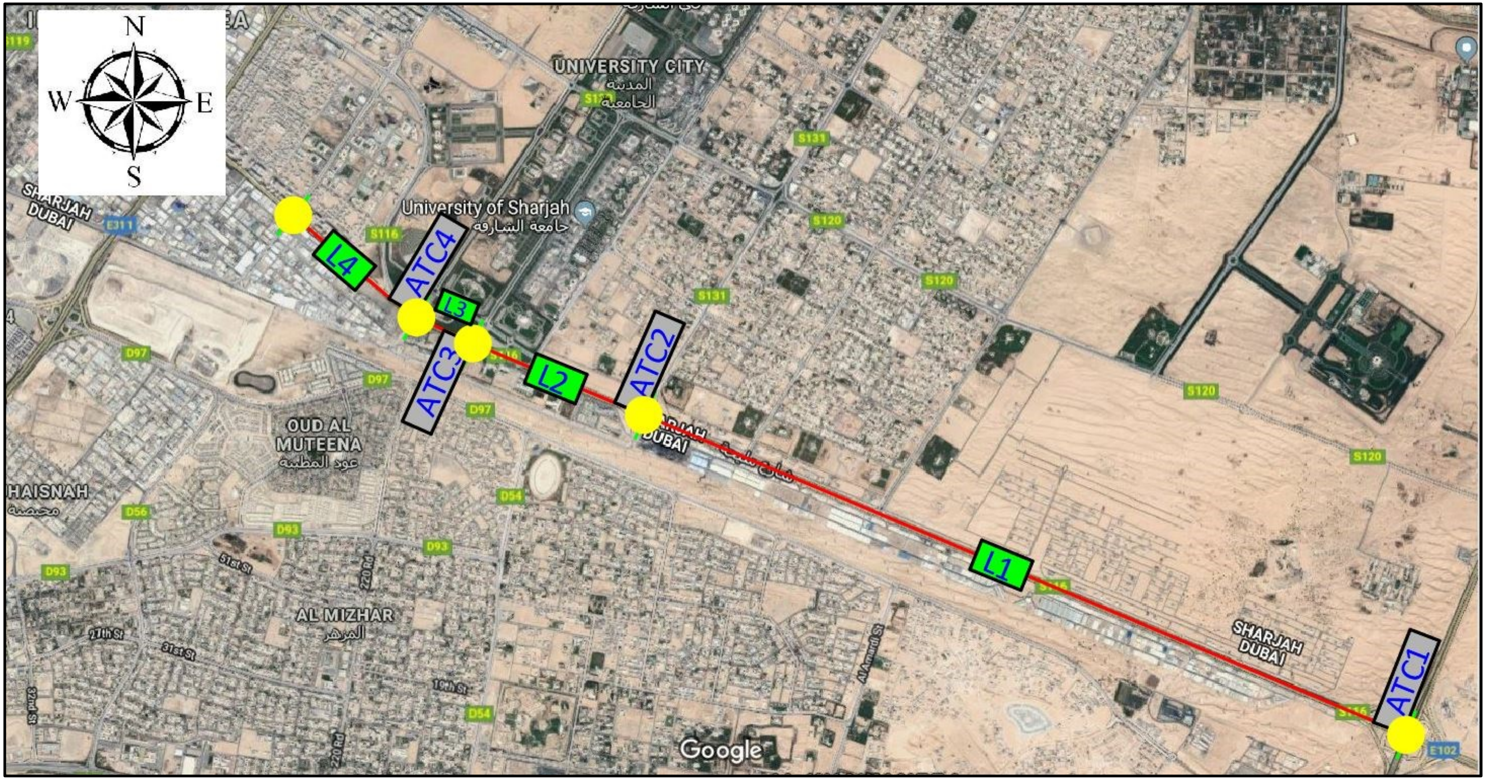


Fig. 11 - Overview of the considered toy network – Maliha Highway

### *4.3.2. SIMULATION OF UNDERSATURATION CONDITIONS EMPLOYING GREENSHIELDS SPEED-DENSITY RELATION*

In this section, the proposed model adopts Greenshields speed-density formula (Greenshields *et al.*, 1935) to propagate the flow over the time horizon.

Particularly, the packet speed is a function of density, which means that the speed starts to decrease from the departure flow moment until the assumed creeping speed holds (see section 3.2.1).

As for, the evaluation of the proposed model in terms of resulted flow values are compared to the real flow set which aggregated by the available sensors ATC1-ATC4 as depicted in Fig. 11. For a better analysis of the proposed model outcomes, a comparison with a well-known commercial traffic simulator, Aimsun Next 8.2.3 (R54491) has been performed. The (Figures 12-23) illustrate the compression outcomes for real data, proposed model estimations and the Aimsun model results based on mesoscopic simulation.

Table.2 - Maliha Highway characteristics- Model input /Greenshields

| **Link characteristics** | **Link 1** | **Link 2** | **Link 3** | **Link 4** |
|---|---|---|---|---|
| **Length [km]** | 8.9 | 2.0 | 1.0 | 1.38 |
| **Free flow speed [km/h]** | 120 | 100 | 60 | 60 |
| **Creeping speed [km/h]** | 10 | 10 | 10 | 10 |
| **Jam density [pcu/km]** | 450 | 450 | 450 | 300 |

Each figure designates the dynamic flow variations over time on the route link for one class. To be more precise, a time step of 1 min has been selected over a time horizon of one day of traffic. The real data set for each route's link are provided in the Annexes A and B.

However, three classes of vehicles have been considered: passenger car, bus and heavy vehicles class. The flow estimations compared to the real observations for Maliha Highway for all classes are depicted in Fig. 12 - 23.

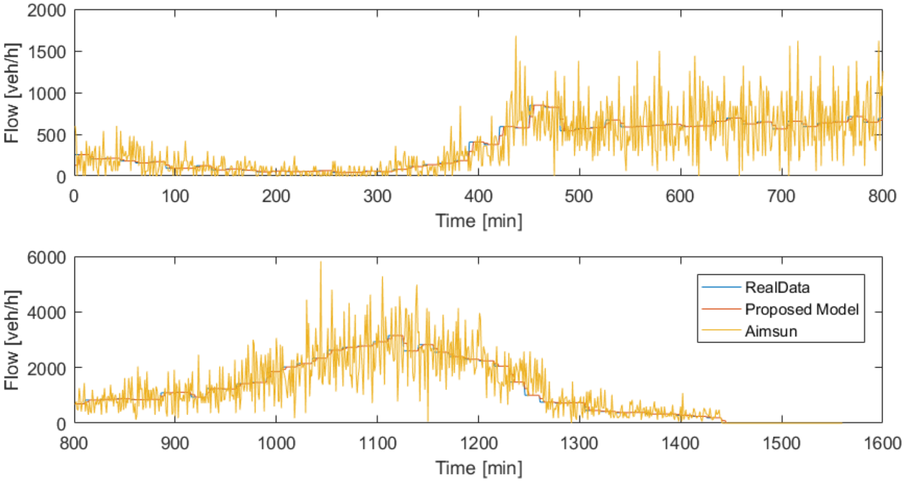


Fig. 12 - Flow estimations of the proposed model passenger car class compared to Aimsun results and real observations for link 1 (Greenshields model)

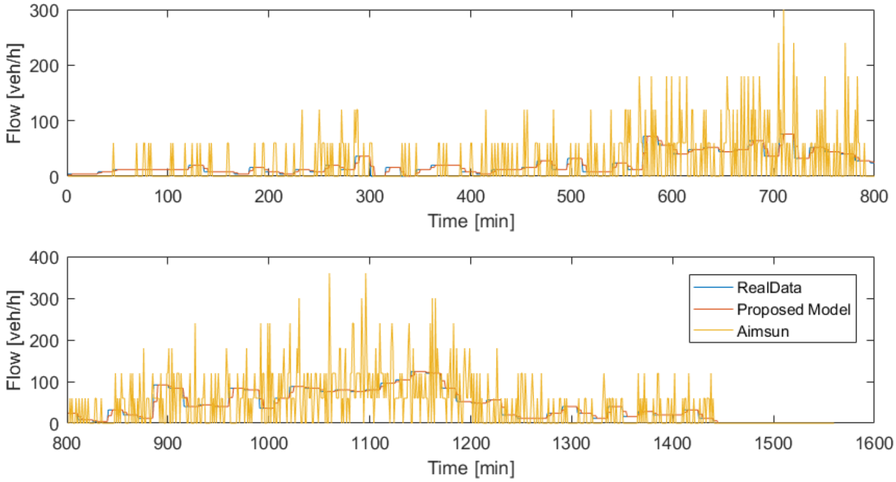


Fig. 13 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 1 (Greenshields model)

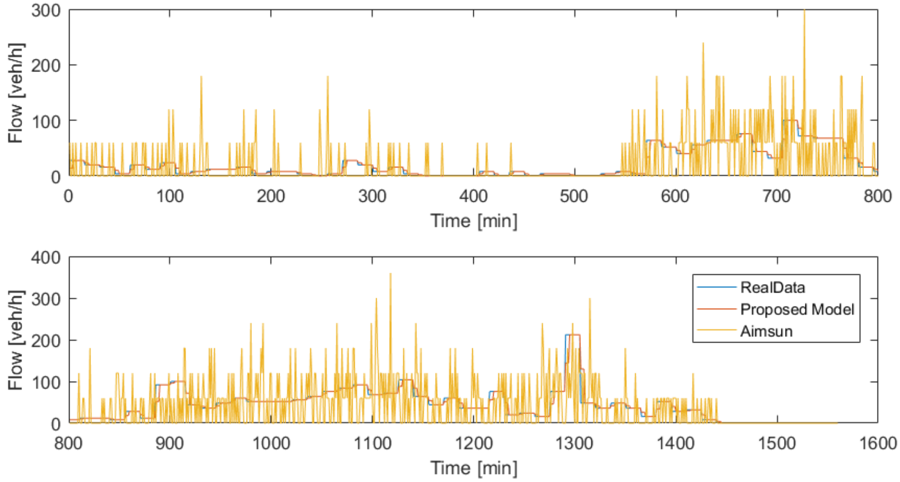


Fig. 14 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 1 (Greenshields model)

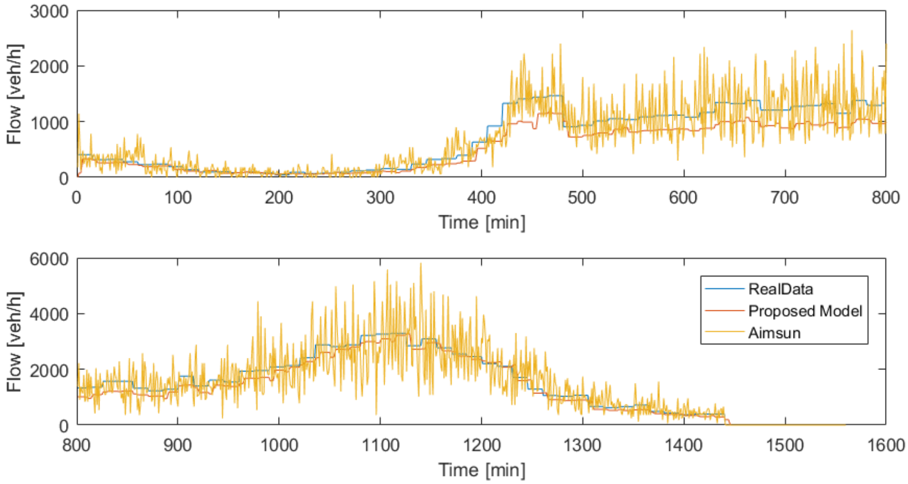


Fig. 15 - Flow estimations of the proposed model passenger car class compared to Aimsun results and real observations for link 2 (Greenshields model)

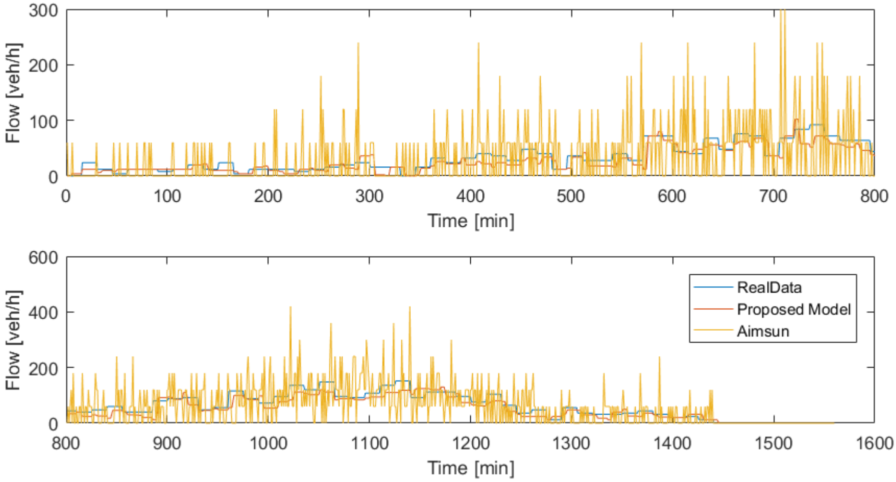


Fig. 16 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 2 (Greenshields model)

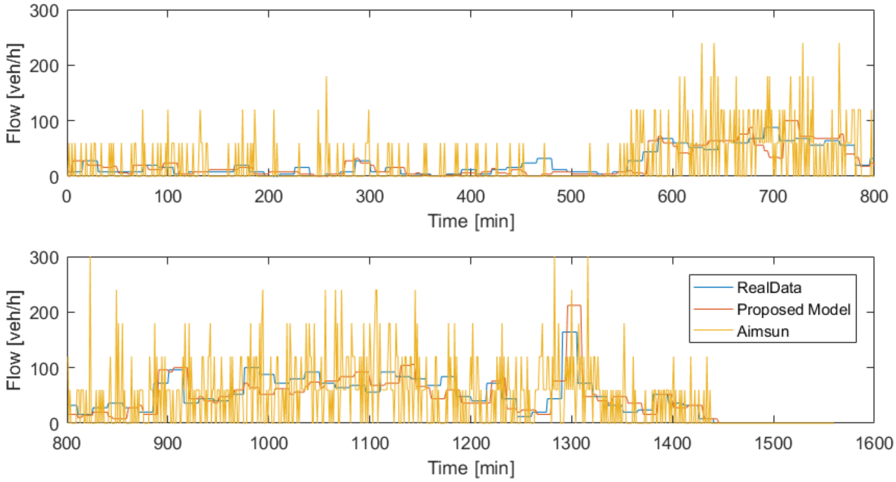


Fig. 17 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 2 (Greenshields model)

