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Şcoala Doctorală de Studii Inginereşti

REFINED CAR-FOLLOWING MODEL INCORPORATING THE BEHAVIOR OF THE VEHICLES FROM THE ADJACENT LANES

PhD Thesis – Summary

for obtaining the Scientific Title of PhD in Engineering from
Politehnica University Timişoara
in the Field of SYSTEMS ENGINEERING
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Chapter 1, INTRODUCTION, describes the motivation of the chosen research topic with a clear definition of the problem and a description of the research objectives. The presentation of the current drawbacks of the car-following models supports the understandability of the motivation of the author to find solutions to real road traffic issues.

Driver behavior introduces uncertainties in road traffic modeling at the microscopic level. Various car-following models are single-lane oriented and cannot emphasize the influence of the vehicles moving on the adjacent traffic lanes. A lane change decision made by a vehicle from the current lane leads to a “leader change” in the modeling process and the FV shall adapt its acceleration control mechanism to respond to this stimulus. This control mechanism is mandatory for the assurance of collision avoidance.

Solutions to introduce the behavior of vehicles moving in the same direction on adjacent lanes into the modeling process are mandatory. In this regard, the development of new car-following models shall provide control strategies for the follower vehicle (FV) movement by incorporating the interactions with the vehicles from adjacent traffic lanes. This not only plays an important role in better understanding the phenomenon of traffic, but also represents an important step for the development of autonomous driving systems.

The objectives of this thesis are as follows:

- providing an analysis of the intersections configuration methods;
- obtaining a more accurate prediction of the origin-destination traffic volumes and implicitly creating a better overview of the driver behavior;
- developing new microscopic road traffic models capable of incorporating the lane choice behavior with high accuracy;
- developing new car-following models for multiple-lane roads;
- developing models for fault detection and analysis of car-following models that can highlight the faults introduced by the modeling process;
- developing new solutions for car-following model calibration that are easily adaptable to multiple-lane car-following models.

This thesis represents a synthesis of the author’s achievements during his PhD research program besides his already published contributions, as follows:

- 1 scientific article published in a journal indexed ISI Web of Science (WoS) with quartile Q1 and impact factor (IF) equal to 3.576;
- 1 scientific article published in a journal indexed ISI WoS without quartile and IF;

- 11 scientific papers published in ISI WoS indexed proceedings of international conferences, one of these papers, [1], being awarded with the *Best Paper Award “Honorable Mention”*;
- 1 scientific paper published in the proceedings of international conferences indexed BDI.

This thesis provides a deeper overview of the microscopic traffic modeling concept and describes the current research directions in this domain. All these information have been structured in 7 chapters on 133 pages, containing 60 figures, 10 tables, and having as a source of inspiration 130 bibliographic references, including the previously mentioned 14 papers as the original author contributions.

Chapter 2, STATE OF THE ART IN ROAD TRAFFIC MODELING AT THE MICROSCOPIC LEVEL, presents a complete analysis of the state of the art in road traffic modeling at the microscopic level. This analysis starts with an overview of current developments in terms of road traffic simulators and shows how important the following characteristics are: scalability, workload partitioning, and partition organization.

This chapter continues with a critical review of recent trends in car-following control and modeling. Researchers improved many of the existing car-following models by applying current development approaches based on neural networks [2-3]; genetic algorithms [3-4]; machine learning [5]; fuzzy systems [6-7] or stochastic processes [8-11].

Other works try to improve the accuracy of microscopic traffic models by employing some features from macroscopic models. Borsche and Meurer [12] coupled these models to provide a better overview of the interaction between traffic flows and pedestrian dynamics. However, this approach has weaknesses in describing traffic in the case of studying vehicle movement when the density of pedestrians on the road is small. In reverse, Gkania and Dimitriou [13] proposed the usage of microscopic traffic flow mechanics in combination with traffic information resulting from online traffic maps to overcome the drawbacks of estimation of macroscopic fundamental diagrams.

The interests of current researchers cover the improvements of car-following derivative models such as Gipps [5, 14-15]; Gazis-Herman-Rothery (GHR) [2, 12, 15]; optimal velocity difference (OVD) [16-17]; full velocity difference (FVD) [5, 14, 16, 18-20]; intelligent driver model (IDM) [21-22]. In addition, special attention is paid to the adaptation of the mentioned models to meet the needs of autonomous driving [5, 20-21, 23-26], connected vehicles [16, 20-21, 23-24] and electric vehicles [6, 20, 27-28]. Furthermore, in **Sections 2.3.1-2.3.3**, this thesis discusses in detail some of these approaches.

Another section has been designed to pay special attention to the calibration process. This step plays a crucial role in the development of new models because it is responsible for providing a better approximation of the model parameters compared to the real observed road traffic parameters. This section will provide several approaches in this regard.

