Microscopic Simulation-based Testing of Internal Boundary Control of Lane-free Automated Vehicle Traffic

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SHORT SUMMARY

The TrafficFluid concept allows vehicles to move in a lane-free environment and enables capacity sharing between two directions without lane restrictions. In this context, Internal Boundary Control (IBC) has recently been introduced by the authors and its application has been investigated using macroscopic models. This paper presents a microscopic simulation-based validation of IBC using SUMO TrafficFluid-Sim, i.e. a simulation tool able to implement lane-free traffic. A Linear Quadratic Regulator (LQR), that is a feedback control scheme, is employed for IBC. An extension of the well-known Cell Transmission Model (CTM) is utilized for the design of the controller. Simulation investigations confirm the effectiveness of the proposed scheme.

Keywords: internal boundary control, lane-free traffic, feedback control, SUMO.

1. INTRODUCTION

Recently, a new concept for vehicular traffic called TrafficFluid, which is applicable for high penetration rates of vehicles equipped with high-level automation and communication systems, was introduced by Papageorgiou et al. (2021). The TrafficFluid concept proposes: (1) lane-free traffic, whereby vehicles are not bound to fixed traffic lanes, as in conventional traffic; (2) vehicle nudging, whereby vehicles may exert a "nudging" effect on, i.e. influence the movement of, vehicles in front of them.

In this context, it turns out to be feasible to utilize Internal Boundary Control (IBC), a control strategy that aims to maximize the use of the road infrastructure (Malekzadeh et al., 2021a). IBC in lane-free traffic takes advantage of the fact that the traffic flow and capacity demonstrate incremental changes in reaction to corresponding incremental changes of the road width. Thus, on a highway or arterial with two opposite traffic directions, the total cross-road capacity (for both directions) may be shared between the two directions in real-time, according to the prevailing demand per direction, by virtually moving the internal boundary that separates the two traffic directions and communicating this decision to Connected automated Vehicles (CAVs), so that they respect the changed road boundary. The characteristics of IBC are analyzed by Malekzadeh et al. (2021a), where its high improvement potential is demonstrated by formulating and solving an open-loop optimal control problem. Additionally, a feedback-based Linear-Quadratic Regulator (LQR) for IBC was developed by Malekzadeh et al. (2021b), aiming at balancing the relative densities in the two directions; and has been demonstrated to be robust and similarly efficient as the open-loop optimal control solution, while avoiding the need for accurate modelling and external demand prediction.

So far, IBC has been investigated utilizing macroscopic models. This work demonstrates that the concept and the proposed control scheme can be similarly efficient even in a more realistic environment, as a microscopic simulator. We make use of the SUMO TrafficFluid-Sim, a simulation tool able to implement lane-free traffic (Troullinos et al., 2021).

2. INTERNAL BOUNDARY CONTROL (IBC)

To implement IBC, a feedback control strategy is considered. The proposed control scheme is designed based on an extension and linearization of the well-known Cell Transmission Model (CTM) (Daganzo, 1994). Let us assume two opposite traffic directions subdivided into n sections. Then, the total section capacity q_{cap}, the total critical density ρ_{cr} and the total jam density $\rho_{\max}$, are shared between the two directions in each section based on the sharing factor $0 < \varepsilon_{i,\min} \le \varepsilon_i \le \varepsilon_{i,\max} < 1$, that is applied per section and which is known in IBC as the control input (Malekzadeh et al., 2021b).

In conventional traffic management, traffic densities (in veh/km) characterize clearly the state of traffic, depending on their value versus the critical density: free traffic (when density is lower than critical density), critical traffic (when density is around critical density) or congested traffic (when density is higher than critical density). However, in the proposed IBC concept, the critical density for each direction and section is not constant, but a linear function of the sharing factor and is changing according to the applied control action. Therefore, the density value by itself is not sufficient, in the IBC context, to characterize the traffic situation in a section. To address this issue, the following relations define the relative densities (dimensionless) per section and per direction. The relative density of section i and direction a or b is given by dividing the corresponding traffic density with the corresponding critical density, which, on its turn, depends on the sharing factor prevailing during the last time-step, as follows

$$\tilde{\rho}_i^a(k) = \frac{\rho_i^a(k)}{\varepsilon_i(k-1)\rho_{cr}}, \; \tilde{\rho}_i^b(k) = \frac{\rho_i^b(k)}{(1-\varepsilon_i(k-1))\rho_{cr}}. \quad (1)$$

The relative densities reflect clearly the state of the traffic in the IBC context. Specifically, if the relative density of a section and direction is less than 1, it reflects under-critical (free-flow) traffic conditions; if it is around 1, it reflects capacity flow; and if it is greater than 1, it reflects over-critical (congested) traffic conditions (Malekzadeh et al., 2021a).

