Evaluation of Traffic Controller Performance via Systematic Exploration

Krešimir Kušić[1], Davide Calvaresi[2*], Amy Liffey[2*], Lora Fanda[3*],
Martin Gregurić[1], Edouard Ivanjko[1], René Schumann[2]

[1] University of Zagreb Faculty of Transport and Traffic Sciences
kresimir.kusic@fpz.unizg.hr
[2] HES-SO Valais-Wallis, University of Applied Sciences Western Switzerland
[3] University of Geneva, Switzerland

***Abstract*—Traffic controllers must operate reliably across diverse traffic states. Due to the stochastic non-linear characteristics of traffic flow, commonly used feedback-based controllers require parameter tuning for each specific traffic regime, which is done offline using simulations. Generating representative traffic scenarios for large-scale simulations is often computationally expensive. To reduce the computational burden, this paper proposes a systematic exploration of the Structured Simulation Framework (SSF). This approach aims to approximate controller performance with a minimal number of simulations, by adjusting the parameter space continuously to regions where controller performances are weakly approximated. This process continues until controller performance is well approximated across the entire input domain. Results show SSF convergence of performance estimate of the controller while reducing the number of required simulations. This helps identify traffic scenarios where the controller performs poorly, and, thus, can be used as a framework towards guided controller tuning.**

***Keywords*—Structured simulations; Function approximation; Microscopic Traffic Simulation; Traffic control.**

I. Introduction

Motorways are designed to serve higher traffic volumes. However, anticipated demands are often reflected under the assumption of average traffic volume trends. Rush hours are specific cases where traffic volume exceeds the available designed capacity of the road infrastructure in which case congestion occurs. Nevertheless, such events are carefully studied by traffic researchers and one of the solutions is to apply dynamic traffic management e.g. variable speed limit (VSL) is an often used intelligent transport systems (ITS) technique to optimize traffic on motorways [1].

For designing VSL often classical feedback controllers are designed and used. In general, the VSL controller adjusts the speed limit on motorway sections based on prevailing traffic conditions. Overloaded motorway sections are subjected to lower speed limit values in order to slow down and harmonize traffic flow and, thus, prevent capacity drop of problematic motorway locations (e.g. areas in proximity to the on-ramps) [2]. However, to set up a feedback-based VLS controller the process of modeling and linearization of characteristic working points are needed. Regarding a wide spectrum of underlying governing random variables of the traffic process and its non-linear nature, different values of controller parameters are used for different working points.

Thus, a structured approach to generating the testing scenarios is needed to ensure that the VSL controller is evaluated and tuned for the most prominent traffic scenarios. Microscopic simulation models offer a high level of detail in terms of interactions between vehicles and the road network. This allows for in-depth analysis of traffic networks such as motorways [3] or to analyze advanced traffic control approaches [4]. Generating representative traffic scenarios for large-scale microscopic simulations is often computationally expensive. To reduce the computational burden, we propose the usage of the Structured Simulations Framework (SSF) and its systematic exploration technique. SSF aims to approximate the controller performance with a minimal number of simulations. Approximated controller performances can then be used for a guided tuning process of controller's parameters. This systematic approach ensures that the controller can successfully operate in a wider spectrum of traffic scenarios that can appear in the real world.

II. Related work

In search-based structural testing, search techniques like Monte-Carlo simulation approach have been commonly used to automate test data generation. However, due to the wide state space of dynamic (stochastic) processes and, thus, high variance of output space (due to many underlying independent variables), it is hard to examine all the possible input-output pairs of the process [5].

In the paper [6], a data-driven surrogate model for train rescheduling in railway networks is proposed. To compensate for the limits of incomplete historical data, a relatively low-cost yet accurate surrogate model is developed from simulation data of the realistic but computation-intensive simulator. To reduce the demand for data and the number of costly simulations, a multi-surrogate search method is provided.