Sensor networks and the Internet of Things (IoT) play an important role in microscopic traffic control. Currently, IoT services meet the following limitations with respect to their integration with intelligent transportation systems (ITS):

- network infrastructure efficiency and scalability;
- “*lack of flexibility in the interaction between the vehicles and other applications based on the IoT*” [29];
- “*limited power sources that cannot ensure highly intensive full functionalities*” [29];
- “*limitation in self-recovery mechanisms to handle the transition from an error state to the normal operational mode for ITS systems*” [29].

Future networks 2030 aim to provide solutions to these limitations through “*a common platform that allows the deployment of a wide variety of technologies and architectures*”

[29-30], “*cost reduction by using low-cost sensors, deployment services and reducing energy consumption*” [29, 31], “*self-recovering mechanisms from failure states*” [29, 32], “*appropriate policies and regulation*s *systems*” [29, 33] or “*systems designed for the storage and management of large volumes of road traffic data*” [29-30, 34-35].

The review of recent works showed the current gaps in the car-following control and modeling process and also the implications of the continuous developments in the field of ITS.

Chapter 3, ROAD TRAFFIC MODELING AT THE MICROSCOPIC LEVEL, highlights the importance of road traffic modeling at the microscopic level. This chapter provides the author’s contributions related to road traffic modeling. Simulations are performed using AnyLogic Simulation Software to analyse the impact of different crossroad configuration methods (uncontrolled intersections, signalized intersections, and roundabouts) on the velocities of vehicles and the evolution in the number of vehicles passing through an intersection. The results analysis shows the advantages of choosing the roundabout as a traffic coordination method, but also highlights its drawback in case of crowded traffic that leads to gridlocks after the capacity of the roundabout has been exceeded.

“*Microscopic traffic models* [36] *pay more attention to the details of the traffic flow and are vital for traffic analysis, especially in the presence of ITS. Initial model calibration is necessary to identify the parameter values. It requires the activities of all traffic participants in order to have feedback of the traffic with parameters such as vehicle position, accelerations/decelerations, and vehicle speed*” [37].

In addition to microscopic models, there are two types of models in traffic modeling theory, macroscopic and mesoscopic models. “*Macroscopic models are approached from the perspective of continuous traffic flow theory. The objective of these models is to provide a description in time and space of the evolution of macroscopic flow variables. To achieve this description, the concepts of flow and density are used. Flow means the number of vehicles that cross a part of the road network (x) in a previously set time (Δt)*” [38]. “*Mesoscopic models can be seen as a combination of microscopic and macroscopic models. In most cases, in these models, the behavior of the parameters corresponding to microscopic models is studied under the influence of specific parameters of macroscopic models. The classic example of this approach is to model the behavior of a vehicle with respect to others in traffic, taking into account aspects related to its dynamics*” [38].

Car-following represents one of the “*four levels of representation of the microscopic road traffic network model together with crossroads configuration, links and lane choice*” [39-40]. To better understand the factors that influence the car-following modeling process, lane change behavior modeling has been described. Special attention was paid to the definition of incentive criteria that controls the acceleration behavior of the FV considering the behavior of the vehicle ahead, also called the leader vehicle (LV). These incentive criteria play a crucial role in collision avoidance actions by proper control of the FV acceleration.

The last two subchapters provide a critical overview of the car-following models. Some well-known models are presented such as Gipps, Pipes, GHR, OVD, FVD, IDM, fuzzy-based model, and other variations of these models. Taking into account the theoretical foundation of the car-following modeling process, this study identifies the main advantages and disadvantages of this modeling approach.

The biggest disadvantage of car-following models is their orientation towards the examination of road traffic on a single lane. In this way, problems arise in the case of the integration of a new vehicle as a result of the driver's decision to change its current traffic lane. In this case, there is a need for an adaptive model that is able to manage LV / FV role changes in cases such as:

- entry of a new vehicle on the modeled traffic lane;

- leaving the lane by one of the vehicles;
- the departure by the FV of the current lane with return as a reason for the initial movement of the LV at low speed, in which case we are talking about the change of roles of the two vehicles (the FV becomes the new LV).

Another problem specific to this type of modeling is the integration of heavy vehicles. A study in this regard is presented in [41] and aims to demonstrate the low capability of car-following in terms of removing disturbances in traffic parameters in the case of mixed travel, having both cars and heavy vehicles. A delayed response of the heavy vehicle driver was observed in the case of deceleration, in response to the LV deceleration represented by a vehicle, but also to the timely takeover of the previous velocity level during and after the execution of an acceleration operation. If a car follows a heavy vehicle, a higher deceleration trend was observed than LV, which continued with gradual acceleration, following the perception of a deceleration action of the heavy vehicle.

