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Infrastructure-dependent ramp-metering control for METANET-s

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Abstract— **In this paper, we propose a novel infrastructure-dependent ramp-metering control for the recently proposed METANET with service station (METANET-s) model, i.e., a second-order macroscopic traffic model that, compared to the classical METANET, incorporates the dynamics of service stations on highways. We study the effect of a ramp-metering control scheme on a highway stretch with a service station and show that it is capable of actively regulate internal traffic demand attempting to exit the service station via its on-ramp, on top of contributing to decrease the traffic congestion on the mainstream. In fact, the proposed control scheme effectively prevents the backlog of vehicles attempting to merge back onto the mainstream. This dynamic control mechanism is further endowed by a route guidance control strategy increasing the share of vehicles stopping at the service station during main-stream congestion periods, e.g. via incentives. The combined effect of our control schemes allows to take full advantage of the presence of service stations, reducing the overall traffic congestion. Simulation results demonstrate the effectiveness of the proposed control strategies.**

I. INTRODUCTION

In recent years, the need of advanced surveillance and control strategies in freeway traffic networks has considerably increased due to the persistent rise in traffic congestion and its consequent impacts on both people and the environment [1]. Although originally designed to deal with high traffic volumes, nowadays freeway networks face challenges in accommodating the growing demand, making it necessary to adopt specific control strategies as an effective means of improving system performance [2], [3].

Ramp-metering and route guidance represent two widely used control strategies for managing traffic flows on highways [2], [4]. The first strategy is a direct and effective approach to control the flow of vehicles entering the freeway mainstream from an on-ramp [5]. One of the most used ramp-metering controllers is the well-known ALINEA [6], an integral controller that regulates the flow entering into the mainstream from an on-ramp and it is computed based on the error between the density downstream of the on-ramp and a desired reference. Other ramp-metering control strategies have been proposed in [7]–[10].

Route guidance control is another effective control technique for managing traffic flows within the network [11]. This control approach continuously monitors travel times along various routes and identifies the fastest or most efficient paths [12], [13]. Based on feedback control theory, route guidance algorithms using real-time travel time data from alternative paths have been proposed in [14], [15]. To estimate in real time these different travel times, iterative route guidance control strategies have been proposed in [16], while predictive approaches have been developed in [17].

Further studies are underway to develop solutions aimed at enhancing the performance of traffic control systems. One of the main challenges is the necessity of cooperation among all the different actors that can play a role in traffic management, such as infrastructures, and maximizing performance leveraging them [18]. For these reasons, in [19], [20], the Cell Transmission Model with service station (CTM-s) was introduced, which is a modified version of the well-known Cell Transmission Model (CTM) that additionally incorporates the dynamics of Service Stations (STs) on the highways. Furthermore, following this research line, the METANET-s was proposed in [21], which extends the well-known METANET (i.e., a second-order macroscopic traffic model) by including the dynamics of STs. More precisely, within the METANET-s, the ST is dynamically characterized by a Store-and-forward (saf) link, which contributes to generating internal demand for the on-ramp, prompted by traffic conditions downstream on the freeway.

In this paper we propose a novel *infrastructure-dependent ramp-metering control* for the METANET-s model. The overall control approach involves two different control actions that aim to efficiently operate the STs to avoid (or reduce) traffic congestion on highways. One control action consists of the well-known ramp-metering control ALINEA, applied to the ramp exiting the ST. More precisely, the ST actively monitors the downstream traffic density and generates internal traffic demand to regulate the flow of vehicles exiting the ST and merging onto the mainstream. Then, the second control action of the proposed infrastructure-dependent ramp-metering control consists of a route guidance strategy that regulates (e.g. via financial incentives) the flow of vehicles entering and stopping at the ST during congested periods, thereby enhancing overall traffic flow management. Finally, simulation results show the effectiveness of the proposed control strategy to effectively unlock the full advantage of