The concept of structured simulation offers a similar alternative approach. The underlying idea is to obtain information about the overall system behavior while minimizing the total number of data points, i.e. simulation runs. It, thereby draws on ideas of systematically exploring the search space, similar to

*These authors contributed equally to this work

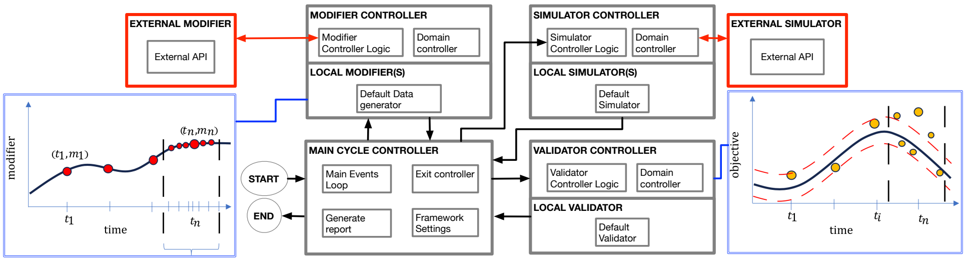

Figure 1. General SSF scheme for modifying the granularity of the input space (traffic scenario)

approaches like novelty search strategy [7]. This enables systematic exploration of the parameter space while keeping the total number of simulations needed to obtain these results at a lower level, as e.g. the aforementioned Monte-Carlo simulation [8], and as it is conceptually not training a NN to approximate overall system behavior, it will not require extensive training data sets, that would otherwise been generated by simulations.

For the case of analysis of a VSL controller, the application of the SSF still has been conceptualized in [9], however a particular proof-of-concept has not been provided so far. Such a proof-of-concept also needs to contain the required methodological challenges in coupling all relevant tools.

This motivates our research to develop SSF able to minimize the needed number of simulation computations to estimate the VSL controller performance as a step towards an automated indication of traffic scenarios for which it has poor performance and thus they have to be created more frequently.

III. Systematic Exploration Concept

Systematic exploration is part of SSF. Its main purpose is to approximate the overall system behavior, which is obtained by simulations. Thus, it allows the execution of general-purpose studies as well as the definition of distinct scenarios (via fully customizable parameters) and the possibility of seamlessly integrating third-party modules/components. An overview is given in Figure 1. The *Modifier Controller* allows the generation of inputs for the given simulation via predefined customizable functions or plugging in external data sources. The *Simulator Controller* includes mechanisms to execute simple pre-implemented customizable simulators or to plug in external components. The *Validator Controller* enacts the control, discriminating whether satisfiable results have been achieved (stopping the generation-simulation cycle) or if more data points are needed. The framework provides a default (customizable) validation module. Nevertheless, it provides the possibility to connect/include third-party components. Finally, the *Orchestrator* handles the overall loop (data generation - simulation - validation) and implements the Controller modules alignment to produce the desired logic.

IV. Structured Simulation-based VSL Performance Evaluation

As a prerequisite for applying VSL in a real world application it requires an appropriate training and evaluation processes. To ensure good controller quality, parameters for

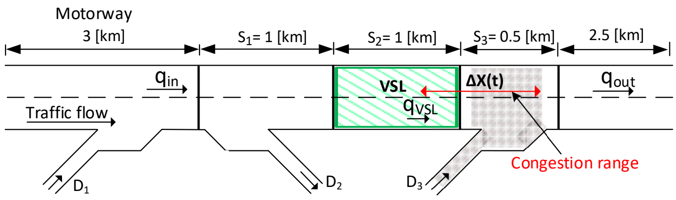

Figure 2. Application of VSL to increase throughput in congested areas

relevant traffic scenarios and quality of approximation needs to be provided, to allow for the SSF to create systematically appropriate traffic scenarios. This however requires expert knowledge, i.e. expected behavior of the controller, to actually valorize the speed-up potential of the SSF.

A. Applied VSL controller

The simple proportional speed controller (SPSC) is a traffic-responsive speed limit controller that computes the new speed limit based on motorway section traffic density disturbances. We assume disturbance has occurred in the most downstream section of the controlled motorway segment (congested section S_3 in Figure 2). In such a case, the SPSC implemented upstream will be active and will react to the downstream density changes [10]. If the density increases the SPSC decreases speed limits and vice versa. For simplicity further on we will refer to SPSC simply as the VSL controller.