In addition to all the mentioned contributions, this chapter serves as a foundation for building a refined car-following model that easily addresses the multiple-lane roads that are widely found nowadays. The new car-following model shall be adapted to multiple lane roads by considering the lane change behavior of the drivers during the movement on a road network. The next chapter will present in detail this new approach.

Chapter 4, REFINEMENT OF THE CAR-FOLLOWING MODEL, illustrates the proposed methodology for the refinement of the standard discrete-time car-following model consisting of the extension of this single-lane oriented model to multiple-lane roads.

This chapter begins with an analysis of the driver behavior modeling (DBM) concept and its main implementation approaches. The most used DBM implementation techniques are the "*Gaussian mixture model (GMM) and the piecewise auto-regressive exogenous (PWARX) model*" [42] which are presented in detail in this thesis. Both approaches are studied with respect to the concept of car-following and underline the influence of the observed LV parameters on the changes in FV driver behavior during the movement process. Further, the thesis presents how traffic modeling can be modeled using Markov chains. The application of this modeling approach proves its benefits, especially in the simplification process of the origin-destination (OD) volumes estimation. The accuracy of these estimations brings improvements in traffic lights management through real-time control of green-interval settings.

This chapter also discusses the application of "*a DBM at the maneuvering level based on tactical route execution, more explicitly based on lane change behavior*" [43]. The proposed procedure for the refinement of the car-following model consists of the application of the "*decisions taken to fulfill small and coordinated portions of a trip*" [43-44]. Here arises one of the main contributions of this thesis consisting of the modeling of the road traffic lanes as Markov nodes, and the transitions between several nodes of the modeled road network represent the lane change maneuvers. The probabilities associated with each node of the Markov chain consist of the probability of changing the movement by joining a specific traffic lane. The probability calculation uses the traffic data from time t-1 and updates these values in real-time by permanently retrieving the traffic parameters from the inductive loops placed on the road network.

Because of the uncertainties introduced by drivers behavior, the lane change action is modeled further as a Bayesian specific problem. The use of the Bayesian probabilistic concept at this level of traffic modeling represents another important contribution to this thesis. This Bayesian-based computation considers the movement parameters for the FV from the current traffic lane and also some specific probabilities related to the target lane. These target lane related probabilities arise from the driver decision to leave the road network through an exit that is accessible only from an adjacent lane. Another case that leads to a lane change decision of the FV relates to the LV velocity changes (acceleration/deceleration behavior), and the FV changes its current traffic lane just for passing the LV with a return to its initial lane after the maneuvering execution.

The proposal of the multiple-lane car-following model considers the traffic lanes as Markov nodes of a road network modeled as a Markov chain, and the lane change predictions are included as part of the car-following model. The modeling approach starts from the state space representation of the single-lane oriented car-following model, referred in this thesis also as the standard car-following model, and permanently updates the acceleration value of the FV according to the lane change predictions based on Bayesian reasoning. Furthermore, lane change prediction harmonizes the incentive criteria equations with respect to the predicted driver decision and makes this proposed model suitable for multiple-lane traffic environments. Figure 1 illustrates the steps followed during the refinement process of the single-lane car-following model. The main sources of influence of driver decision are:

- the entrance lane of the target vehicle (e_{FV});
- the destination lane of the target vehicle (d_{FV});
- the influence of LV behavior on the velocity changes of the FV (v_{FV}), represented as a coefficient in the interval [0;1].

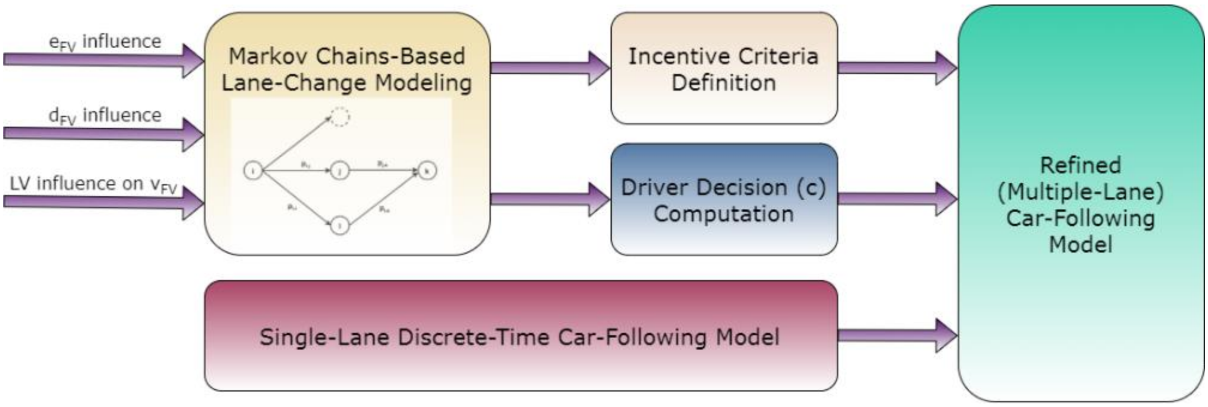

Figure 1. Refinement process of the single-lane car-following model.