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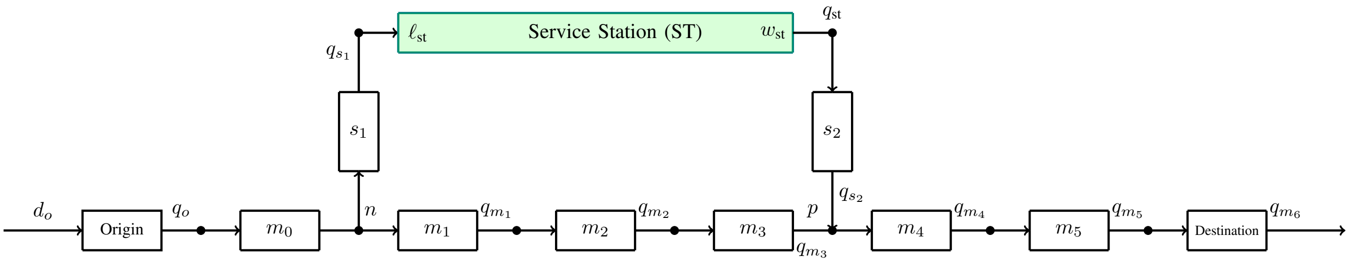

Fig. 1. METANET-s: The freeway links (m_0 to m_5, s_1, and s_2) represent the mainstream and on-ramp/off-ramp of service station which are connected by the nodes (black dots), an origin link (o), a destination link (m_6), and the ST is modeled via a saf link.

the presence of STs in highways, leading to a significant reduction of the overall traffic congestion and total time spent.

II. Traffic network model: METANET-s

In this section, we first propose a brief introduction of the METANET-s traffic model that was first introduced in [21].

A. Main variables

METANET-s is a discrete-time second-order model where the time intervals of length $T \in \mathbb{R}$ are indexed by $k \in \mathbb{N}$. To comply with the notation in [22], we divide the highway stretch into $N \in \mathbb{N}$ *links* collected in the set $\boldsymbol{N}$. In turn, each link $m \in \boldsymbol{N}$ is composed of only one *section* consisting of λ_m lanes of length L_m. Consecutive links are connected via *nodes* if from the upstream one, it is possible to access the downstream link. The traffic evolution in link m during k is described by: the *density* $\rho_m(k)$, the *mean speed* $v_m(k)$, and the *flow* $q_m(k)$. Furthermore, $J_m \subseteq \boldsymbol{N}$ is the set of destination links accessible from $m \in \boldsymbol{N}$, thus for each $j \in J_m$ the partial density in m with destination j is denoted by $\rho_{m,j}(k)$.

B. Model dynamics

The structure depicted in Figure 1 is used to simplify the exposition, but it can be easily modified to describe different highway configurations, e.g., one with a different number of links. Following Figure 1 the set of all the links is $\boldsymbol{N} := \{o, m_0, \cdots, m_6, s_1, s_2, \text{st}\}$. The origin link $o \in \boldsymbol{N}$ injects the traffic demand $d_o(k) \in \mathbb{R}$ into the highway and thus the flow exiting o to enter m_0 is defined as

$$q_o(k) = \min\left[d_o(k) + \frac{\ell_o(k)}{T}, q_{\max,o}, q_{\max,o}\frac{\rho_{\max,m_0} - \rho_{m_0}(k)}{\rho_{\max,m_0} - \rho_{\text{cr},m_0}}\right], \tag{1}$$

where $q_{\max,o}$ is the constant flow capacity of $o \in \boldsymbol{N}$, while $\rho_{\max,m_0}$ and ρ_{cr,m_0} are maximum density and critical density of m_0, respectively. Notice that the third term is the minimum if link m_0 is congested or close to it. In this case, a queue of vehicles forms in o, resulting in

$$\ell_o(k+1) = \ell_o(k) + T\left[d_o(k) - q_o(k)\right], \tag{2}$$

this ensures that the total demand enters m_0. Density and speed dynamics of links $m_0, \cdots, m_6$ read as

$$\rho_{m_\ell}(k+1) = \rho_{m_\ell}(k) + \frac{T}{L_{m_\ell}\lambda_{m_\ell}}\left[q_{m_{\ell-1}}(k) - q_{m_\ell}(k)\right] \tag{3a}$$

$$q_{m_\ell}(k) = \rho_{m_\ell}(k)v_{m_\ell}(k)\lambda_{m_\ell} \tag{3b}$$

$$\begin{aligned} v_{m_\ell}(k+1) = v_{m_\ell}(k) &+ \frac{T}{\tau}\left[v(\rho_{m_\ell}(k)) - v_{m_\ell}(k)\right] \\ &+ \frac{T}{L_{m_\ell}}v_{m_\ell}(k)\left[v_{m_{\ell-1}}(k) - v_{m_\ell}(k)\right] \\ &- \frac{VT[\rho_{m_{\ell+1}}(k) - \rho_{m_\ell}(k)]}{\tau L_{m_\ell}[\rho_{m_\ell}(k) + K]} \end{aligned} \tag{3c}$$