Linear Quadratic Regulator (LQR)

Linearization of the CTM dynamic equations around a nominal point was presented analytically by Malekzadeh (2021b). To achieve this, the one-step retarded control input was defined as a new state variable according to $\gamma_i(k+1) = \varepsilon_i(k), \; i = 1, 2, \ldots, n.$ Following the linearization procedure by Malekzadeh (2021b), the linearized state-space model is

$$\mathbf{x}(k+1) = \hat{\mathbf{A}}\mathbf{x}(k) + \hat{\mathbf{B}}\mathbf{u}(k) \quad (2)$$

where $\mathbf{x}(k) = [\Delta\tilde{\rho}_1^a(k), \Delta\tilde{\rho}_1^b(k), \Delta\gamma_1(k), ..., \Delta\tilde{\rho}_n^a(k), \Delta\tilde{\rho}_n^b(k), \Delta\gamma_n(k)]^T$ is the state vector and $\mathbf{u}(k) = \mathbf{\Delta\varepsilon}(k)$ is the control vector, whereby $\mathbf{\Delta\varepsilon}(k) = [\Delta\varepsilon_1(k), \ldots, \Delta\varepsilon_n(k)]^T$. Also, $\Delta(.)(k) = (.)(k) - (.)^N$, the superscript N denoting the nominal values, while it has been assumed that $\Delta(.)(k) = 0$ for all disturbances (upstream mainstream inflows, as well as the on-ramp flows, of each direction). $\hat{\mathbf{A}} \in \mathbb{R}^{3n\times 3n}$ and $\hat{\mathbf{B}} \in \mathbb{R}^{3n\times n}$ are the time-invariant state and input matrices, respectively, while $\mathbf{x} \in \mathbb{R}^{3n}$ and $\mathbf{u} \in \mathbb{R}^{n}$. If the control time-step is defined as a multiple of the model time-step, i.e. $T_c = MT$, where M is an integer, then the discrete control time index is $k_c = \lfloor kT/T_c \rfloor$. Thus, the linear state-space equation may be changed as follows, in order to be based on the control time-step T_c,

$$\mathbf{x}(k_c + 1) = \mathbf{A}\mathbf{x}(k_c) + \mathbf{B}\mathbf{u}(k_c) \tag{3}$$

where $\mathbf{A} = \hat{\mathbf{A}}^M$, and $\mathbf{B} = (\hat{\mathbf{A}}^{M-1} + \hat{\mathbf{A}}^{M-2} + ... + \mathbf{I})\hat{\mathbf{B}}$.

When employing the LQR methodology, as done by Malekzadeh (2021b), the control goal is the minimization of the quadratic criterion.

$$J = \frac{1}{2}\sum_{k_c=0}^{\infty}\left[\mathbf{x}^T(k_c)\mathbf{Q}\mathbf{x}(k_c) + \mathbf{u}^T(k_c)\mathbf{R}\mathbf{u}(k_c)\right] \tag{4}$$

where $\mathbf{Q} \in \mathbb{R}^{3n\times 3n}$ is a diagonal positive semidefinite matrix and $\mathbf{R} \in \mathbb{R}^{n\times n}$ is a diagonal positive definite matrix. The first term penalizes deviations of the state variables from zero, i.e. deviations of $\tilde{\rho}_i^a(k_c)$, $\tilde{\rho}_i^b(k_c)$, $\gamma_i(k_c)$, $i = 1, 2, \ldots, n$, from their respective desired nominal values. The second term penalizes deviations of the control inputs from the nominal values.