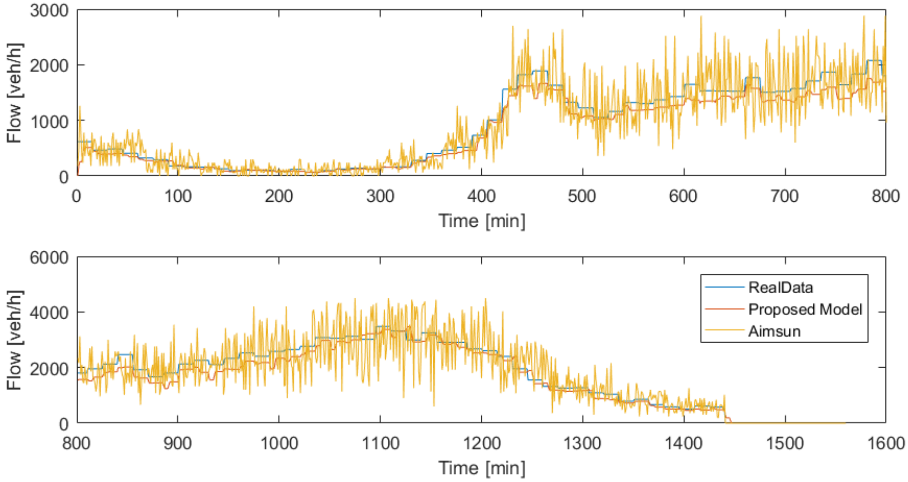


Fig. 18 - Flow estimations of the proposed model for passenger car class compared to Aimsun results and real observations for link 3 (Greenshields model)

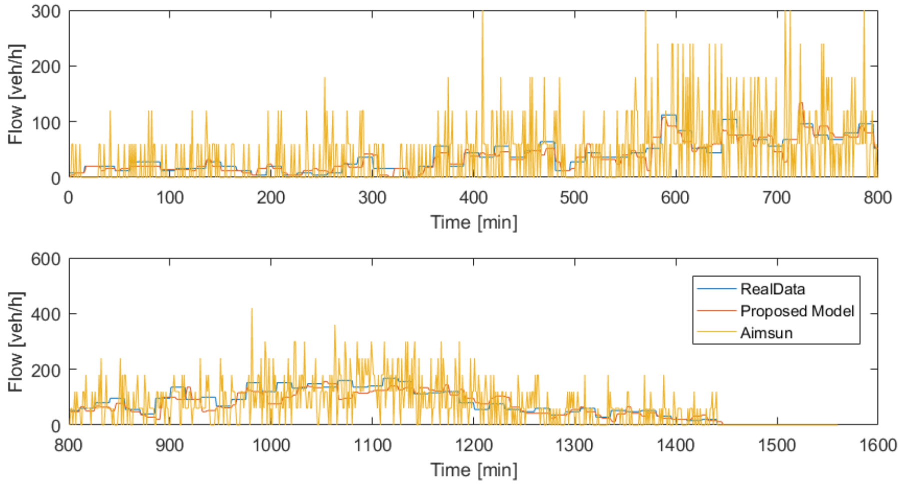


Fig. 19 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 3 (Greenshields model)

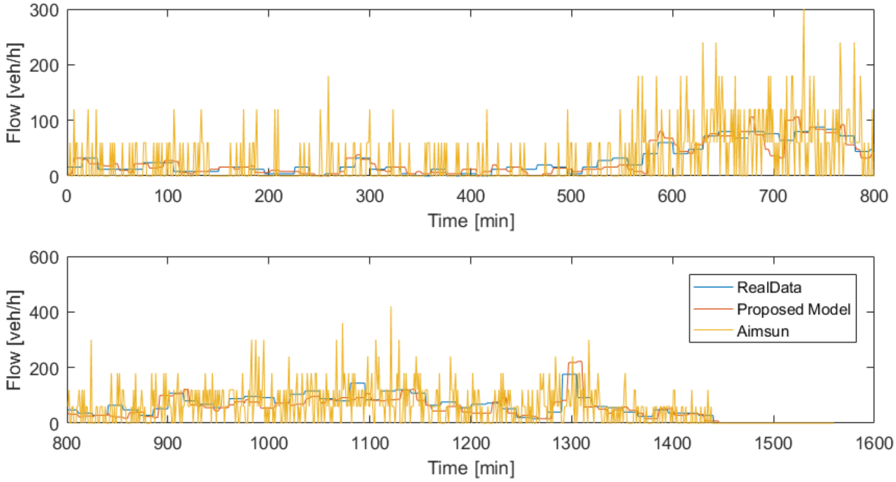


Fig. 20 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 3 (Greenshields model)

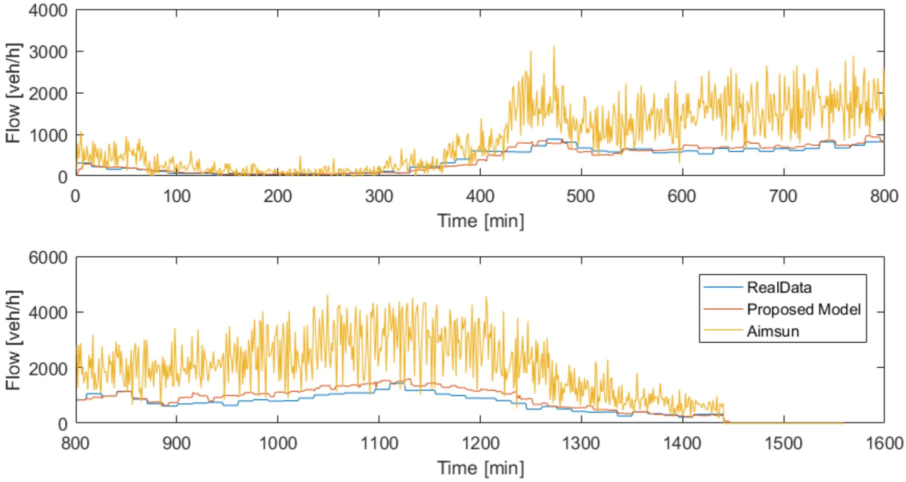


Fig. 21 - Flow estimations of the proposed model for passenger car class compared to Aimsun results and real observations for link 4 (Greenshields model)

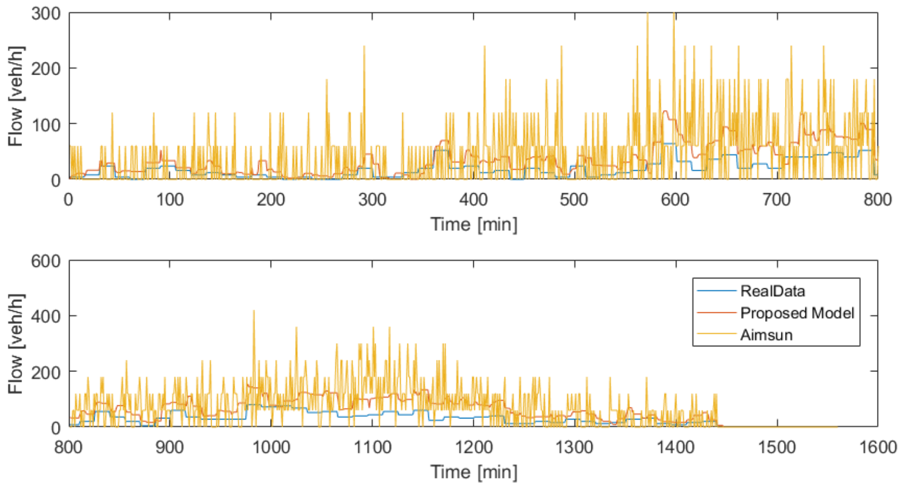


Fig. 22 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 4 (Greenshields model)

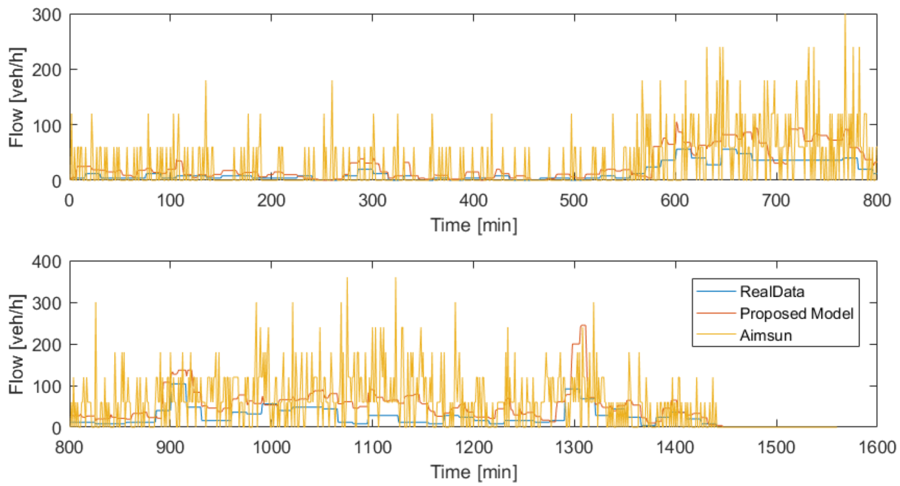


Fig. 23 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 4 (Greenshields model)

### *4.3.3. SIMULATION OF UNDERSATURATION CONDITIONS EMPLOYING THE TRIANGULAR FUNDAMENTAL DIAGRAM*

In this section, the proposed model uses the triangular shape fundamental diagram in network loading model. Similarly to the previous section, this simulation aims to compare the model results using the triangular shape fundamental diagram (see section 3.2.2), with the same real data set of Maliha Highway and Aimsun estimations.

In the end, model results obtained using each of both relations will be compared to the real data and Aimsun estimation in terms of bias from the observed measurement.

Table. 3 - Maliha Highway characteristics- Model input/triangular

| Link characteristics | Link 1 | Link 2 | Link 3 | Link 4 |
|---|---|---|---|---|
| **Length [km]** | 8.9 | 2 | 1 | 1.38 |
| **Free flow speed [km/h]** | 120 | 100 | 60 | 60 |
| **Creeping speed [km/h]** | 10 | 10 | 10 | 10 |
| **Capacity [pcu/h]** | 8000 | 8000 | 6000 | 4500 |
| **Jam density [pcu/km]** | 450 | 450 | 450 | 300 |

The flow estimations to real observations for all classes are depicted in the

Figures 24-35:

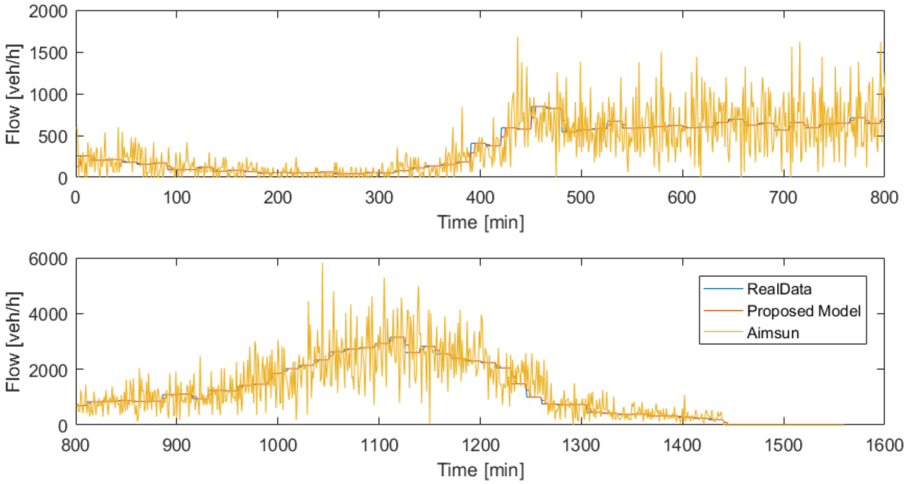


Fig. 24 - Flow estimations of the proposed model for passenger car class compared to Aimsun results and real observations for link 1 (Triangular model)

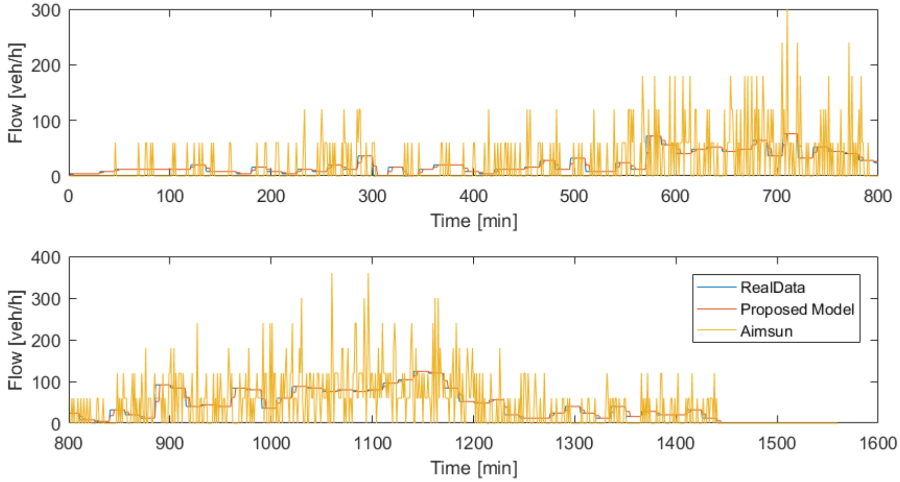


Fig. 25 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 1 (Triangular model)