B. Combining SSF and VSL

The SSF is going to determine for which scenarios parameters the corresponding simulations have to be performed, to obtain information about the overall system behavior. Thus, it requires a particular glue-code that is able to provide the appropriate encoding of the input for the simulator, start simulations, and also obtain results from the simulator. We refer the interested reader to [9] for more technical details. The functionality of SSF can be split into four blocks among which the validator and modifier are most important (see Figure 1). Once the first run of traffic simulations is done using the initial input space data that contains order pairs of simulation time and traffic flow volume all input-output data pairs are used to approximate the simulated system performance for the entire input domain. In our preliminary results, we used polynomial functions to fit the data. Once approximated, the validator is used to check if some data point lays out of the threshold region (Figure 1). If so, such regions are marked by the validator. Starting and ending points of such regions are sent back to the modifier controller that generates a new set of input data with a finer granularity of the input space for weakly approximated regions. Detected unfitted regions are, thus, simulated more frequently. This is ensured by a modifier controller that systematically changes the granularity of input space to ensure a higher number of input-output data pairs for unfitted regions. Generally, the process is repeated for n steps until the process performance is approximated well over the entire input space.

V. Simulation setup

Since VSL needs to cope with diverse traffic scenarios, multiple simulation runs with different input parameters are required. In our experiment, traffic scenario diversity is ensured by variable mainstream traffic demand. Later on in experiments, traffic demand is modified by the SSF that further systematically changes the granularity of input space.

a) Motorway Model: The motorway model is based on previous work [11]. The speed limit is simulated for the chosen control time by directly assigning the allowed speeds to the corresponding VSL zone starting at 4000 $[m]$ and ending at 5000 $[m]$. The new speed limit is calculated and deployed for each control time step $T_c = 150$ $[s]$ in motorway section S_3. The bottleneck is generated on the motorway section S_3. On-ramp traffic demands can also be found in [11].

b) Static Traffic Parameters: The input traffic demands are synthetic, and we assume the model to be already calibrated, as this is not in the scope of this work. Within the simulation, we use the $Krauss$ car-following model with the default setting parameters in SUMO [12]. On-ramp demands can be found in [11]. In the downstream section S_3 (Figure 2), a bottleneck is induced due to interaction between mainstream and the traffic flow entering the motorway at the on-ramp D_3. The induced downstream congestion activates the VSL and, thus, is used as the main test for SSF-VSL integrated framework. Each simulation lasts 1.5 hours to cover all relevant aspects of the simulated rush hour scenario (breakdown, congested conditions, recovery, and uncongested conditions).

c) Mainstream traffic flow: The modified parameter used in our example is the mainstream traffic demand. It starts with the value 2500 $[veh/h]$ and it increases for each new simulation by an additional traffic load of 100 $[veh/h]$ ending with traffic demand of 4000 $[veh/h]$. This input space is then additionally changed by a modifier in case the function approximator needs additional data pairs with finer granularity to fit the controller performance curves (see Figure 1).

For the validator (Figure 1), an important parameter is the threshold value. The threshold value is set to be ± 15 $[veh \cdot h]$ around the fitted curve. For fitting purposes, polynomial functions are used ranging from degree 2 up to degree 9. As mainstream traffic flow is meant to be modified, the settings of the modifier are as follows. Domain interval ranges from 2500 to 4000 $[veh/h]$, and minimal modifier incremental unit is 25 $[veh/h]$.

The SPSC gain is K_v=4.5 and activation threshold is 25 $[veh/km/lane]$ [11]. The allowable speed limit change between each control time steps is 20 while minimum and maximal speed limits are 60 and 120 $[km/h]$, respectively.

VI. Results and discussion

This section presents the simulation results and investigates the functionality of SSF in the evaluation of the VSL controller's performance. Note that the objective of this study was not to improve VSL approaches, they only serve here as an application for the SSF application can be used. Thus, we do not expect improvement over the baseline scenario but will address instead how the SSF foster the evaluation of the approaches.

a) Baseline: case without VSL (NOVSL): In Figure 3, the system performance measured in total time spent (TTS) is presented. For different mainstream traffic demands (inputs) ranging from $[2500, 4000]$ veh/h outputs as TTS are collected from the traffic simulator, and a function approximator is used to fit the curve for given input-output pairs. As can be seen from the first approximation operation not all input space data points are correctly fitted. Those regions are detected by the validator part of SSF and are marked by yellow stripes. For NOVSL three stripes are present mainly for high traffic load.