The nominal value for relative densities on both directions is set equal to 1 so that the controller is motivated to operate the system near capacity, which is good for traffic efficiency. In particular, due to the quadratic penalty terms, the controller tends to mitigate strong density departures from the critical density at specific sections, i.e., mitigate traffic congestion. In addition, if capacity flow is not feasible (e.g. due to lack of demand), then minimizing a sum of squares has the tendency to balance deviations from the nominal values at different sections and directions, something that is conform with the secondary operational sub-objective of balancing the margin to capacity across sections and directions. On the other hand, the nominal value for the sharing factors is set to 0.5, so as to have smooth and moderate internal boundary changes. Thus, minimization of the second term in (4) mitigates deviations of the sharing factors from 0.5 and balances these deviations in space and time, which is a secondary operational sub-objective, as unnecessarily strong internal boundary changes over space and time should be avoided. The optimal controller minimizing criterion (4) subject to the model (3) is given by a linear state-feedback control law of the form $\mathbf{u}(k_c) = \mathbf{K}\mathbf{x}(k_c)$, where $\mathbf{K} \in \mathbb{R}^{n\times 3n}$ is a constant gain matrix given by

$$\mathbf{K} = (\mathbf{R} + \mathbf{B}^T\mathbf{P}\mathbf{B})^{-1}\mathbf{B}^T\mathbf{P}\mathbf{A} \tag{5}$$

and $\mathbf{P}$ is a unique positive semidefinite solution of the discrete-time algebraic Riccati equation.

Lane-Free Microscopic Simulation for IBC

Experimental evaluation is performed using TrafficFluid-Sim (Troullinos et al., 2021), a lane-free extension of the well-known microscopic simulator SUMO (Lopes et al., 2018). For IBC, additional functionalities had to be developed in order to facilitate the use of moving boundaries, some of which are outlined as part of future work in (Troullinos et al., 2022). Consider a network with multiple routes, e.g., a highway with on-ramps and off-ramps. Each vehicle entering the network is assigned a specific route. In conventional lane-based traffic, the vehicle would need to do appropriate lane-changing operations in order to follow its routing scheme, whereas in lane-free environments, this would be translated to the vehicle operating according to left and right boundaries that guide its lateral placement appropriately, e.g., a vehicle entering from an on-ramp would need to merge appropriately in the main highway. Consequently, the boundaries are designed with the use of sigmoid functions that specify the lateral availability of the associated route and allow for smooth lateral movement.

In TrafficFluid-Sim, monitoring and control of vehicles is feasible through an API, which now includes additional functionality that provides density information according to the sectioning of the network, and controls the moving boundaries' lateral level in an online manner. As such, the user can now specify the sectioning of a bidirectional highway containing on-ramps and off-ramps, rendering the lane-free microscopic environment compatible with the proposed IBC problem formulation. Density information per section and direction of movement can be directly requested from the updated API for the calculation of relative densities $\tilde{\rho}_i^a(k)$, $\tilde{\rho}_i^b(k)$. The control vector stemming from LQR is parsed appropriately to the control function of the API, updating the lateral level of the left boundary (from the perspective of each direction) for each section. The left boundaries of each direction are essentially "synced" according to the control input, while the right boundaries corresponding to the exterior part of the road remain unaffected.

For practical purposes, the microscopic simulator includes a lateral distance margin between the two directions so that vehicles traveling near the boundary retain a safety distance from the other direction. Additionally, a moderate delay time is specified in every section at the direction that the road widens, so that vehicles travelling on the other direction have the necessary time to comply with the reduced lateral space. Figure 1 demonstrates a snapshot of the employed simulator. This snapshot includes an on-ramp and its acceleration area before merging with direction *a* as well as direction *b* that is separated from direction *a* using internal boundaries (red and green).