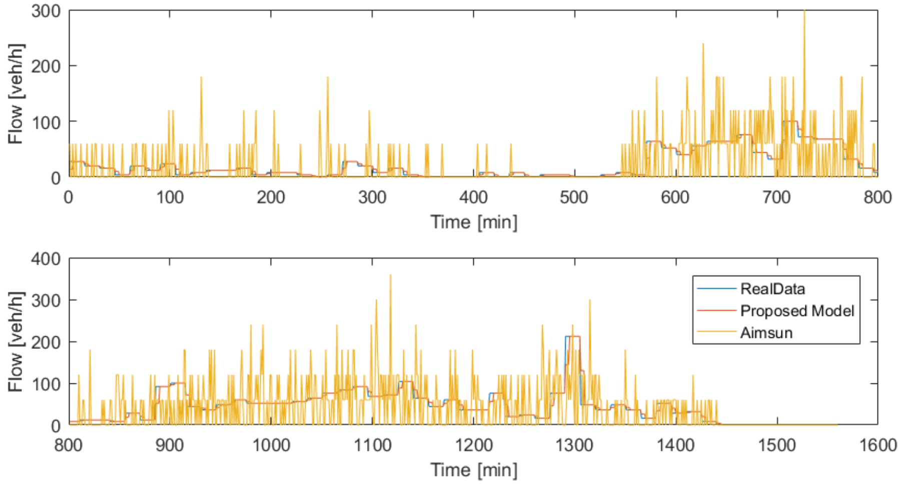


Fig. 26 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 1 (Triangular model)

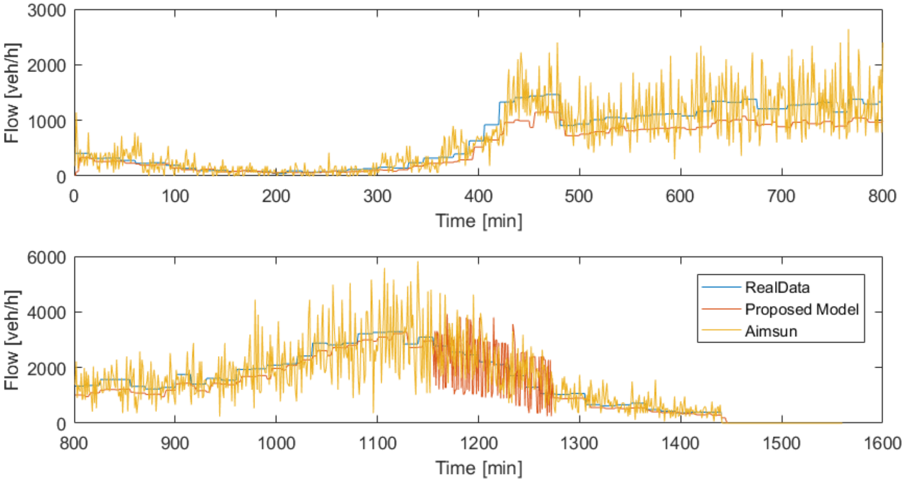


Fig. 27 - Flow estimations of the proposed model for passenger car class compared to Aimsun results and real observations for link 2 (Triangular model)

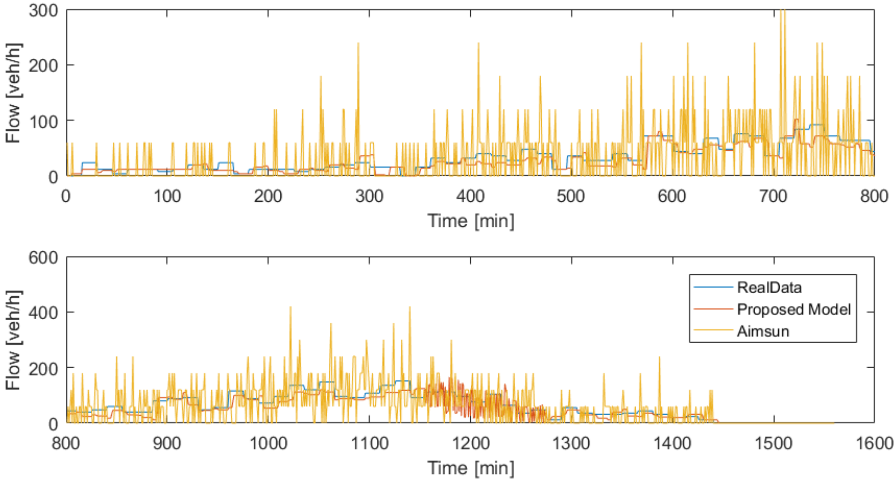


Fig. 28 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 2 (Triangular model)

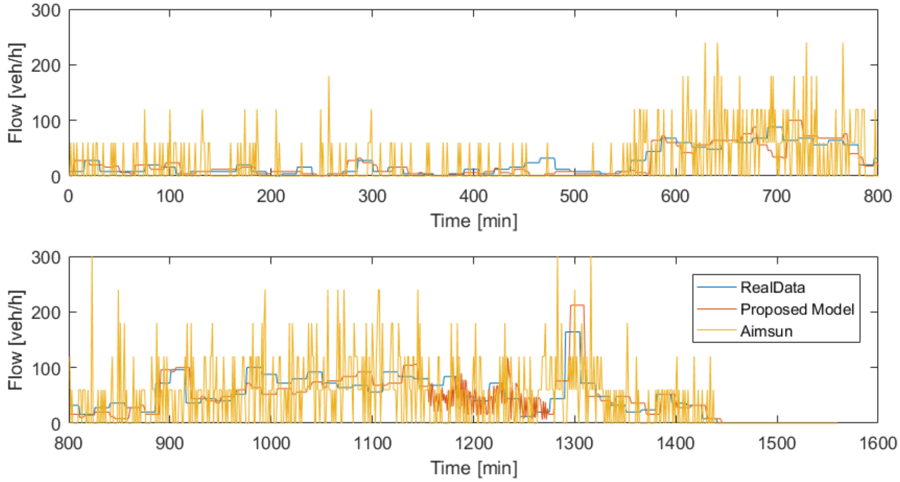


Fig. 29 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 2 (Triangular model)

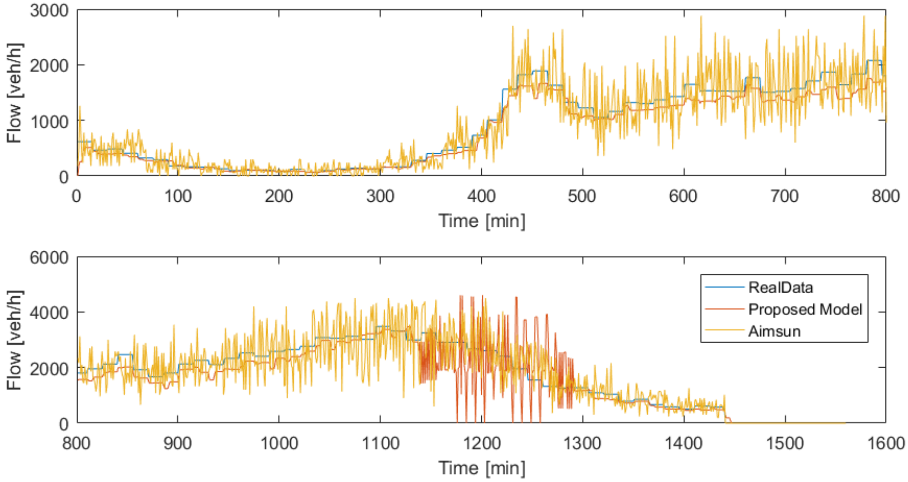


Fig. 30 - Flow estimations of the proposed model for passenger car class compared to Aimsun results and real observations for link 3 (Triangular model)

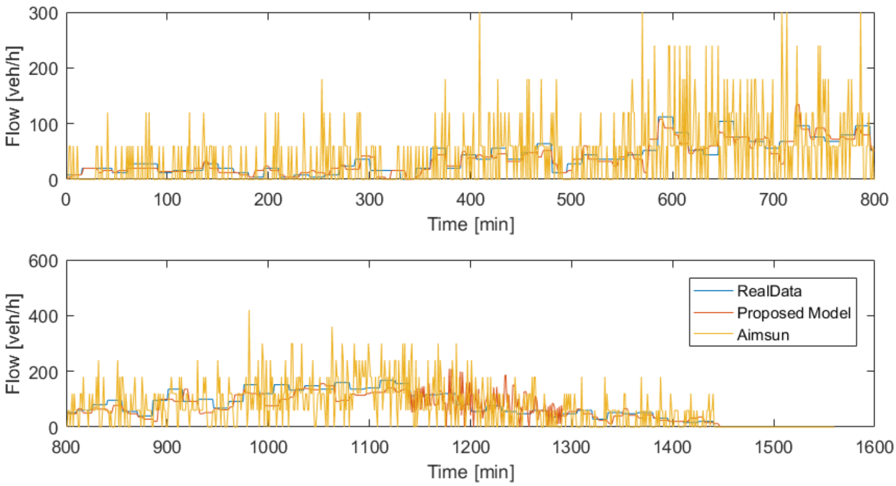


Fig. 31 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 3 (Triangular model)

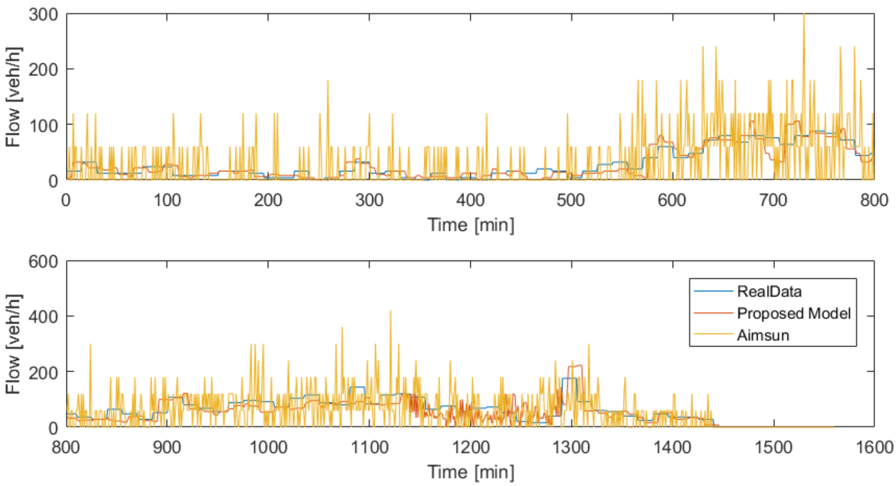


Fig. 32 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 3 (Triangular model)

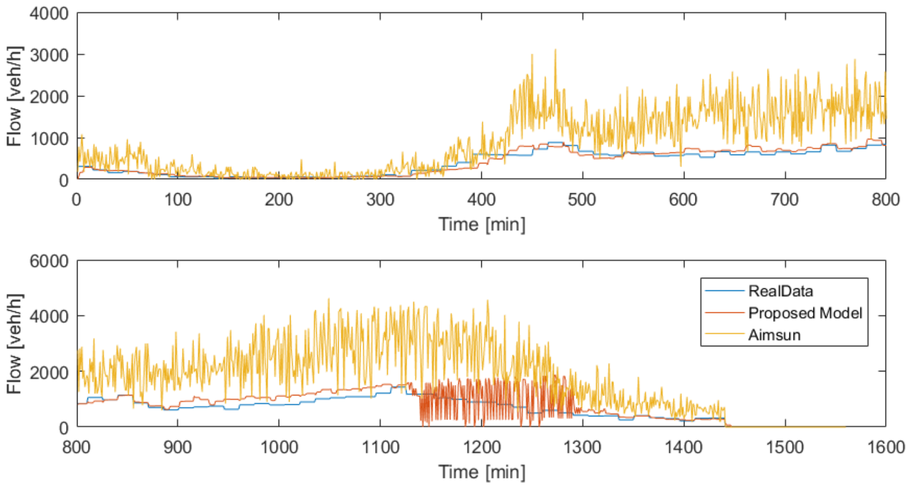


Fig. 33 - Flow estimations of the proposed model for passenger car class compared to Aimsun results and real observations for link 4 (Triangular model)

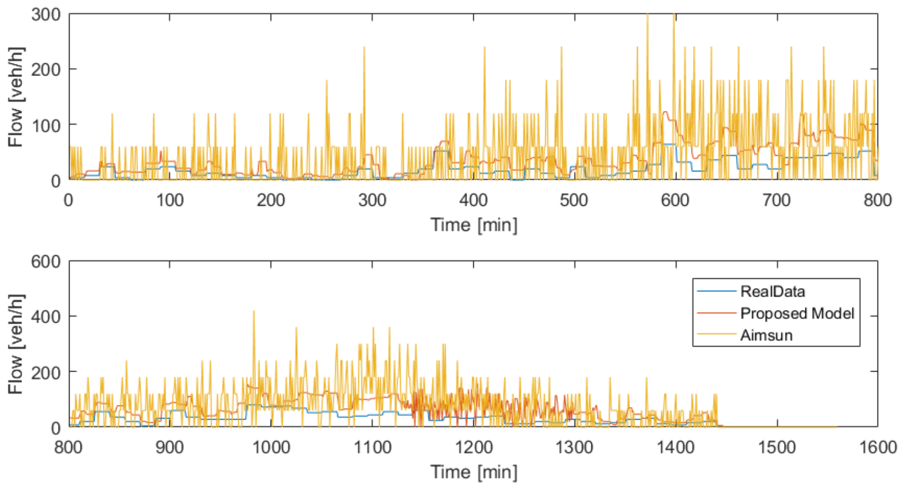


Fig. 34 - Flow estimations of the proposed model for Bus class compared to Aimsun results and real observations for link 4 (Triangular model)

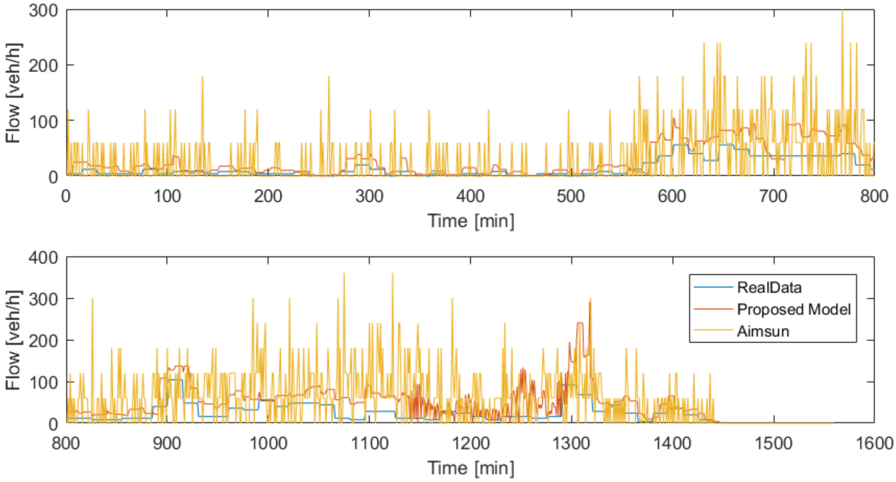


Fig. 35 - Flow estimations of the proposed model for HGV class compared to Aimsun results and real observations for link 4 (Triangular model)

### *4.3.4. DISCUSSION AND CONCLUSION*

The obtained link flows from different models of dynamic network loading are compared with observed link flows from ATC sensors for Maliha highway, using the triangular and Greenshields speed-density formula presented in the proposed methodology (see section 3.2.1-2). Aimsun simulation model was tuned according to the route characteristics in Table. 3. Moreover, the Aimsun mesoscopic simulation model was used for the comparison.