After the presentation of the refinement proposal of the standard car-following model, a simulation has been performed in Simulink, part of MATLAB R2020a (MathWorks, Natick, MA, USA) to prove that it is implementable. The results show good results in the estimation of the target vehicle movement behavior. The main disadvantage of the proposed approach consists of the neglection of the FV vehicle from the new joined traffic lane of the FV from the current lane. This situation, recognized as ”leader change”, allows the FV from a lane *i* to become LV for the vehicle moving behind on the lane *j*.

“Figure 2 *shows the acceleration profiles and the internal update of the acceleration values for LV and FV after c is greater or lower than the threshold. The threshold value was set at 0.50 and showed a greater than 50% chance of changing lanes. In this case, the simulated values for LV and FV were set to the calculated values, taking into account the incentive criteria for asymmetric lane change rules - lane change from left to right. For a better understanding of these switches of simulated acceleration values incorporating lane change actions, the case of a lane change action from* L_i *to* L_{i-1} *at time 0.2 s can be considered. The LV from the lane* L_i *performs this action and starts to follow the movement behavior described by vehicles moving into the lane* L_{i-1}*. The FV from the lane* L_i *will also change its movement behavior due to the new LV after the initial LV changes lane. Another similar case, but with a lane change from* L_i *to* L_{i+1}*, is observable at time 6.3 s*” [45].

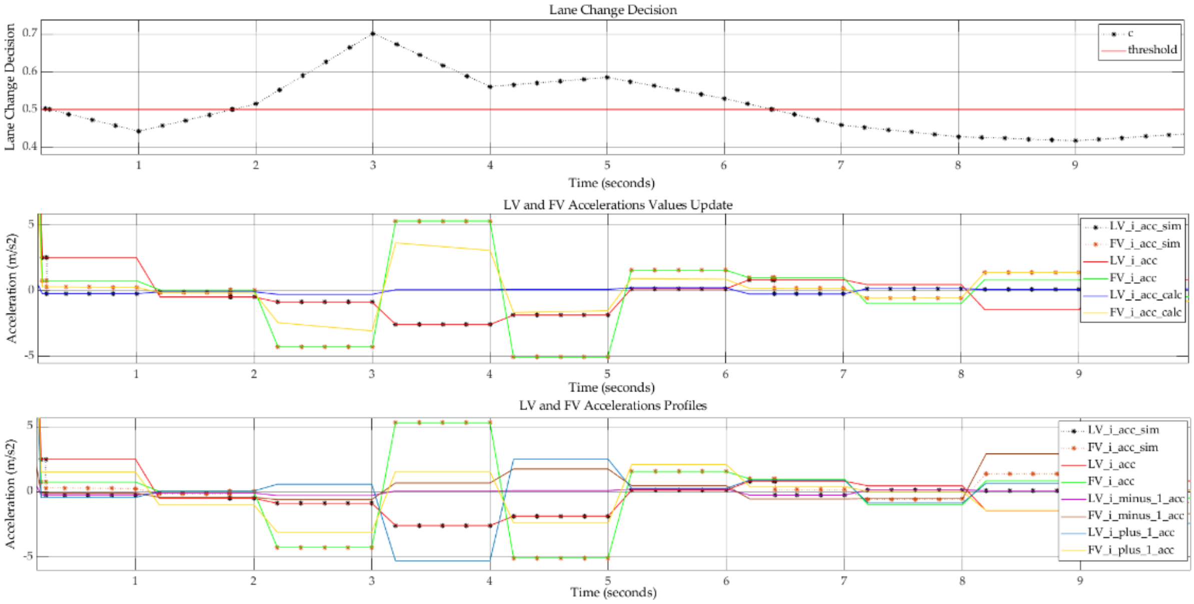

Figure 2. "*LV and FV from lane L_i – accelerations values update*" [45].

The last section of this chapter highlights the contributions made by the employed approach in the refinement process of the car-following model. This part also provides an overview of the benefits and drawbacks of the proposed multiple-lane car-following model and defines possible future improvements. In addition, a subchapter contains the conclusions of this work.

Chapter 5, FAULT DETECTION OF DISCRETE-TIME MICROSCOPIC TRAFFIC MODELS, provides a fault analysis of the proposed refined model. The fault analysis assumes that the refined model introduces faults through internal calculations and is used both as an observed model and as a model with the defect. The nominal model consists of three standard car-following models, one for each traffic lane included in the experiment. The applied methodology consists of the usage of parity equations, as described by Kratz et al. [46] and Isermann [47-48]. According to this methodology, "*the identified residuals are the relative velocity residual and the dynamic running distance residual*" [45].