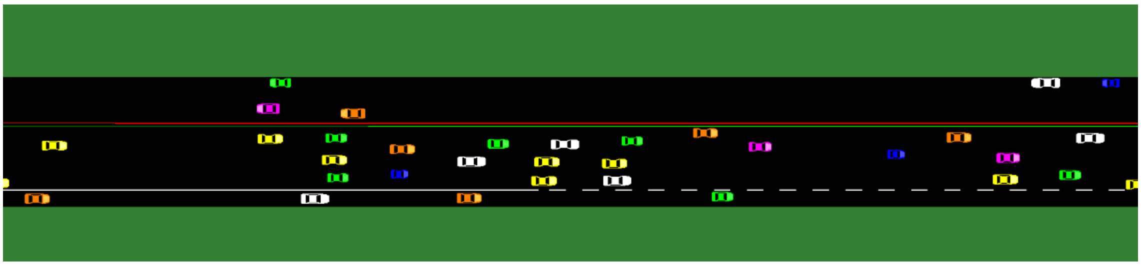

Fig. 1: A snapshot of the simulation environment TrafficFluid-Sim

3. RESULTS AND DISCUSSION

The hypothetical highway for the simulation is depicted in Fig. 2. Its length is 3 km and, when no control action is applied, the width for each direction is 10.2 m (corresponding to the width of 3 lanes). The highway is subdivided to 6 equal virtual sections in order to design and apply IBC. The vehicles are moving following the Ad-hoc strategy presented by Malekzadeh et al. (2022). The dimensions for each one of the vehicles are determined by choosing randomly (with uniform distribution) one of the six "dimension classes" reported in Table 1.

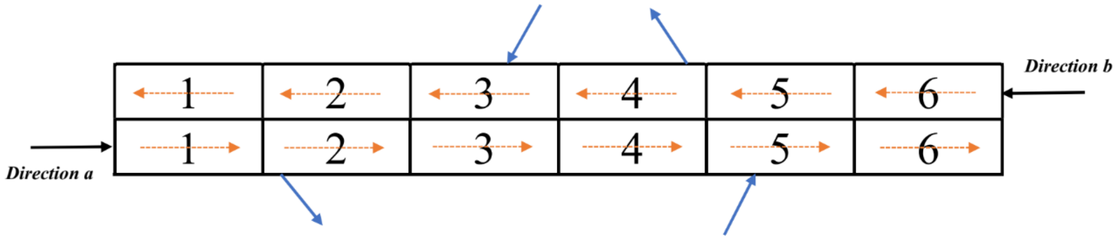

Fig. 2: The considered highway stretch

Table 1. The different dimension classes for the vehicles used in the simulation

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Length (m)	3.20	3.90	4.25	4.55	4.60	5.15
Width (m)	1.60	1.70	1.80	1.82	1.77	1.84

The nominal values for the control design are defined based on observations as $q_{cap}\big|_N = 28000$ veh/h and $\rho_{cr}\big|_N = 360$ veh/km, while the CTM time-step and the control time-step used are $T = 10$ s and $T_c = 60$ s, respectively. The weighing matrices used in the objective function are selected to be $\mathbf{Q} = \text{diag}(\mathbf{S}_1, \mathbf{S}_2, \ldots, \mathbf{S}_n)$ where $\mathbf{S}_i = [\mathbf{I}_2, \mathbf{0}_{2\times1}; \mathbf{0}_{1\times3}]$ and $\mathbf{R} = 10^{-2}\mathbf{I}_{n\times n}$. The upper and lower bounds for the sharing factors, used to avoid utter blocking of any of the two directions, are equal for all sections $i = 1, 2, \ldots, 6$ and are given the values $\varepsilon_{i,\min} = 0.1$ and $\varepsilon_{i,\max} = 0.9$. These values are used to truncate the LQR outcome.

The mainstream and on-ramp demand flows per direction are presented in Fig. 3 while the exit rate used for the off-ramps is on average 5%. If no control is used and the mainstream capacity is shared evenly between the two directions, the highway faces congestion. Figure 4 displays the corresponding spatio-temporal evolution of the relative density defined in (1). It can be observed that congestion is formed around time 23 min for direction *a* and time 53 min for direction *b* due to on-ramp merging. In both cases, congestion spills back and covers upstream sections.