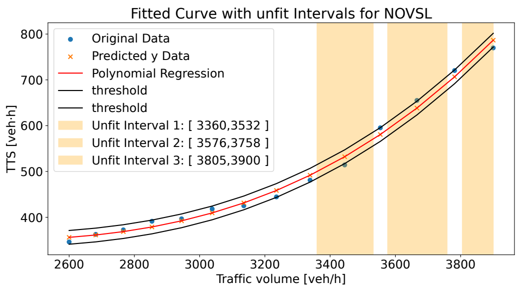

Figure 3. Obtained TTS without VSL

b) VSL: Similar behavior of the system performance can be observed in the case of the VSL application. However, two stripes are detected by the validator one for low traffic and the second one in case of higher traffic load.

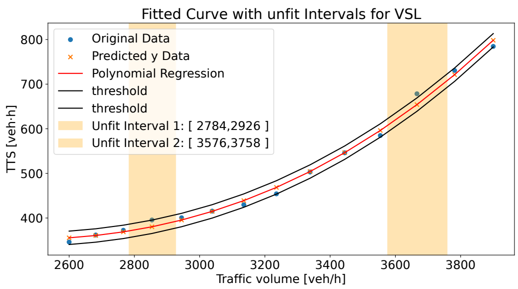

Figure 4. Obtained TTS with VSL

Finally, the motorway's level of service under VSL and without VSL are approximated by piece-wise functions as shown in Figure 5 using the TTS measure. The most prominent benefit of VSL is detected for input interval $[3300, 3800]$ where it outperforms the NOVSL. This is because we set $K_v = 4.5$ which is an optimal value for a VSL controller to operate near the critical point in the fundamental diagram for which traffic volume is close to its maximal rate.

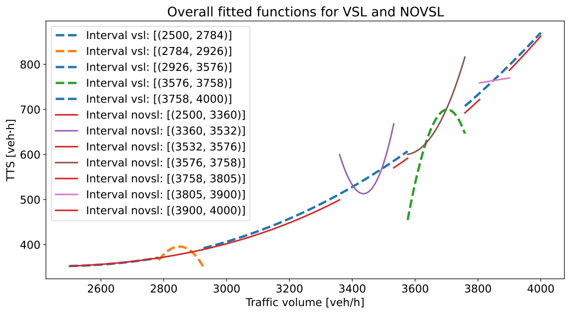

Figure 5. Final fitted function for VSL and no control case

In other intervals, VSL even worsens the performance compared to NOVSL. From Figure 5 one can easily detect regions in which the VSL controller has satisfactory performance and where it does not perform well. Thus, once approximated it provides useful information to perform further systematic controller tuning in regions with poor performances.

Hidden non-linearity of the traffic controller performance can be noticed as further finer partitioning of input space is done by the modifier. Take for example the case where we were able to fit system performance in the first run (that is we didn't have stripes in Figures 4 and 3). In such a case, the approximated system performance will be far away from the realistic one obtained in Figure 5 that uses finer input-output mapping and piece-wise functions over input space. This suggests that a control mechanism should be developed that will try (even if system performance is well approximated in the early runs of SSF) to do additional systematic input space partitioning in order to detect possible non-linearity in the process. Such non-linear behavior is also present in traffic flows, particularly by observing e.g., the fundamental traffic diagram. Thus, this control mechanism should rely on domain knowledge of the simulated process, otherwise, wrong conclusions might be drawn about the process performance.