Obviously, the proposed model resulted a stable flow trend in both cases when employing different speed-density relations, in contrast to the fluctuating flow values simulated by Aimsun model. This means that the Aimsun model seems to consider flow characteristics of the microscopic level (e.g., start-and-stop behaviour). Instead, the proposed model offered a stable flow trend adopting average flow values typical of the macroscopic characteristic embedded in the mesoscopic simulation.

Graphically, as can be seen in the Figures 24-35 the proposed model has provided flows with a smaller difference compared to the Aimsun model especially in link 4 for all classes. A comparison for both models in term of the bias from the real observations is presented in Table.4 in terms of Root Mean Square Error (RMSE) defined in the Eq (4.1)

Table. 4 - RMSE for different models estimations

| | **First class (PCU)** | | |
|---|---|---|---|
| | **Triangular** | **Greenshields** | **Aimsun** |
| Link 1 | 0.64 | 0.64 | 7.79 |
| Link 2 | 5.82 | 3.44 | 8.73 |
| Link 3 | 6.98 | 3.13 | 8.52 |
| Link 4 | 4.32 | 2.50 | 7.79 |
| | **Second class (Bus)** | | |
| | **Triangular** | **Greenshields** | **Aimsun** |
| Link 1 | 0.08 | 0.08 | 0.80 |
| Link 2 | 0.31 | 0.25 | 0.89 |
| Link 3 | 0.37 | 0.30 | 0.98 |
| Link 4 | 0.53 | 0.51 | 0.80 |
| | **Third class (HGV)** | | |
| | **Triangular** | **Greenshields** | **Aimsun** |
| Link 1 | 0.13 | 0.13 | 0.81 |
| Link 2 | 0.32 | 0.30 | 0.80 |
| Link 3 | 0.36 | 0.31 | 0.88 |
| Link 4 | 0.48 | 0.46 | 0.81 |

As shown in Table.4, the proposed model using Greenshields relation has shown a smaller RMSE value when compared to the triangular relation in calculating the packets speed, especially in the passenger car class. However, the Aimsun RMSE is greater than the proposed model error in both cases.

Concluding, in undersaturation conditions the proposed model provided a smaller RMSE from the real data in both cases and showed the lowest RMSE values when adopting the Greenshields relation in the methodology.

## *4.4 SIMULATION CASE STUDY II: ASSESSING THE MODEL IN THE OVERSATURATION CONDITIONS USING NUMERICAL DATA*

The limitation in the availability of a real data set which is appropriate to assess the proposed model capabilities in oversaturation conditions (e.g., the dynamic queue spillback), motivated the author to construct this numerical application. This case study aims to compare the performance of the proposed model together with its methodology to the commercial simulator Aimsun Next 8.2.3 (R54491) which is widely used internationally to real cases as described in (Casas *et al.*, 2010).

### *4.4.1. INVESTIGATED TOY NETWORK*

For the sake of simplicity, a simple network with four links is suggested as shown in Fig. 36 to test the proposed model. As this thesis presents a new model which offered to capture traffic dynamics in under and in oversaturation conditions taking into account multiclass properties, a bottleneck is assumed. In more details, the maximum speed in the network dropped from 60 km/h in link 2 to 20 km/h in link 3.

In addition, a simulation period of 12 hours is adopted, and the traffic states as illustrated in Table.5, have been loaded dynamically as discrete packets.

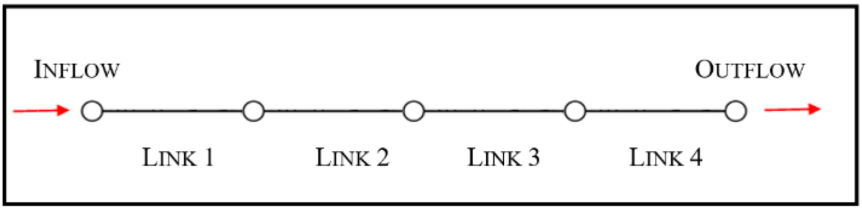


Fig. 36 - The considered network.

Table. 5 - Traffic states used in the simulation

| | Flow states | | | |
|---|---|---|---|---|
| | **0h-1h** | **1h-2h** | **2h-3h** | **3h-4h** |
| **PCU [pcu/h]** | 200 | 1400 | 1600 | 460 |
| **Bus [bus/h]** | 15 | 135 | 165 | 40 |
| **HGV[HGV/h]** | 12 | 130 | 170 | 40 |

### *4.4.2. SIMULATION OF OVERSATURATION CONDITIONS EMPLOYING GREENSHIELDS SPEED-DENSITY RELATION*

In this section, the simulation in oversaturation conditions performed adopting Greenshields formula for speed calculation to compare different traffic dynamics to Aimsun outcomes. The proposed model and Aimsun tuned to load the same dynamic load presented in Table.5. Detailed route characteristics are described in Table.6.

Table. 6 - Route characteristics- Model input/Greenshields

| Link characteristics | Link 1 | Link 2 | Link 3 | Link 4 |
|---|---|---|---|---|
| **Length [km]** | 4 | 5 | 4 | 6 |
| **Free flow speed [km/h]** | 60 | 60 | 20 | 60 |
| **Creeping speed [km/h]** | 10 | 10 | 10 | 10 |
| **Jam density [pcu/km]** | 450 | 450 | 450 | 300 |

Figures 37-42 illustrate the flow estimations for both models:

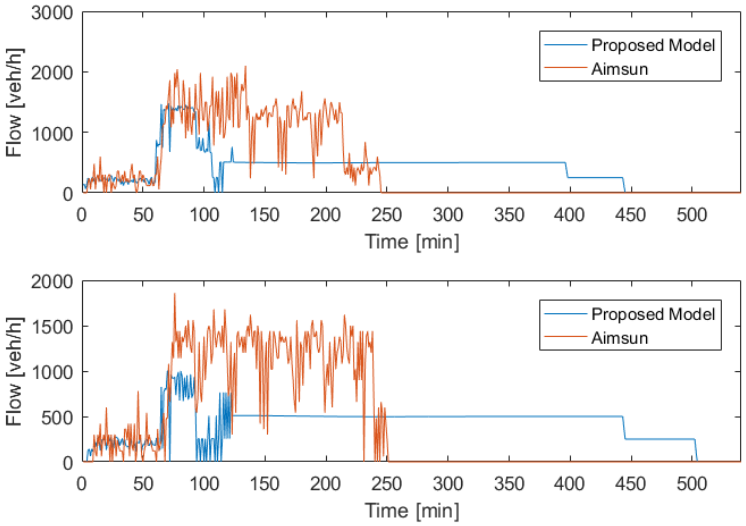


Fig. 37 - Estimated flow obtained by Aimsun and the proposed model for passenger car class for link 1-2 (Greenshields relation)

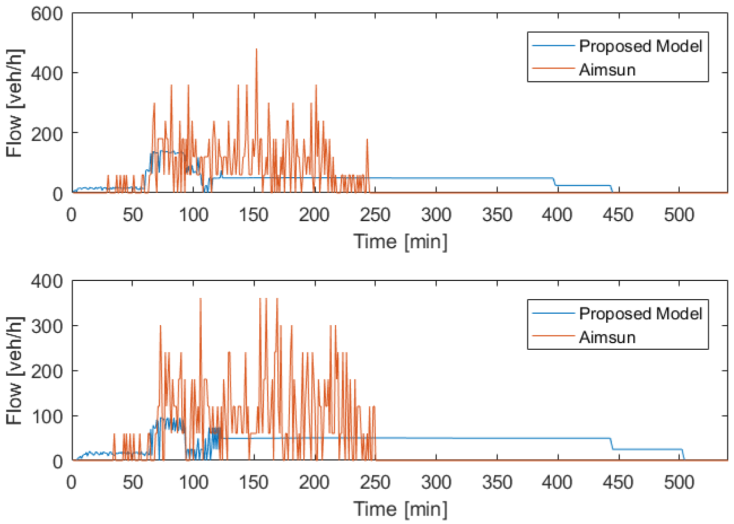


Fig. 38 - Estimated flow obtained by Aimsun and the proposed model for Bus class for link 1-2 (Greenshields relation)

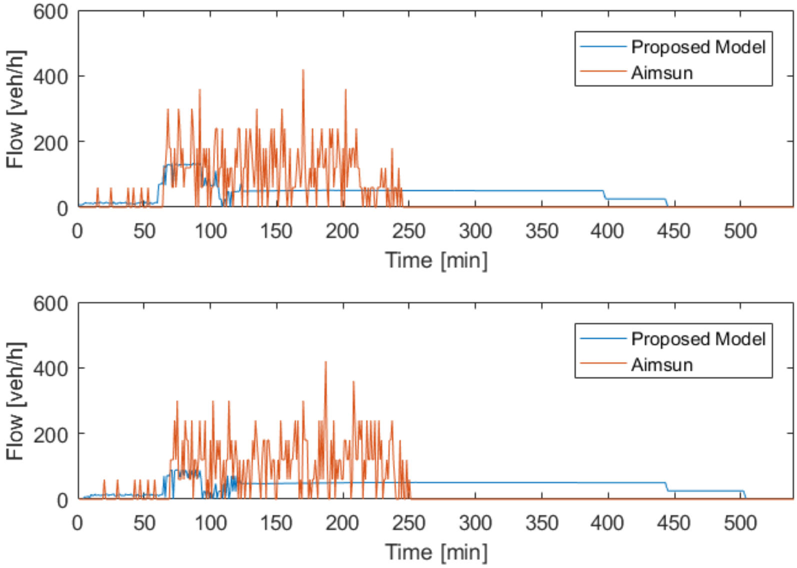


Fig. 39 - Estimated flow obtained by Aimsun and the proposed model for HGV class for link 1-2 (Greenshields relation)

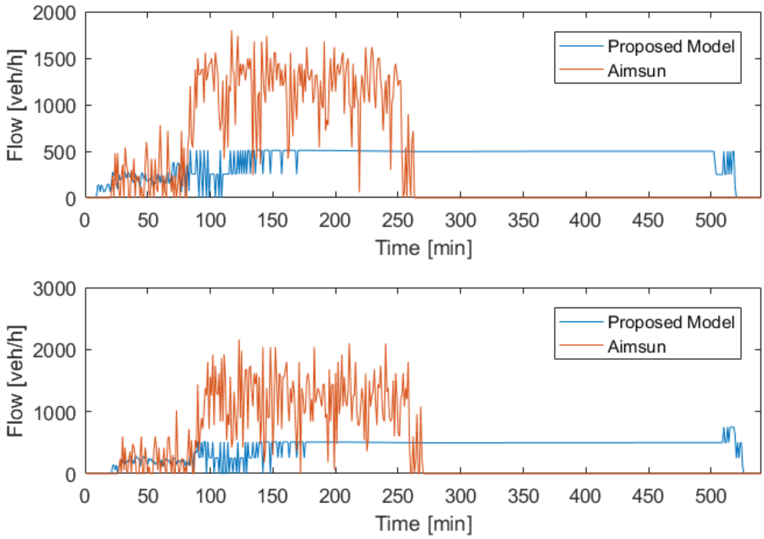


Fig. 40 - Estimated flow obtained by Aimsun and the proposed model for passenger car class for link 3-4 (Greenshields relation)