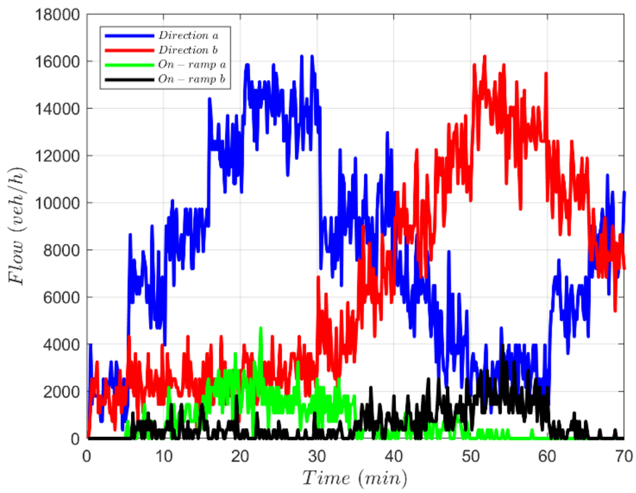

Fig. 3: Demand flows per direction and on-ramps

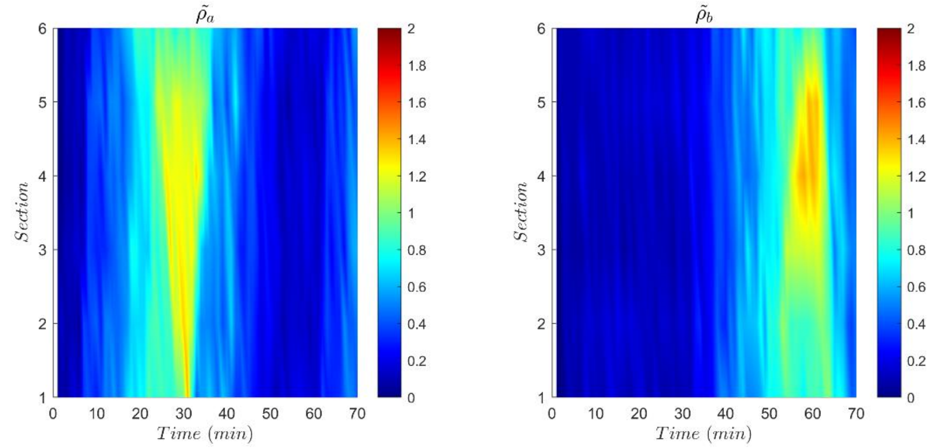

Fig. 4: Relative density for the two directions in the no-control case

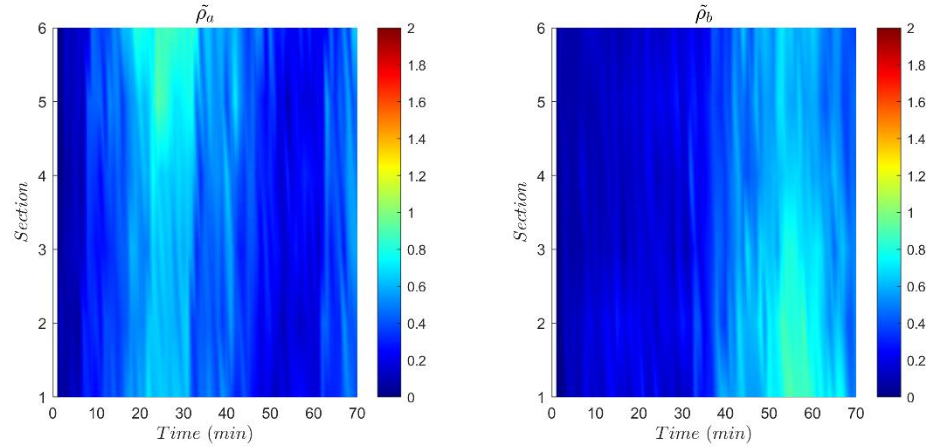

Fig. 5: Relative density for the two directions in the IBC case

On the other hand, congestion is solved utterly when IBC is activated. The corresponding spatio-temporal evolution of the relative density in the presence of IBC is presented in Fig. 5. It is evident that the relative densities in both directions are under 1. More insights can be gained by the trajectories for flow, relative density and the sharing factor per direction that are presented in Figs 6-8 over the whole simulation period. It can be seen that flow and relative density increase in section 5 for direction *a* due to the presence of inflow from the corresponding on-ramp. Likewise, this happens in section 3 for direction *b*. However, the controller is able to avoid the congestion by proper capacity sharing between the two directions.