VII. Conclusions and Future Work

This paper presented an application of the simulation framework to obtain a representative VSL controller's performance estimate while minimizing the number of required simulations runs. The paper provides detailed insight into functional integration between the SSF, the VSL controller, and the SUMO simulator. Therefore, the proposed approach requires a lower number of data points to estimate the evaluated controller behavior. Accordingly, less computing power is required for simulations. Yet, it is still able to detect regions of good as well as poor controller performance, i.e. it provides a satisfactory generalization of evaluated controller overall behavior. As a first step for our future work, the process of extrapolating the system's behavior with the SSF and here presented approach will be transferred to learning-based controllers with a more complex realistic traffic model.

While in general, the SSF framework can support the design/tuning and validation phase of the construction of machine-learning based controllers. We will in our next steps include the use of SSF framework in the tuning phase of the traffic controller. This will allow for a systematic search for process states in which the controller might not perform well and based on these section appropriate additional training data can be automatically generated. Later in the validation phase, the SSF can provide empirical evidence that the controller is capable of handling various traffic situations.

Also, the SSF framework can be expanded, e.g. by enabling it to handle multi-dimensional parameter space for potentially both input and output parameters.

Acknowledgment

This work was supported by the Croatian Science Foundation under project IP-2020-02-5042.

References

[1] A. Maimaris and G. Papageorgiou, "A review of Intelligent Transportation Systems from a communications technology perspective," in *2016 IEEE 19th International Conference on Intelligent Transportation Systems*, pp. 54–59, 2016.

[2] E. R. Müller, R. C. Carlson, W. Kraus, and M. Papageorgiou, "Microsimulation Analysis of Practical Aspects of Traffic Control With Variable Speed Limits," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 1, pp. 512–523, 2015.

[3] M. Guériau and I. Dusparic, "Quantifying the impact of connected and autonomous vehicles on traffic efficiency and safety in mixed traffic," in *23rd IEEE Int. Conference on Intelligent Transportation Systems*, 2020.

[4] T. Yuan, F. Alasiri, and P. A. Ioannou, "Selection of the Speed Command Distance for Improved Performance of a Rule-Based VSL and Lane Change Control," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–10 , 2022.

[5] A. Sangwongwanich and F. Blaabjerg, "Monte Carlo Simulation With Incremental Damage for Reliability Assessment of Power Electronics," *IEEE Transactions on Power Electronics*, vol. 36, no. 7, pp. 7366–7371, 2021.

[6] R. Liu, D. Cui, X. Dai, P. Yue, and Z. Yuan, "A data-driven surrogate modeling for train rescheduling in high-speed railway networks under wind-caused speed restrictions," *IEEE Transactions on Automation Science and Engineering*, vol. 21, no. 2, pp. 1107–1121, 2024.

[7] M. Boussaa, O. Barais, G. Sunyé, and B. Baudry, "A novelty search approach for automatic test data generation," *Proceedings of the 8th International Workshop on Search-Based Software Testing*, 2015.

[8] R. Schumann and C. Taramarcaz, "Towards systematic testing of complex interacting systems," *Proceedings of the First Workshop on Systemic Risks in Global Networks co-located with 14. Internationale Tagung Wirtschaftsinformatik (WI 2019)*, pp. 55–63, 2019.

[9] K. Kušić, R. Schumann, M. Gregurić, E. Ivanjko, and M. Šoštarić, "Reliable Learning-based Controllers and How Structured Simulation is a Path towards Them," in *5th Int. Conference on Advances in Signal Processing and Artificial Intelligence (ASPAI' 2023)*, pp. 268–274, 2023.

[10] Y. Wang, *Dynamic Variable Speed Limit Control: Design, Analysis and Benefits*. Ph.D. thesis, University of Southern California, 2011.

[11] K. Kušić, E. Ivanjko, F. Vrbanić, M. Gregurić, and I. Dusparic, "Dynamic variable speed limit zones allocation using distributed multi-agent reinforcement learning," in *In Proceedings of the 2021 IEEE 24th Int. Conference on Intelligent Transportation Systems (ITSC)*, pp. 1–8, 2021.

[12] P. A. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.-P. Flötteröd, R. Hilbrich, L. Lücken, J. Rummel, P. Wagner, and E. Wiessner, "Microscopic Traffic Simulation using SUMO," in *2018 21st International Conference on Intelligent Transportation Systems*, pp. 2575–2582, 2018.