"*To perform fault detection based on parity equations for the multiple-lane car-following model, a simulation was done in Simulink, part of MATLAB R2020a (MathWorks, Natick, MA, USA). Usually, the fault detection considers three types of models: nominal, observed, and the model with a defect. This thesis assumed that the observed model had already incorporated faults as a result of the proposed computational approach. In this case, the implementation consisted of two main types of subsystems, as shown in* Figure 3*: three separate blocks for the standard implementation of a car-following model, consisting of the nominal model (orange); and the proposed model for multiple-lane car-following, consisting of the observed model (blue)*" [45]. The inputs of these blocks are the acceleration values obtained as outputs of the *input handler* subsystem described in **Section 4.5.3** of this thesis.

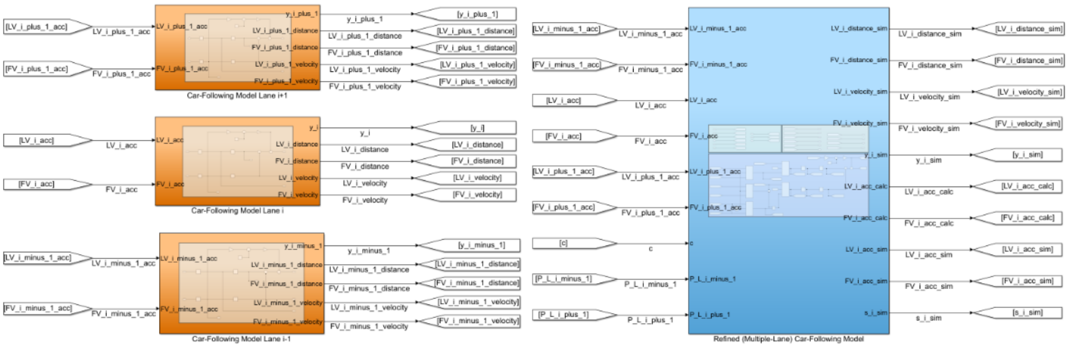

Figure 3. “*Main subsystems overview − implementation using Simulink (MATLAB R2020a)*” [45].

“*The subsystem shown in* Figure 4 *covers the residual computation. The outputs are the relative_velocity_residual and dynamic_distance_residual, and consist of the differences between the values of* $\bar{x}_1$ *and* $\bar{x}_2$ *obtained by using the nominal model and the observed model with faults introduced by the computation approach”* [45].

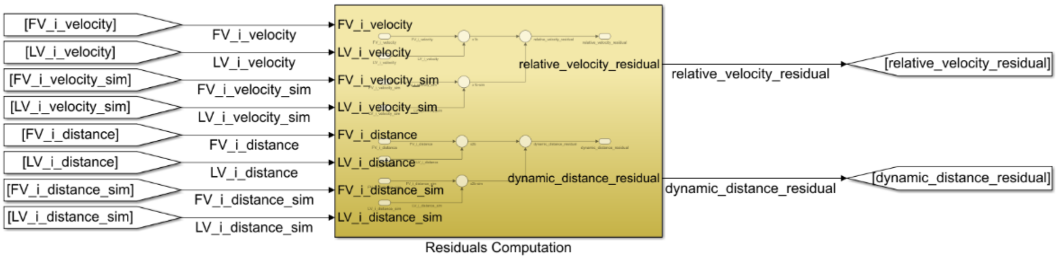

Figure 4. “*Residuals computation subsystem overview – implementation using Simulink (MATLAB R2020a)*” [45].

The evaluation of residuals (Figure 5) showed that the refined model provides an accurate description of the behavior of the LV and FV from the target lane if a new vehicle from an adjacent lane joins the target lane. “*The proposed model introduces faults when the driver decision c has a low degree of uncertainty (i.e., c is near the 0.50 threshold with ±0.10). In other cases, when the driver decision is not affected by this low level of uncertainty, the relative velocity residual tends to zero. The dynamic distance residual has a continuously increasing trend based on the same pattern, and its value remains relatively constant in the absence of a low level of uncertainty”* [45].