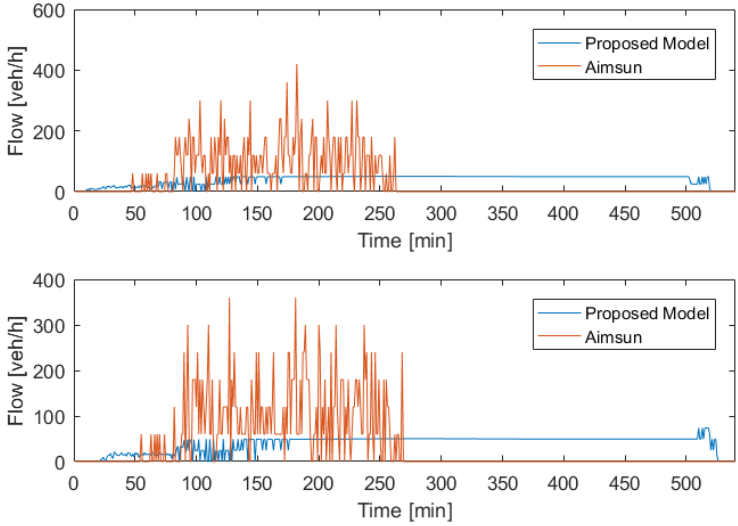


Fig. 41 - Estimated flow obtained by Aimsun and the proposed model for Bus class for link 3-4 (Greenshields relation)

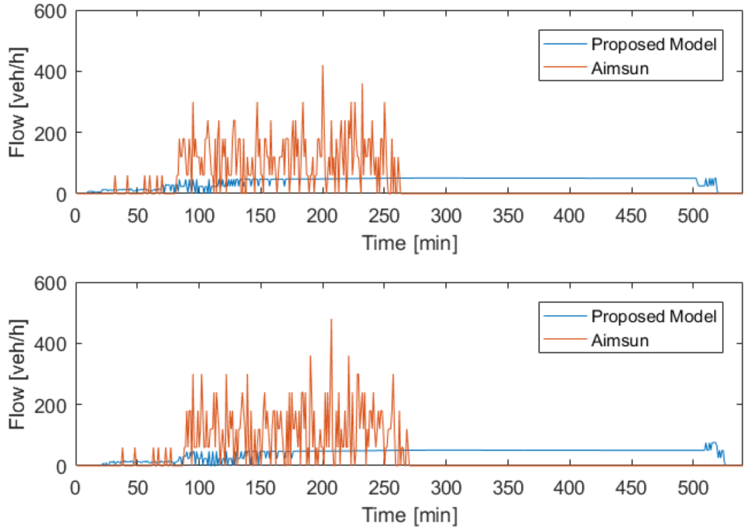


Fig. 42 - Estimated flow obtained by Aimsun and the proposed model for HGV class for link 3-4 (Greenshields relation)

The Figures 43-48 show links densities determined by both models:

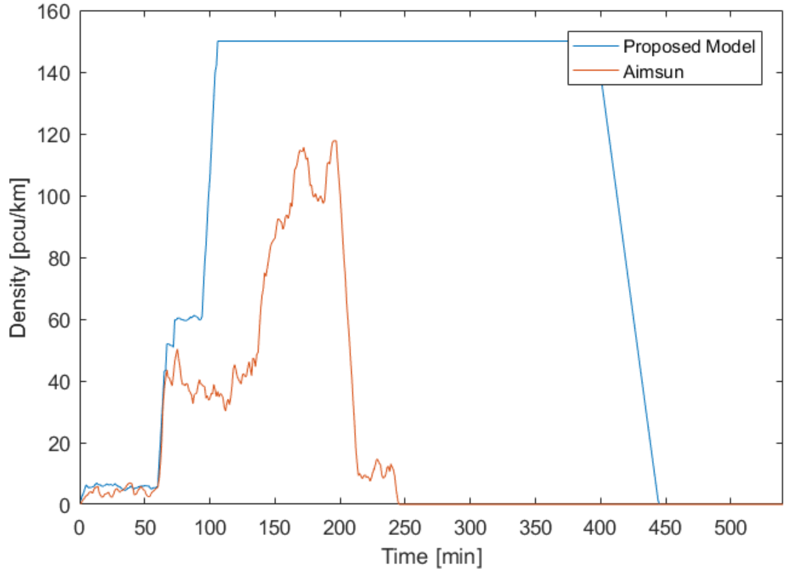


Fig. 43 - Estimated density by the Aimsun and the proposed model link 1 (Greenshields relation)

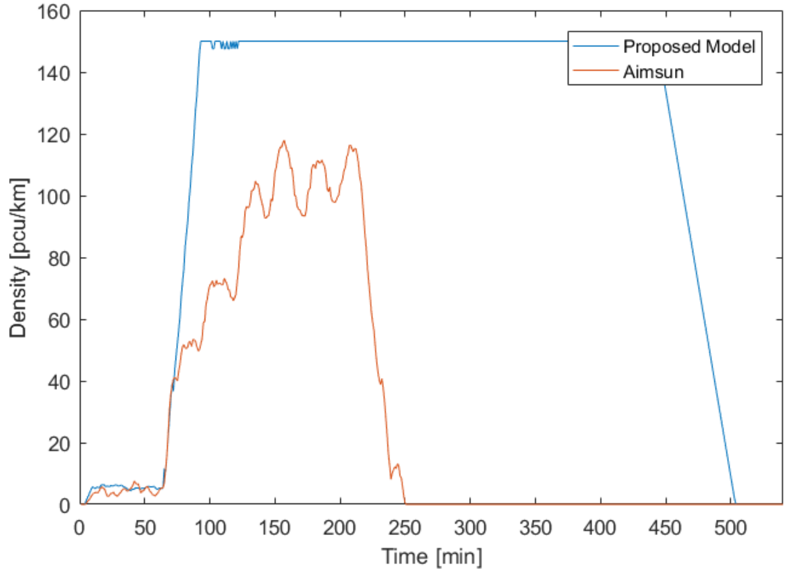


Fig. 44 - Estimated density by the Aimsun and the proposed model link 2 (Greenshields relation)

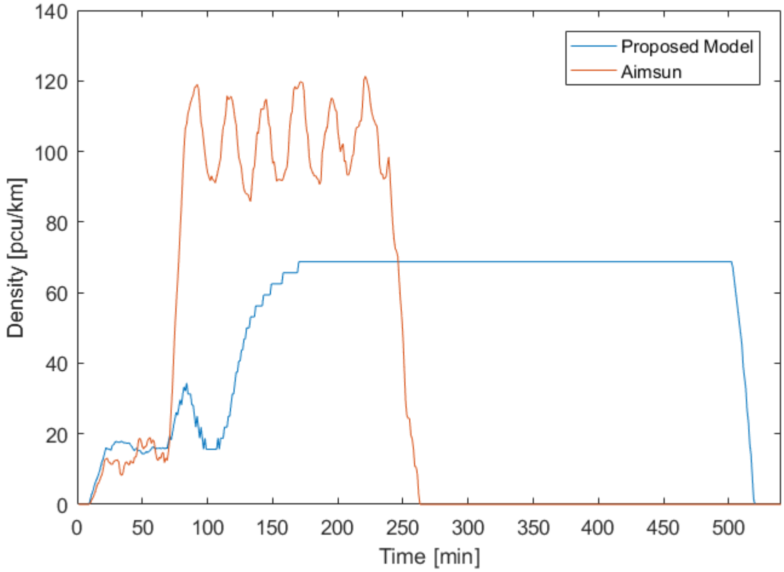


Fig. 45 - Estimated density by the Aimsun and the proposed model link 3 (Greenshields relation)

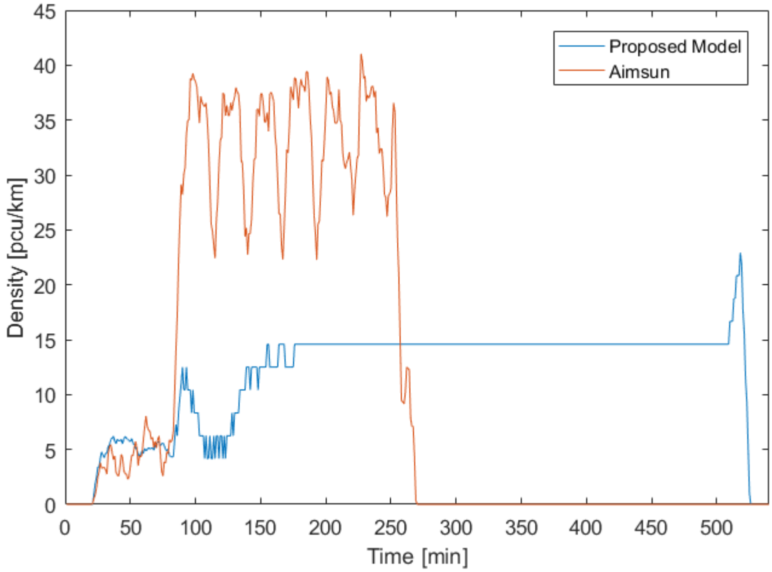


Fig. 46 - Estimated density by the Aimsun and the proposed model link 4 (Greenshields relation)

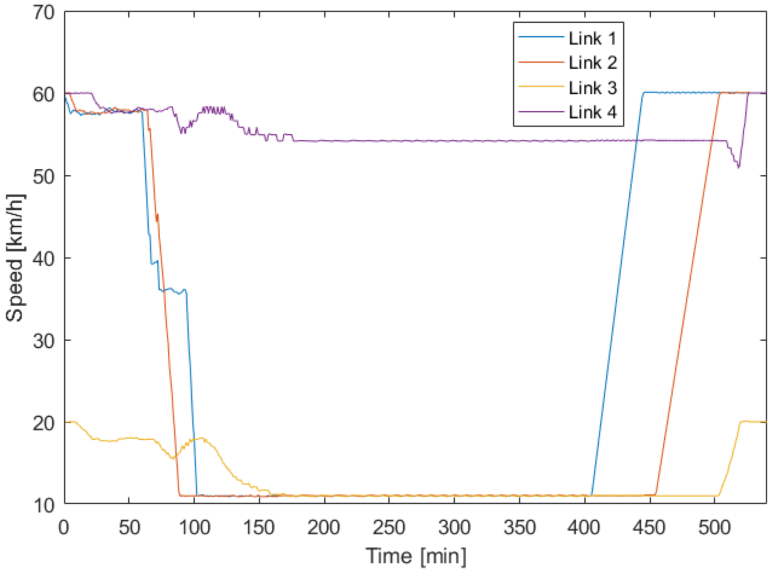


Fig. 47 - Simulated speed by the proposed model (Greenshields relation)

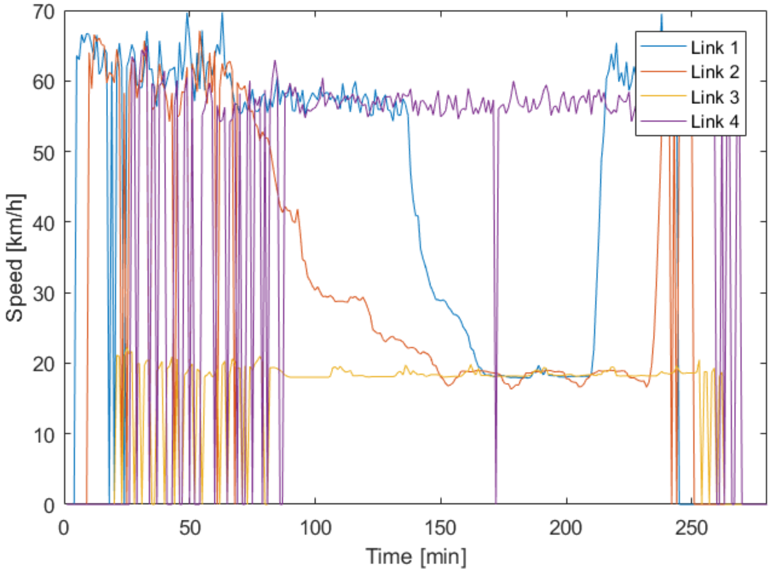


Fig. 48 - Simulated speed by the Aimsun model

### *4.4.3. SIMULATION OF OVERSATURATION CONDITIONS EMPLOYING THE TRIANGULAR FUNDAMENTAL DIAGRAM*

As in the previous section, the simulation in oversaturation conditions by Aimsun and the proposed model using the triangular approach for speed calculation to compare the resulted traffic dynamics provided by both simulators. Again, the proposed model and Aimsun tuned to load the same dynamic load presented in Table.5. In addition, route characteristics are listed in Table.7

Table. 7 - Route characteristics- Model input/ Triangular

| **Link characteristics** | **Link 1** | **Link 2** | **Link 3** | **Link 4** |
|---|---|---|---|---|
| **Length [km]** | 4 | 5 | 4 | 6 |
| **Free flow speed [km/h]** | 60 | 60 | 20 | 60 |
| **Creeping speed [km/h]** | 10 | 10 | 10 | 10 |
| **Capacity [pcu/h]** | 4000 | 4000 | 2200 | 4000 |
| **Jam density [pcu/km]** | 450 | 450 | 450 | 300 |

The Figures 49-54 show the flow approximations for Aimsun and the proposed model:

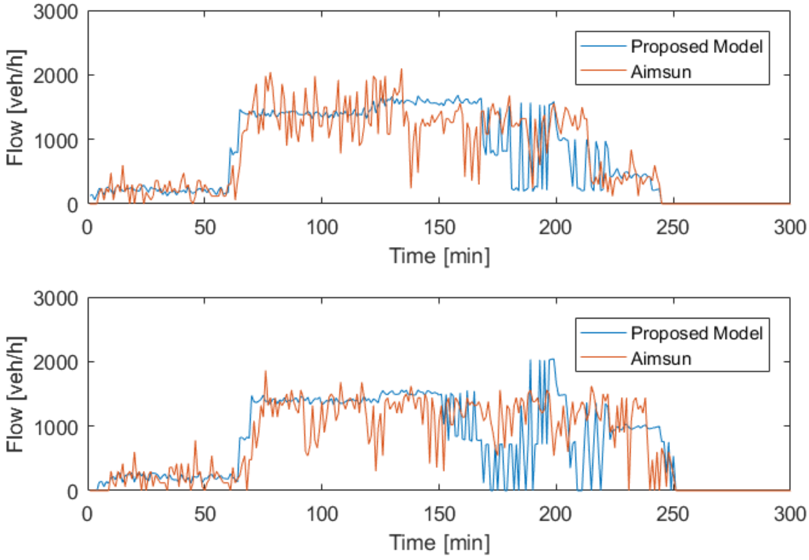


Fig. 49 - Estimated flow obtained by Aimsun and the proposed model for passenger car class for link 1-2 (Triangular diagram)