$$v(\rho_{m_\ell}(k)) := \bar{v}_{m_\ell} \exp\left[-\frac{1}{a}\left(\frac{\rho_{m_\ell}(k)}{\rho_{\text{cr},m_\ell}}\right)^a\right], \tag{3d}$$

for $\ell \in \{0, \cdots, 6\}$ where $\bar{v}_{m_\ell}$ is the free-flow speed, and a, τ, V, and K are constant model parameters. For $\ell = 6$, $\rho_{m_{\ell+1}}(k)$ in (3c), is replaced by the boundary condition $0 < \rho_{\text{boundary}} < \rho_{\text{cr},m_\ell}$. Similarly, for $\ell = 0$ the quantities $\rho_{m_{\ell-1}}$, $v_{m_{\ell-1}}$ refer to the upstream link that is the origin o.

From link m_0 it is possible to access the ST via s_1 and thus the upstream density $\rho_{m_{\ell+1}}(k)$ used in (3c) depends not only on m_1 but also on s_1. Thus, it is replaced by $\rho_{\text{div}}(k) = \frac{\rho^2_{s_1}(k)+\rho^2_{m_1}(k)}{\rho_{s_1}(k)+\rho_{m_1}(k)}$. Similarly, the velocity in link m_4 depends on the one in m_3 and s_2. So, in the calculation of $v_{m_4}(k)$ the upstream influence $v_{m_{\ell-1}}(k)$ is replaced by $v_{\text{merge}}(k) = \frac{v_{m_3}(k)q_{m_3}(k)+v_{s_2}(k)q_{s_2}(k)}{q_{m_3}(k)+q_{s_2}(k)}$.

The density of vehicles exiting m_0 is divided into two: the one stopping at the ST via s_1, and the one entering m_1. They are respectively defined as

$$\rho_{m_0,s_1}(k+1) = \rho_{m_0,s_1}(k) + \frac{T}{L_{m_0}\lambda_{m_0}}\left[q_o(k) - \gamma_{m_0,s_1}(k)q_{m_0}(k)\right] \tag{4}$$

$$\rho_{m_0,m_1}(k+1) = \rho_{m_0,m_1}(k) + \frac{T}{L_{m_0}\lambda_{m_0}}\left[q_o(k) - \gamma_{m_0,m_1}(k)q_{m_0}(k)\right], \tag{5}$$

where $\gamma_{m_0,s_1}(k) = \frac{\rho_{m_0,s_1}(k)}{\rho_{m_0}(k)}$ and $\gamma_{m_0,m_1}(k) = \frac{\rho_{m_0,m_1}(k)}{\rho_{m_0}(k)}$ represent the split rates of the flow hence $\gamma_{m_0,s_1}(k) + \gamma_{m_0,m_1}(k) = 1$.

Vehicles have the option to leave the main traffic stream through $s_1 \in \boldsymbol{N}$ to access the ST, which is modeled by the saf link st $\in \boldsymbol{N}$ with maximum capacity $\ell_{\text{max,st}} > 0$, refer to [23] for background on saf links. The flow of vehicles effectively entering the ST is the minimum between the demand of s_1 and the supply of st. The latter depends on how many vehicles ℓ_{st} are currently at the ST compared to the maximum capacity $\ell_{\text{max,st}}$, and thus we define it as

$$q_{s_1}(k) = \min\left[\rho_{s_1}(k)v_{s_1}(k), \frac{\ell_{\text{max,st}} - \ell_{\text{st}}(k)}{T}\right], \quad (6)$$

where $\rho_{s_1}(k)$ and $v_{s_1}(k)$ are respectively defined similarly to (3a) and (3c) and the third term in (3c) is not necessary since s_1 connects to a safe link. The number of the vehicles at the ST varies as follows

$$\ell_{\text{st}}(k+1) = \ell_{\text{st}}(k) + T\left[q_{s_1}(k) - q_{\text{st}}(k)\right], \quad (7)$$