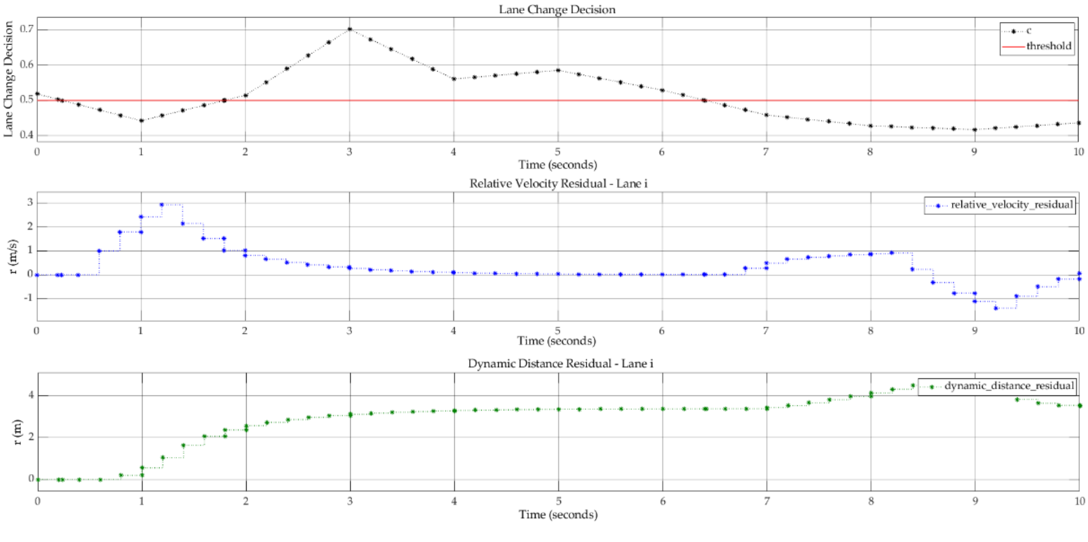

Figure 5. “*Fault detection – residuals overview*” [45].

However, the fault analysis also illustrates the main disadvantage of the proposed multiple-lane car-following model consisting of the fact that "*the model is not suitable for a real-time switch from one lane to another to ensure lane change behavior monitoring for each lane*" [45].

Chapter 6, CALIBRATION OF MICROSCOPIC TRAFFIC MODELS, describes the calibration process of the car-following models and proposes a new approach consisting of a hybrid online calibration solution that combines the concept of Kalman filtering with a Takagi-Sugeno fuzzy inference system (FIS) to eliminate the noises introduced by the modeling process. "*The calibration step shall establish the offset values to be applied to the model inputs to reduce the difference compared to the real data. Calibration is performed until these offset values become equal to zero*" [37].

After presenting the theoretical overview of the calibration concept that applies to microscopic traffic models, this chapter discusses the new calibration method proposed by Pop et al. (Figure 6) [37]. "*As part of the modeled microscopic traffic system, the calibration model has the feature of providing the necessary data to adapt the internal model parameters based on the evaluation received as input from the system responsible for the model validation. Together with the validation result, two sets of parameters consisting of simulation values and microscopic traffic real data will be sent to the calibration subsystem*" [37].

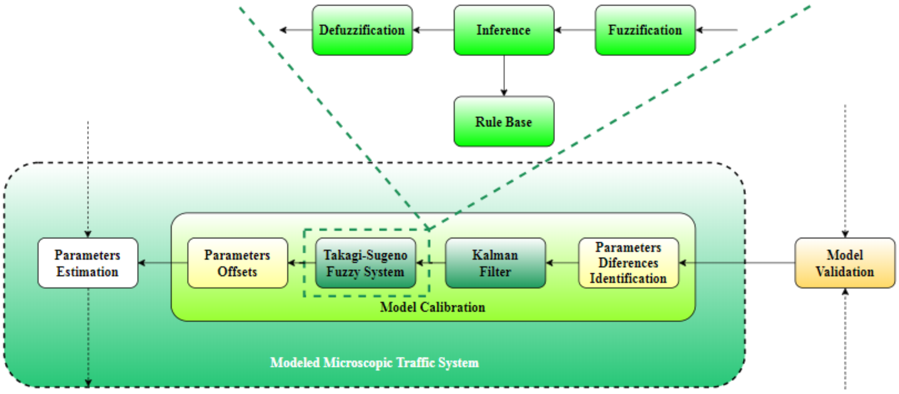

Figure 6. The proposed approach for microscopic traffic model calibration [37].

"*The first internal subsystem of a calibration system is intended for identifying the differences between real and simulation data. These will be forwarded to the Kalman filter. The filtered values will be forwarded to the final decision step regarding the offset values consisting of a Takagi-Sugeno FIS. This last subsystem embeds the fuzzy specific components. Fuzzification ensures that the identified differences between the real and simulation parameters are converted to a fuzzy variable. Further, after the fuzzy rules have been defined, the output fuzzy variables will consider them in establishing the connections with the input fuzzy variables through an inference step. Defuzzification will convert the fuzzy variables to the corresponding types of analyzed parameters. These values consisting of offsets that shall be applied to the simulation parameters will also be saved by a subsystem that will build a knowledge base for the parameters offset*" [37].