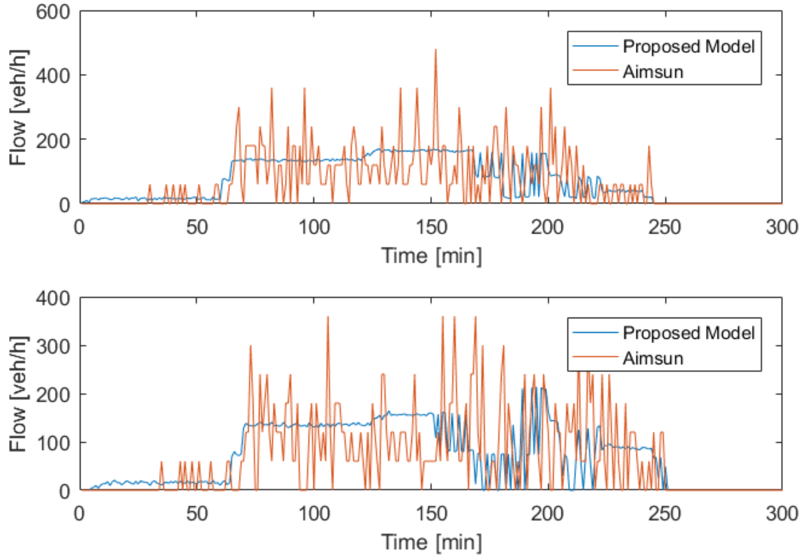


Fig. 50 - Estimated flow obtained by Aimsun and the proposed model for Bus class for link 1-2 (Triangular diagram)

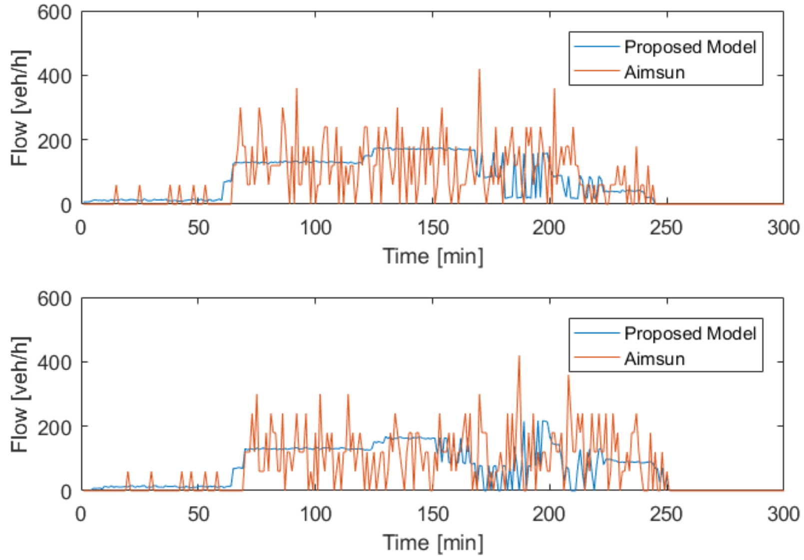


Fig. 51 - Estimated flow obtained by Aimsun and the proposed model for HGV class for link 1-2 (Triangular diagram)

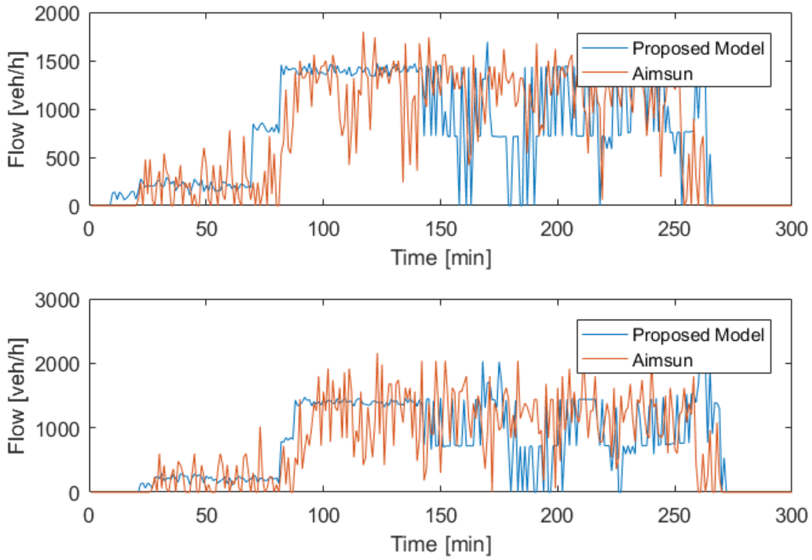


Fig. 52 - Estimated flow obtained by Aimsun and the proposed model for passenger car class for link 3-4 (Triangular diagram)

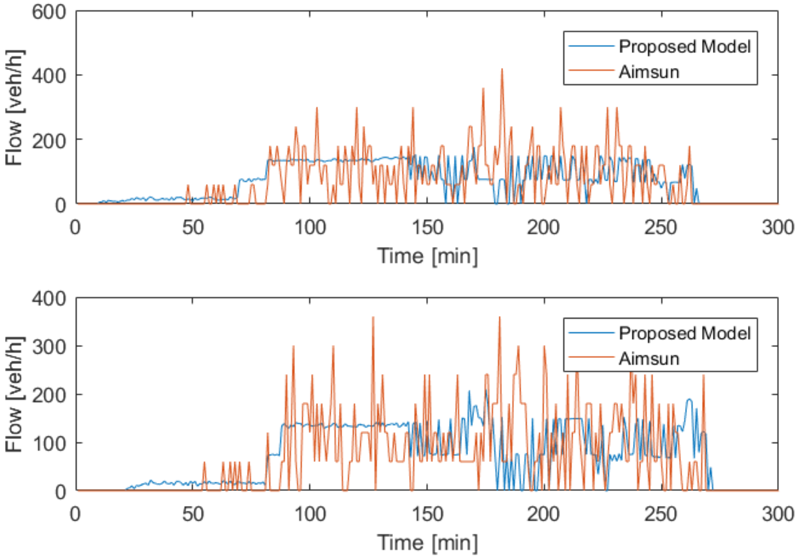


Fig. 53 - Estimated flow obtained by Aimsun and the proposed model for Bus class for link 3-4 (Triangular diagram)

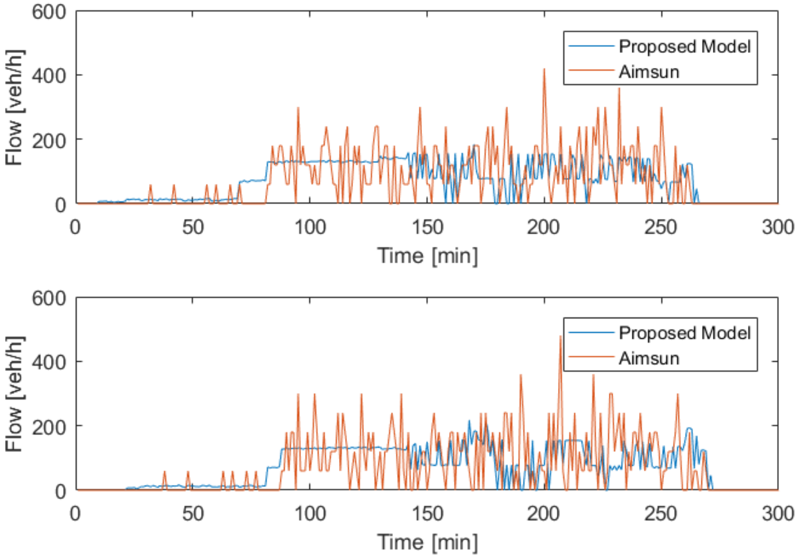


Fig. 54 - Estimated flow obtained by Aimsun and the proposed model for HGV class for link 3-4 (Triangular diagram)

Links densities provided in the Figures 55-59:

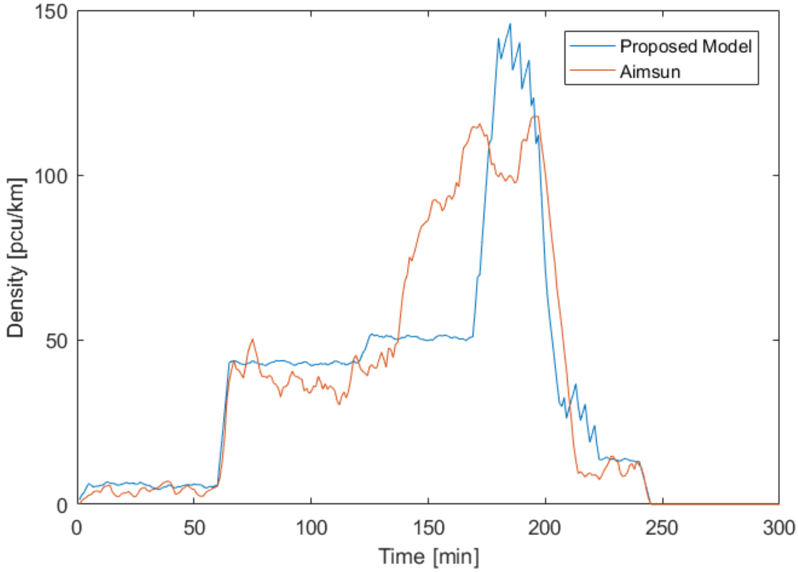


Fig. 55 - Estimated density by the Aimsun and the proposed model for link 1 (Triangular diagram)

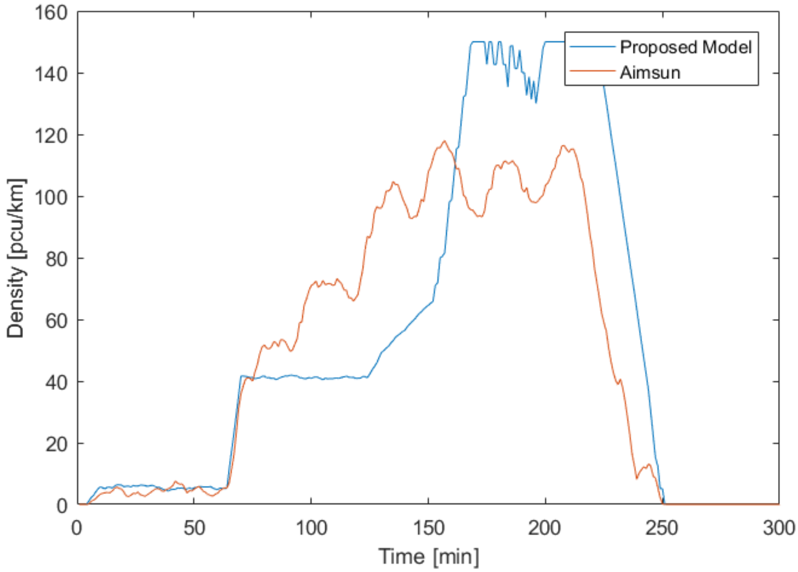


Fig. 56 - Estimated density by the Aimsun and the proposed model for link 2 (Triangular diagram)

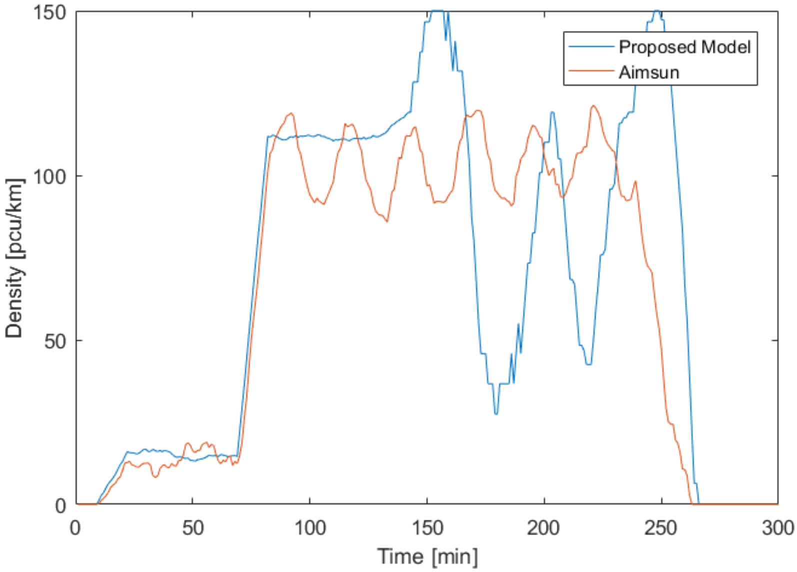


Fig. 57 - Estimated density by the Aimsun and the proposed model for link 3 (Triangular diagram)

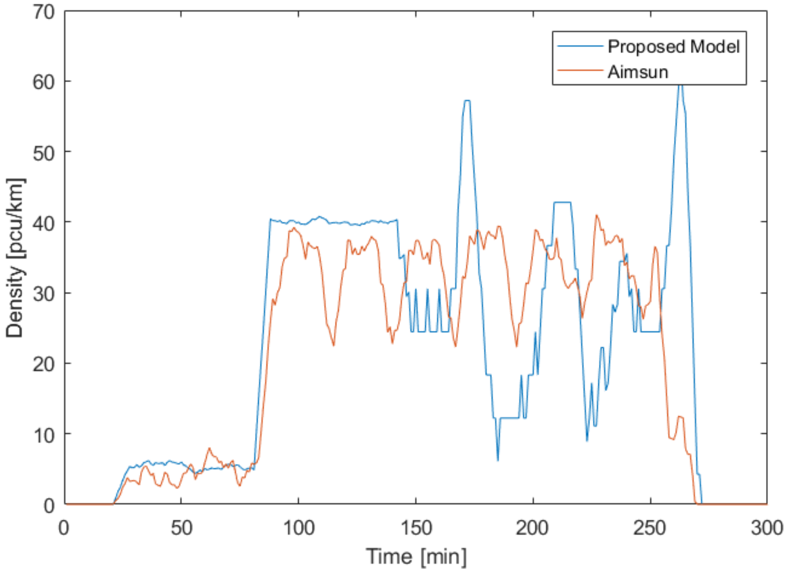


Fig. 58 - Estimated density by the Aimsun and the proposed model for link 4 (Triangular diagram)