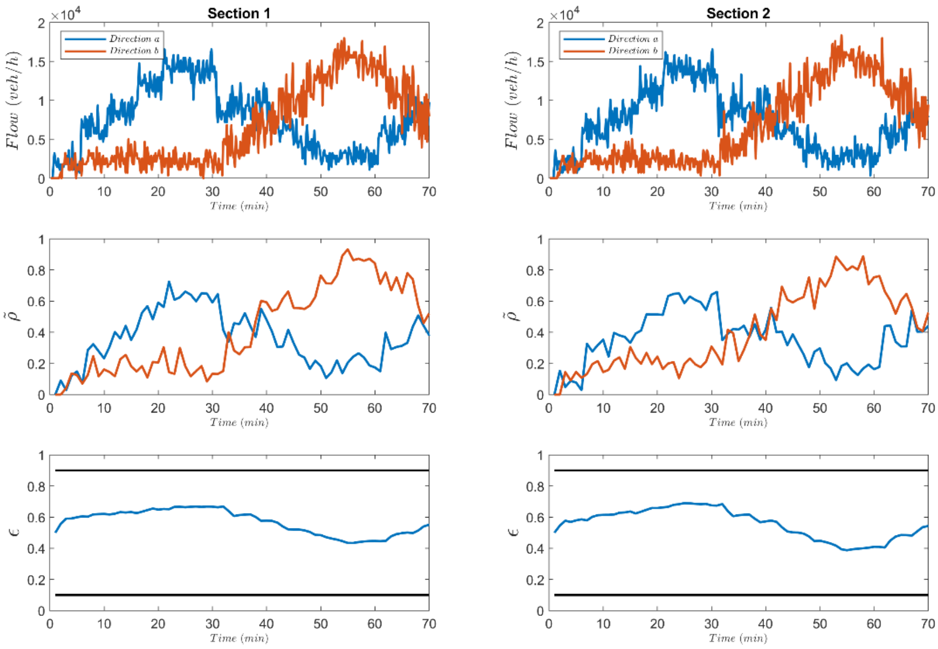

Fig. 6: Flow, relative density and control input for the IBC case (Section 1 & 2)

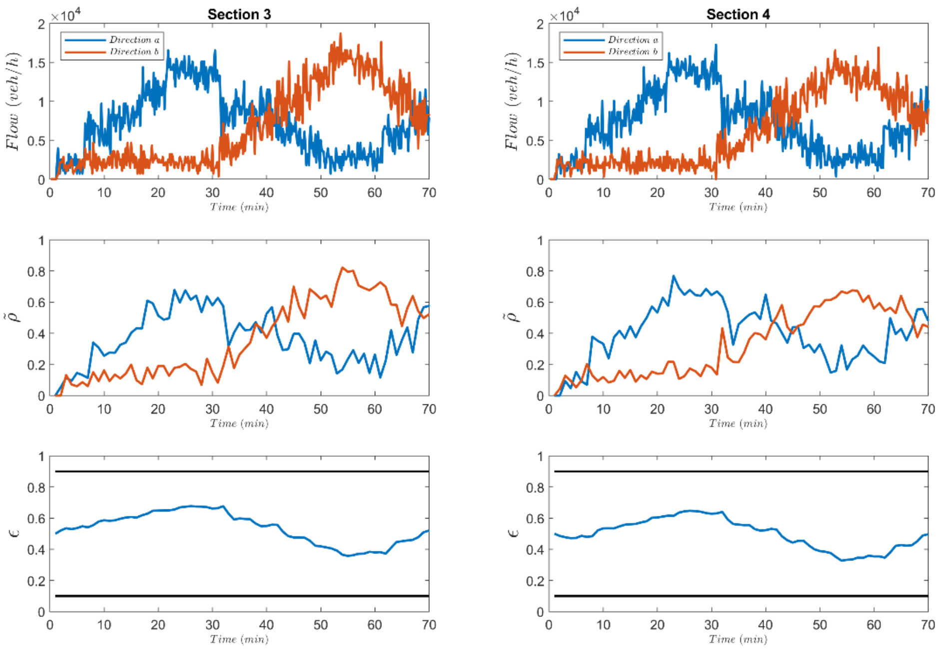

Fig. 7: Flow, relative density and control input for the IBC case (Section 3 & 4)

Fig. 8: Flow, relative density and control input for the IBC case (Section 5 & 6)

4. CONCLUSIONS

In this study, applicability of internal boundary control for lane-free traffic has been investigated via microscopic simulation. In order to implement the IBC scheme, the LQR controller has been employed. The controller was designed based on the well-known Cell Transmission Model. Then, a feedback control scheme that uses the relative densities in each section as input has been implemented. The simulation results validated the effectiveness of the proposed IBC scheme. Future work includes testing of the same and other control schemes, e.g. those developed by Malekzadeh et al. (2023), on longer highways.

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