The proposed calibration method proves its efficiency through a faster identification of the correct offsets to be applied to the model parameters compared to a simple Kalman filtering (Figure 7)."*The Kalman filtering-only approach cannot reproduce the real behavior through its neglect of inter-vehicle interaction from a relative velocity perspective. The hybrid approach takes advantage of this interaction between FV and LV and succeeds at identifying the time-varying appropriate offset value that reproduces the real behavior. This advantage can be visually observed from trajectory evolution where, after* $t = 18$ *s, the system is calibrated using* *the hybrid approach. At the same time, the Kalman filter-only approach introduces a uniform increase in computation error that leads to a scaled running distance compared to real traffic conditions. From a computational complexity perspective, both approaches fit to real-time processing. The Takagi-Sugeno FIS does not introduce computational delays that can lead to a major increase in the real-time data processing timings*” [37].

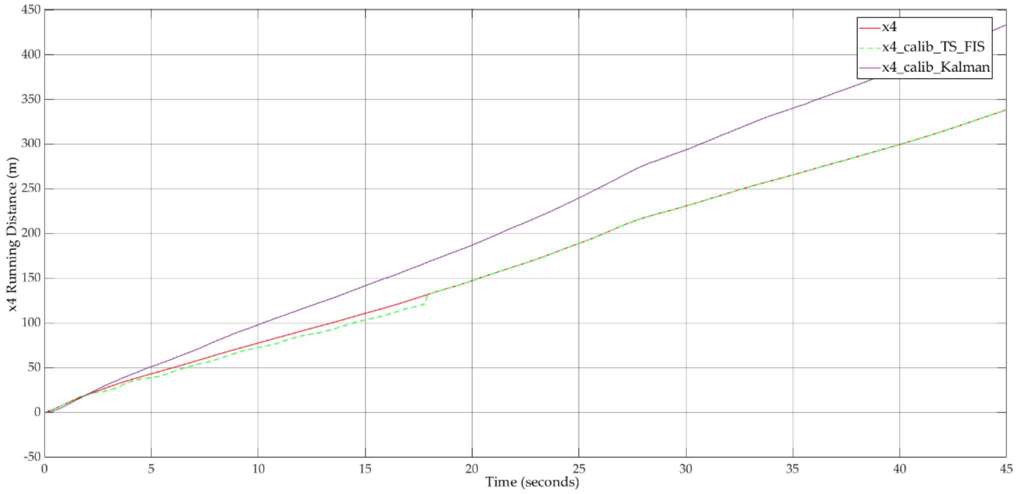

Figure 7. “*Running distance for FV (x_4) - comparison of calibration result for the Kalman filtering-only approach and the hybrid Kalman filtering and Takagi-Sugeno FIS approach*” [37].

In addition to the outcome of the research of Pop et al. [37], this chapter adapts this calibration method and applies it to the refined car-following model. The most challenging aspect is the adaptation of the initially proposed version for the continuous-time system to a discrete-time environment. Designed initially for continuous-time, the adaptation to the discrete-time version of the refined car-following model proposed by this thesis involved the usage of an *ode45* solver for continuous states.

The offsets determined through the calibration process can also reduce the impact of computational faults resulting from the fault analysis performed in the previous chapter. The calibration method succeeds in “learning” different patterns of changes in the running distance value and after approximately $t = 5\ s$ the calibration process is completed and the refined car-following model is fully calibrated (Figure 8).

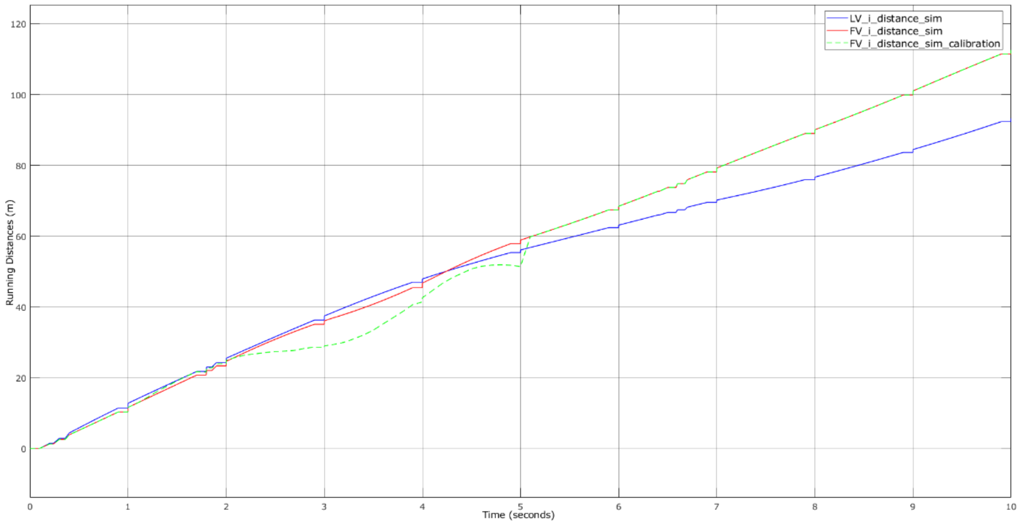

Figure 8. Calibration result for FV (*FV_i_distance_sim*) in the case of refined car-following model.