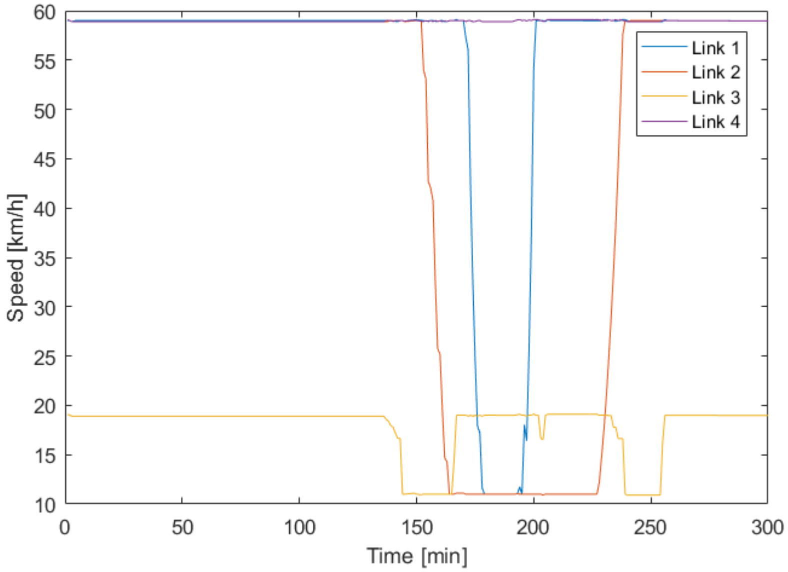


Fig. 59 - Simulated speed by the proposed model (Triangular diagram)

#### *4.4.4. DISCUSSION AND CONCLUSION*

To evaluate the proposed model more efficiently, in oversaturation conditions, the spillback was simulated using different speed-density relations in the proposed methodology compared to Aimsun model. Likewise, Aimsun mesoscopic simulator adjusted according to the route characteristics described in Table. 7. Moreover, toward a comparison that is more effective, the results of the proposed model using both speed formulas compared with the Aimsun outcomes separately.

#### 4.4.4.1 AIMSUN ESTIMATIONS COMPARED TO THE PROPOSED MODEL RESULTS USING GREENSHIELDS SPEED-DENSITY RELATION

Link 2 was selected to evaluate the spillback dynamics. In more details, the simulation results obtained from both models are similar in describing the density variation in the undersaturation conditions (see Fig. 44). This condition was held for 72 minutes. After a short time, the density in the proposed model reached the jam value conversely to Aimsun simulator where the density never achieved the maximum value.

Similarly, the flow obtained was similar for both models until they achieve congestion. To take the point in the case, the flow provided by both models for passenger car class stayed identical until they approached the timeline of 71 minutes (see Fig. 37). Likewise, bus class flow for both model remained analogous for 70 minutes (see Fig. 38). In addition, Fig. 39) shows the flow for HGV class obtained by both models which start to separate after 69 min.

Obviously, the simulation obtained by the proposed model using the Greenshields formula took much longer than the Aimsun model (see Figures 37-42). This is mainly related to the Greenshields formula that adopts a behaviour, which affects the link speed from the first minute of the load until reaching the designed minimum speed earlier than other speed relations reach. This justification is confirmed in the next section by adopting the triangular diagram formula.

The dynamic queue spillback impact can be described by the speed profile as shown in Fig. 47 and Fig. 48 related to the proposed model and Aimsun, respectively. Since the link 2 is influenced by a bottleneck, the average speed decreased to the assumed creeping speed after 87 min. Soon after 16 min, link 1 reached the minimum speed affected by the spillback because of the spillback propagation.

Generally, these behaviours were almost similar to Aimsun estimations but on much more extended time. And fluctuations remained as for density and flow evaluation (see Figures 37-48).

### 4.4.4.2 AIMSUN ESTIMATIONS COMPARED TO THE PROPOSED MODEL RESULTS USING TRIANGULAR SPEED-DENSITY RELATION

As for, link 2 was selected to evaluate the spillback dynamics as well. Moreover, the simulation results obtained for density variation are similar in the undersaturation conditions; this condition was remained for 75 minutes, (see Fig. 56). Immediately following, and in contrast to the Aimsun simulator, the density in the proposed model reached the jam value.

This behaviour held as well as in the case of using the Greenshields model (see Fig. 44), as an effect of the capacity constraints of the proposed model. Identically, the flow estimated was similar for both models until they achieved congestion (see Figures 49-51). Conversely, to the case of using Greenshields formula, both of the proposed model and Aimsun ended the simulation together for all classes. To exemplify, for pcu, bus and HGV class (Link 2), the simulation ends in 251 minutes for the proposed model and the Aimsun. Instead, in Greenshields case, the simulation spent 504 minutes.

Clearly, for all simulated classes, the flow estimated by the proposed model was stable during the oversaturation time using both of speed-density relations. In contrast, Aimsun's flow values fluctuated. It means that Aimsun seems to consider flow characteristics of the microscopic level (e.g., start-and-stop behaviour). Conversely, to the proposed model methodology that estimated a stable flow trend taking in the account average flow values typical of the macroscopic characteristic embedded in the mesoscopic simulation.

The performance of the model in describing the dynamic queue spillback impact can be clarified by the speed profile as shown in Fig. 59 and Fig. 48 related to the proposed model and Aimsun, respectively. Since the link 2 is influenced by a bottleneck, the average speed decreased to the assumed creeping speed after 164 min. later on and after 15 min, link 1 travelled adopting the creeping speed as impacted by the spillback because of the spillback propagation.

Similar to what was concluded in section 4.4.4.1, the spillback simulated by the proposed model using triangular relation behaved as well as the Aimsun model in detection the spillback propagation.

These behaviours were almost similar to Aimsun estimations but on much more extended time. Fluctuations remained as for density and flow evaluation (see Figures 49-59).

Consequently, the proposed model using both of speed-density relation has provided the same behaviour in detecting the dynamic spillback propagation but in a completely different simulation time for each one. Aimsun model and the proposed model showed a relatively similar behaviour simulation time but with much more fluctuation for Aimsun model. Of course, acquiring a real data set is needed to judge which speed-density relation provides near estimations to the reality in oversaturation conditions.

# 5. CONCLUSIONS AND RECOMMENDATIONS

Traffic flow models can describe the dynamic loading of the transportation network. Moreover, it is possible to simulate the actual traffic conditions in many detail levels. Flow propagation models can, therefore, evaluate traffic conditions as a microscopic, macroscopic and mesoscopic level of details. More exactly, microscopic models handle the traffic as individual vehicles and describe their interactions whereas the macroscopic gives attention to traffic flow as a whole. The mesoscopic however falls in between them.

In this thesis, a novel model for queue spillback simulation in mesoscopic level is proposed. Furthermore, a multiclass simulation based on vehicular type is correspondingly considered. In addition, the model adopted two different speed-density formulas, Greenshields and the triangular fundamental diagram.

The model was validated in undersaturation conditions by comparing the model estimations to real observations collected by ATC sensors for Maliha Highway in the United Arab Emirates. Moreover, we compared it with Aimsun, which is a commercial traffic simulator. As a result, the proposed model obtained better RMSE values than Aimsun ones.

To reproduce the impact of queue spillback at the mesoscopic level in oversaturation conditions and because of data limitations, we applied the model to a simple network in order to better analyze the simulation results. Following this, Greenshields and the triangular fundamental diagram for speed calculation were used. In addition, they have been compared with Aimsun outcomes. Consequently, the same behaviour in detecting the dynamic spillback propagation has been obtained but in a completely different simulation time for each one.

The proposed model and Aimsun have shown a relatively similar behaviour and simulation time in case of using the triangular fundamental diagram relation but with much more fluctuation in Aimsun model results. On the contrary, using Greenshields relation provided the same behaviour but with much longer simulation time.

Briefly, the proposed model presented the mesoscopic simulation in a more reliable way: Aimsun seemed to include microscopic characteristics in the mesoscopic traffic simulation like start-and-stop behaviour.

Finally, this model can be useful for researchers and planners in the outline of dynamic network assignment problems when simulating a road network in congested situations.

As further developments, we are looking forward to extending the model to take into consideration full networks and to extend the application of oversaturation conditions to a real case study.

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# 8. ANNEXES

## *Annex. A - Sensors observations for Maliha Highway ATC 1-ATC 2*

| Time (15 min) | ATC 1 | | | ATC 2 | | |
|---|---|---|---|---|---|---|
| | PCU | BUS | HGV | PCU | BUS | HGV |
| 00:00 | 64 | 1 | 7 | 102 | 0 | 2 |
| 00:15 | 51 | 1 | 5 | 79 | 6 | 7 |
| 00:30 | 53 | 2 | 4 | 80 | 3 | 2 |
| 00:45 | 45 | 3 | 1 | 70 | 1 | 2 |
| 01:00 | 39 | 3 | 5 | 57 | 3 | 2 |
| 01:15 | 43 | 3 | 3 | 60 | 3 | 5 |
| 01:30 | 23 | 3 | 6 | 48 | 2 | 4 |
| 01:45 | 23 | 3 | 1 | 34 | 3 | 1 |
| 02:00 | 31 | 5 | 2 | 24 | 5 | 2 |
| 02:15 | 18 | 2 | 3 | 25 | 3 | 2 |
| 02:30 | 21 | 2 | 3 | 21 | 6 | 2 |
| 02:45 | 17 | 1 | 4 | 24 | 1 | 5 |
| 03:00 | 12 | 4 | 1 | 20 | 3 | 2 |
| 03:15 | 15 | 2 | 2 | 11 | 3 | 0 |
| 03:30 | 13 | 1 | 2 | 23 | 3 | 1 |
| 03:45 | 14 | 3 | 1 | 17 | 2 | 4 |
| 04:00 | 16 | 2 | 0 | 19 | 3 | 0 |
| 04:15 | 10 | 5 | 1 | 23 | 4 | 1 |
| 04:30 | 11 | 3 | 7 | 29 | 5 | 2 |
| 04:45 | 15 | 9 | 5 | 33 | 6 | 7 |
| 05:00 | 13 | 0 | 2 | 39 | 4 | 2 |
| 05:15 | 20 | 4 | 4 | 36 | 4 | 4 |
| 05:30 | 28 | 0 | 1 | 60 | 0 | 1 |
| 05:45 | 34 | 3 | 0 | 80 | 4 | 1 |
| 06:00 | 38 | 5 | 0 | 84 | 8 | 0 |
| 06:15 | 46 | 5 | 0 | 99 | 6 | 1 |
| 06:30 | 102 | 2 | 0 | 158 | 8 | 3 |
| 06:45 | 94 | 1 | 2 | 230 | 10 | 1 |
| 07:00 | 148 | 3 | 0 | 332 | 9 | 3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 07:15 | 144 | 3 | 2 | 352 | 7 | 4 |
| 07:30 | 212 | 4 | 0 | 360 | 12 | 6 |
| 07:45 | 206 | 7 | 1 | 366 | 10 | 8 |
| 08:00 | 135 | 3 | 1 | 227 | 3 | 3 |
| 08:15 | 142 | 8 | 0 | 234 | 9 | 2 |
| 08:30 | 145 | 2 | 0 | 253 | 7 | 2 |
| 08:45 | 168 | 2 | 1 | 263 | 7 | 1 |
| 09:00 | 147 | 6 | 2 | 259 | 10 | 2 |
| 09:15 | 149 | 3 | 1 | 271 | 7 | 7 |
| 09:30 | 152 | 18 | 16 | 277 | 18 | 11 |
| 09:45 | 155 | 14 | 13 | 279 | 18 | 17 |
| 10:00 | 148 | 10 | 10 | 270 | 11 | 15 |
| 10:15 | 150 | 12 | 14 | 291 | 10 | 13 |
| 10:30 | 164 | 13 | 16 | 336 | 17 | 12 |
| 10:45 | 174 | 11 | 16 | 331 | 12 | 16 |
| 11:00 | 156 | 12 | 19 | 345 | 19 | 15 |
| 11:15 | 162 | 16 | 11 | 302 | 18 | 17 |
| 11:30 | 141 | 9 | 8 | 302 | 9 | 22 |
| 11:45 | 164 | 19 | 25 | 319 | 17 | 16 |
| 12:00 | 148 | 8 | 18 | 322 | 21 | 17 |
| 12:15 | 159 | 13 | 17 | 331 | 23 | 14 |
| 12:30 | 162 | 11 | 17 | 287 | 18 | 16 |
| 12:45 | 178 | 10 | 8 | 345 | 16 | 14 |
| 13:00 | 161 | 7 | 4 | 323 | 16 | 5 |
| 13:15 | 173 | 6 | 2 | 333 | 11 | 8 |
| 13:30 | 207 | 2 | 3 | 339 | 10 | 4 |
| 13:45 | 213 | 1 | 3 | 392 | 12 | 7 |
| 14:00 | 219 | 8 | 2 | 393 | 15 | 9 |
| 14:15 | 211 | 5 | 7 | 331 | 10 | 7 |
| 14:30 | 213 | 3 | 3 | 307 | 10 | 5 |
| 14:45 | 273 | 23 | 23 | 321 | 20 | 18 |
| 15:00 | 278 | 21 | 25 | 438 | 22 | 24 |
| 15:15 | 234 | 10 | 11 | 350 | 23 | 9 |
| 15:30 | 311 | 11 | 9 | 403 | 12 | 11 |
| 15:45 | 307 | 10 | 12 | 385 | 14 | 10 |
| 16:00 | 355 | 21 | 15 | 483 | 29 | 13 |
| 16:15 | 366 | 20 | 13 | 489 | 22 | 25 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 16:30 | 463 | 9 | 13 | 522 | 18 | 22 |
| 16:45 | 505 | 15 | 13 | 533 | 24 | 18 |
| 17:00 | 535 | 22 | 14 | 603 | 34 | 20 |
| 17:15 | 584 | 21 | 16 | 720 | 30 | 23 |
| 17:30 | 656 | 19 | 19 | 703 | 37 | 18 |
| 17:45 | 682 | 20 | 21 | 719 | 24 | 16 |
| 18:00 | 694 | 19 | 23 | 804 | 23 | 17 |
| 18:15 | 731 | 20 | 17 | 816 | 27 | 14 |
| 18:30 | 787 | 24 | 18 | 823 | 34 | 23 |
| 18:45 | 649 | 26 | 26 | 711 | 38 | 21 |
| 19:00 | 705 | 31 | 16 | 773 | 23 | 20 |
| 19:15 | 638 | 30 | 11 | 693 | 28 | 17 |
| 19:30 | 599 | 21 | 15 | 638 | 28 | 21 |
| 19:45 | 574 | 13 | 9 | 614 | 24 | 12 |
| 20:00 | 560 | 12 | 9 | 551 | 19 | 10 |
| 20:15 | 512 | 14 | 19 | 526 | 26 | 18 |
| 20:30 | 369 | 5 | 5 | 427 | 16 | 11 |
| 20:45 | 251 | 3 | 6 | 322 | 9 | 3 |
| 21:00 | 189 | 3 | 4 | 265 | 12 | 5 |
| 21:15 | 181 | 6 | 19 | 258 | 3 | 11 |
| 21:30 | 184 | 10 | 53 | 267 | 14 | 41 |
| 21:45 | 114 | 6 | 12 | 166 | 9 | 18 |
| 22:00 | 105 | 3 | 9 | 156 | 8 | 12 |
| 22:15 | 95 | 10 | 12 | 165 | 8 | 8 |
| 22:30 | 96 | 4 | 9 | 179 | 9 | 5 |
| 22:45 | 82 | 7 | 4 | 122 | 11 | 6 |
| 23:00 | 83 | 5 | 13 | 107 | 8 | 13 |
| 23:15 | 71 | 5 | 7 | 93 | 5 | 9 |
| 23:30 | 61 | 8 | 8 | 98 | 6 | 8 |
| 23:45 | 48 | 3 | 2 | 98 | 3 | 2 |

***Annex. B - Sensors observations for Maliha Highway ATC 3-ATC 4***

| Time (15 min) | ATC 3 | | | ATC 4 | | |
|---|---|---|---|---|---|---|
| | PCU | BUS | HGV | PCU | BUS | HGV |
| 00:00 | 154 | 2 | 4 | 77 | 1 | 1 |
| 00:15 | 116 | 5 | 8 | 56 | 2 | 3 |
| 00:30 | 121 | 5 | 3 | 40 | 6 | 1 |
| 00:45 | 102 | 3 | 3 | 48 | 1 | 1 |
| 01:00 | 81 | 7 | 3 | 38 | 0 | 1 |
| 01:15 | 73 | 7 | 6 | 28 | 5 | 3 |
| 01:30 | 45 | 3 | 6 | 16 | 6 | 1 |
| 01:45 | 41 | 4 | 2 | 15 | 4 | 2 |
| 02:00 | 40 | 4 | 2 | 16 | 2 | 2 |
| 02:15 | 32 | 7 | 2 | 7 | 3 | 1 |
| 02:30 | 24 | 5 | 4 | 16 | 2 | 2 |
| 02:45 | 26 | 3 | 4 | 10 | 1 | 2 |
| 03:00 | 25 | 1 | 3 | 10 | 2 | 1 |
| 03:15 | 20 | 5 | 1 | 9 | 1 | 1 |
| 03:30 | 30 | 1 | 1 | 15 | 0 | 1 |
| 03:45 | 16 | 2 | 4 | 13 | 1 | 2 |
| 04:00 | 24 | 1 | 0 | 11 | 0 | 0 |
| 04:15 | 31 | 2 | 1 | 12 | 0 | 0 |
| 04:30 | 35 | 6 | 4 | 19 | 2 | 2 |
| 04:45 | 31 | 9 | 8 | 19 | 5 | 5 |
| 05:00 | 39 | 4 | 3 | 27 | 1 | 3 |
| 05:15 | 41 | 4 | 4 | 18 | 1 | 0 |
| 05:30 | 70 | 0 | 1 | 54 | 3 | 2 |
| 05:45 | 101 | 5 | 0 | 56 | 5 | 0 |
| 06:00 | 116 | 14 | 3 | 79 | 13 | 1 |
| 06:15 | 129 | 5 | 0 | 101 | 5 | 0 |
| 06:30 | 183 | 11 | 1 | 150 | 6 | 1 |
| 06:45 | 252 | 9 | 0 | 148 | 3 | 1 |
| 07:00 | 390 | 14 | 3 | 145 | 4 | 2 |
| 07:15 | 455 | 9 | 4 | 144 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 07:30 | 472 | 12 | 3 | 181 | 5 | 0 |
| 07:45 | 408 | 16 | 5 | 220 | 3 | 1 |
| 08:00 | 331 | 3 | 4 | 202 | 1 | 1 |
| 08:15 | 306 | 7 | 1 | 168 | 6 | 0 |
| 08:30 | 263 | 11 | 4 | 150 | 1 | 1 |
| 08:45 | 290 | 9 | 7 | 144 | 2 | 2 |
| 09:00 | 330 | 9 | 8 | 162 | 3 | 1 |
| 09:15 | 325 | 11 | 5 | 162 | 4 | 3 |
| 09:30 | 342 | 13 | 10 | 139 | 7 | 6 |
| 09:45 | 357 | 28 | 15 | 143 | 16 | 9 |
| 10:00 | 412 | 21 | 10 | 151 | 8 | 14 |
| 10:15 | 383 | 13 | 12 | 132 | 4 | 10 |
| 10:30 | 382 | 11 | 18 | 166 | 9 | 7 |
| 10:45 | 381 | 26 | 20 | 147 | 11 | 14 |
| 11:00 | 442 | 19 | 17 | 164 | 5 | 12 |
| 11:15 | 376 | 17 | 20 | 148 | 7 | 9 |
| 11:30 | 380 | 14 | 19 | 164 | 5 | 9 |
| 11:45 | 393 | 17 | 16 | 152 | 10 | 9 |
| 12:00 | 427 | 24 | 20 | 165 | 10 | 9 |
| 12:15 | 467 | 19 | 22 | 205 | 11 | 9 |
| 12:30 | 410 | 17 | 21 | 168 | 12 | 9 |
| 12:45 | 459 | 20 | 18 | 184 | 10 | 10 |
| 13:00 | 519 | 24 | 11 | 205 | 13 | 5 |
| 13:15 | 451 | 13 | 12 | 210 | 2 | 3 |
| 13:30 | 489 | 15 | 9 | 265 | 5 | 3 |
| 13:45 | 531 | 20 | 7 | 244 | 14 | 2 |
| 14:00 | 616 | 24 | 16 | 286 | 9 | 2 |
| 14:15 | 480 | 14 | 12 | 217 | 5 | 3 |
| 14:30 | 417 | 10 | 7 | 176 | 1 | 3 |
| 14:45 | 451 | 24 | 13 | 153 | 8 | 10 |
| 15:00 | 532 | 34 | 27 | 172 | 15 | 26 |
| 15:15 | 565 | 23 | 20 | 180 | 9 | 12 |
| 15:30 | 526 | 25 | 17 | 187 | 7 | 4 |
| 15:45 | 582 | 17 | 14 | 159 | 7 | 4 |
| 16:00 | 632 | 23 | 22 | 199 | 7 | 9 |
| 16:15 | 601 | 38 | 24 | 211 | 20 | 8 |
| 16:30 | 646 | 30 | 23 | 198 | 18 | 14 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 16:45 | 662 | 38 | 18 | 201 | 19 | 10 |
| 17:00 | 691 | 33 | 26 | 225 | 17 | 12 |
| 17:15 | 769 | 37 | 29 | 253 | 13 | 12 |
| 17:30 | 763 | 34 | 22 | 262 | 14 | 11 |
| 17:45 | 780 | 40 | 20 | 272 | 9 | 3 |
| 18:00 | 753 | 34 | 36 | 272 | 10 | 2 |
| 18:15 | 869 | 35 | 21 | 304 | 11 | 7 |
| 18:30 | 828 | 42 | 29 | 358 | 14 | 7 |
| 18:45 | 748 | 39 | 30 | 294 | 11 | 3 |
| 19:00 | 812 | 28 | 27 | 296 | 15 | 3 |
| 19:15 | 726 | 29 | 16 | 261 | 6 | 2 |
| 19:30 | 726 | 30 | 19 | 249 | 9 | 7 |
| 19:45 | 668 | 20 | 14 | 225 | 8 | 6 |
| 20:00 | 651 | 14 | 17 | 224 | 9 | 4 |
| 20:15 | 600 | 19 | 18 | 203 | 10 | 2 |
| 20:30 | 489 | 14 | 13 | 178 | 3 | 4 |
| 20:45 | 388 | 12 | 5 | 125 | 3 | 4 |
| 21:00 | 331 | 15 | 4 | 150 | 5 | 3 |
| 21:15 | 315 | 9 | 10 | 128 | 4 | 4 |
| 21:30 | 319 | 12 | 44 | 106 | 7 | 23 |
| 21:45 | 273 | 15 | 23 | 98 | 5 | 17 |
| 22:00 | 260 | 7 | 15 | 101 | 3 | 7 |
| 22:15 | 197 | 13 | 14 | 65 | 4 | 11 |
| 22:30 | 215 | 12 | 10 | 102 | 7 | 6 |
| 22:45 | 166 | 13 | 6 | 84 | 8 | 1 |
| 23:00 | 147 | 8 | 12 | 75 | 3 | 6 |
| 23:15 | 125 | 5 | 9 | 55 | 2 | 9 |
| 23:30 | 154 | 4 | 9 | 78 | 4 | 5 |
| 23:45 | 144 | 5 | 7 | 81 | 5 | 2 |

# *9. CURRICULUM*

## Contact Information


a.alnajajreh@gmail.com

Skype a.alnajajreh


## Personal Information

**First name(s) / Surname(s)** Abedelkareem Alnajajreh

**Date of birth** Dec, 24th 1987

**Gender** Male

## Educational Background

**01 Nov 2016 – 30 Jan 2020** PhD candidate EQF level 8

- The Polytechnic University of Bari, **[ Italy-Bari]**
- Department of Civil, Environmental, Land, Building Engineering and Chemistry
  - Risk And Environmental, Territorial And Building Development
- PhD program:
  - Transportation Engineering
  - Urban and Regional Planning

**01 Oct 2013 –20 Oct 2015** Master of Science (2 years) EQF level 7

- Institute of CIHEAM-IAM Bari, **[ Italy-Bari]**
- M.Sc. in land and water resources management
-

**01 Sep 2008 – 12 Jun 2013** Bachelor's of Science (5 years) EQF level 7

- Palestine Polytechnic University-College of engineering and tech. **[Hebron-Palestine]**
- Bachelor's in Civil engineering: Surveying and Geomatics Eng.

**01 Sep 1992–15 Jul 2005** High School (National Becculruate)

- Nahhalin secondary school **[Bethlehem-Palestine]**
- 12th-grade National baccalaureate -Scientific stream.
- Merit: 93.1%

## Work Experience

**01 Jan 2018 – 15 Sep 2018** Visiting Researcher

- Linköping University **[Norrköping-Sweden]**

**01 Mar 2013 – 01 Oct 2013**
**15 June 2014–01 Oct 2014** Infrastructure Design Engineer **(United States Agency for International Development infrastructure program USAID)**

## Publications list

✓ Alnajajreh, A., Marinelli, M. and Sinesi, S., 2019, June. A dynamic mesoscopic network loading model for spillback queuing assessment. In *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-5). IEEE.

- ✓ Marinelli, M., Caggiani, L., Alnajajreh, A. and Binetti, M., 2019, June. A two-stage Metaheuristic approach for solving the Vehicle Routing Problem with Simultaneous Pickup/Delivery and Door-to-Door service. In *2019 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)* (pp. 1-9). IEEE

- ✓ Alnajajreh, A., 2019, Oct. A new mesoscopic simulation model for dynamic network loading and spillback queuing assessment in a multiclass environment based on the vehicular type. *(Submitted)*

**Mother tongue language:** Arabic

| **Other languages** | UNDERSTANDING | | SPEAKING | | WRITING |
|---|---|---|---|---|---|
| | Listening | Reading | Spoken interaction | Spoken production | |
| English | C1 | C1 | C1 | C1 | C1 |
| Italian | B1 | B1 | A1 | A1 | A1 |

Levels: A1/A2: Basic user - B1/B2: Independent user - C1/C2: Proficient user
Common European Framework of Reference for Languages

**Programming languages**

- **MATLAB**

**Computer skills**

- Have a high professionalism computer maintenance for both Desktops and laptops in terms of hardware and software.

**Professional computer skills**

- **AutoCAD Civil 3D (2010-2019)**
- **AutoCAD (All versions)**
- **ArcGIS 10.1 Desktop**
- **Aimsun 8.2**
- **PTV Visum and Vissim**

**Personal Skills**

- Social, Serious and self-starter.

**Organizational / managerial skills**

- Guide person.
- Responsible.

**References**

| Name | Institute | Email |
| --- | --- | --- |
| Prof. Domenico Camarda | Polytechnic University of Bari | domenico.camarda@poliba.it |
| Dr.Eng. Mario Marinelli | Polytechnic University of Bari | mario.marinelli@poliba.it |