Chapter 7, CONCLUSIONS, CONTRIBUTIONS AND FUTURE RESEARCH, highlights the thesis conclusions, the author's original contributions and possible directions for future research in the field of microscopic modeling of road traffic systems. The **global contribution** of this thesis is to address the disadvantage of single-lane orientation of the car-following models by proposing a refinement process that also considers the behavior of the vehicles moving on the adjacent traffic lanes into the process of car-following modeling.

The outcome of this thesis consists of the following **original contributions**, divided into four main categories:

- a critical analysis of the concepts used in road traffic modeling at the microscopic level and the evaluation of possible factors of influence:
    - a critical analysis and synthesis of microscopic road traffic simulators;
    - a comparative overview of the car-following model and its derivatives;
    - a critical analysis and synthesis of the recent developments of car-following models designed to respond to connected and autonomous vehicles and electric vehicles needs;
    - a critical analysis and synthesis of the car-following calibration methods;
    - identification of the influence of road infrastructure, traffic policies and regulations, and smart mobility solutions in traffic congestion reduction;
    - identification of possible improvements in the modeling of road traffic at the microscopic level;
    - identification of possible improvements in the modeling car-following calibration methods;
- a systemic approach and modeling of road traffic at the microscopic level of representation:
    - modeling and implementation in AnyLogic Simulation Software of different crossroads configuration methods;
    - a comparative analysis of the traffic volumes and velocity profiles corresponding to all crossroad configuration methods;
    - a safety analysis of the single-lane roundabout management systems;
    - modeling and implementation of green-intervals schedulers using AnyLogic Simulation Software and Simulink (MATLAB R2020a);
    - development of new approaches of traffic lanes modeling as nodes in a Markov chain that corresponds to a road network;
    - development of new algorithms based on Bayesian reasoning, genetic algorithms and minimax gaming-specific strategy for driver behavior prediction and, implicitly OD volumes estimation;
    - development of new models for lane change to incorporate the uncertainty of driver behavior;
    - development and implementation of a refined car-following model that overcomes the disadvantage of single-lane orientation of the standard car-following models by considering the behavioral changes according to the lane change actions to adjacent traffic lanes;
    - conducting an experimental study on the proposed refined car-following model based on real road traffic dataset for a three-lane piece of road from Timisoara (Romania);
    - a comparative critical analysis of the results of the proposed refined car-following model with the separate application of the standard car-following model for each lane of a three-lane piece of road;
- a systemic fault detection and analysis of the faults introduced by the modeling process of the refined car-following model:

  - "*defining a fault detection methodology based on parity equations for multiple-lane car-following models*" [45];
  - identification of relative velocity and dynamic running distance as the residuals of the refined car-following model;
  - development and implementation of the fault detection mechanisms in Simulink (MATLAB R2020a);
  - conducting an experimental fault detection study of the proposed refined car-following model using real road traffic dataset for a three-lane piece of road from Timisoara (Romania);
  - providing measurements and evaluation of the obtained residuals values;
  - a critical analysis of the advantages and disadvantages of the proposed refined car-following model as an outcome of the evaluation of the residuals;
- a systemic approach and modeling of the calibration process of car-following models:
  - development and implementation of a new calibration model for car-following models as a hybrid solution that combines Kalman filtering with Takagi-Sugeno FIS;
  - identification of the possible changes in the proposed calibration model to adapt it to the needs of the proposed refined car-following model;
  - conducting an experimental study on the proposed calibration model based on a real road traffic dataset from Timisoara (Romania) for both standard and refined car-following models;
  - a comparative critical analysis of the proposed calibration model in terms of accuracy and performance.

This thesis recommends the following possible directions of further research:

- real-time control for all vehicles moving on multiple traffic lanes, allowing the permanent update of the FVs accelerations for all traffic lanes of a road network, not only for a traffic lane as proposed in this thesis;
- new systemic approaches for microscopic road traffic control based on genetic algorithms, fuzzy algorithms and neural networks concepts to provide safe solutions for traffic congestion reduction;
- new systemic approaches for microscopic road traffic calibration methods based on. genetic algorithms, fuzzy algorithms and neural networks concepts;
- identification of behavioral patterns that describe the relationship between crossroads configuration methods and driver behavior.

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