while $q_{\text{st}}(k)$ denotes the flow entering s_2 from st $\in \boldsymbol{N}$, see Figure 1. The vehicles entering the ST stop for δ time intervals before trying to access s_2 to merge into the mainstream in m_4. If the outflow $q_{\text{st}}(k)$ exceeds the link maximum flow $q_{\text{max,st}} > 0$ then a queue takes shape composed of those vehicles that finished to use the facility but are not able to enter s_2. The queue length dynamics read as

$$w_{\text{st}}(k+1) = w_{\text{st}}(k) + T\left[q_{s_1}(k-\delta) - q_{\text{st}}(k)\right], \quad (8)$$

where $w_{\text{st}} \leq \ell_{\text{st}}$ by construction. We are now ready to define the dynamics of the flow exiting st and entering s_2, they read as

$$q_{\text{st}}(k) = \min\left[q_{s_1}(k-\delta) + \frac{w_{\text{st}}(k)}{T}, q_{\text{max,st}}, q_{\text{max,st}}\frac{\rho_{\text{max},s_2} - \rho_{s_2}(k)}{\rho_{\text{max},s_2} - \rho_{\text{cr},s_2}}\right], \quad (9)$$

where the third term is associated with the congestion level in s_2. Finally, the outflow of the on-ramp s_2 is computed as

$$q_{s_2}(k) = \min\left[q_{\text{st}}(k) + \frac{L_{s_2}\rho_{s_2}(k)}{T}, q_{\text{max},s_2}, r^c(k), q_{\text{max},s_2}\frac{\rho_{\text{max},m_4} - \rho_{m_4}(k)}{\rho_{\text{max},m_4} - \rho_{\text{cr},m_4}}\right], \quad (10)$$

where $r^c(k)$ is the ramp-metering control signal designed in the next section and $\rho_{s_2}(k)$ defined similarly to (3a).

III. Infrastructure-dependent control for METANET-s

In this section, we design the infrastructure-dependent controller for METANET-s. As depicted in Figure 2, it is composed of the combination of a ramp-metering, based on ALINEA applied to link s_2, and a route guidance strategy applied to s_1. The presence of the ST creates a coupling between these two controllers and we show that their coordinated effect creates better performance compared to using them separately.

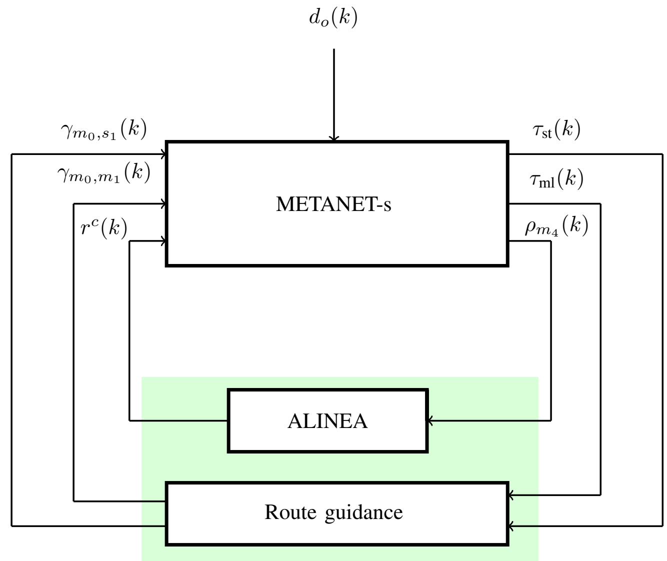

Fig. 2. Feedback Control Scheme for the infrastructure-dependent ramp-metering control (green-highlighted).

A. Ramp-metering control for METANET-s: ALINEA

The controller aims at regulating the build-up of traffic demand exiting the ST to reintegrate into the mainstream via link s_2. The objective is to reduce traffic congestion in the mainstream by limiting q_{s_2} if m_4 is close to (or exceeds) the critical density ρ_{cr,m_4}. Following ALINEA, the control law reads as

$$r^c(k) = r^c(k-1) + k_r\left[\rho_{\text{cr},m_4} - \rho_{m_4}(k)\right], \quad (11)$$

where k_r is the constant control gain. The controller limiting the ST outflow is bound to increase the Total Waiting Time (TWT) of commuters stopping. As we will show in our simulation section there is always a trade-off between reducing mainstream congestion, i.e., the total travel time, and increasing the waiting time for ST users. Notice that the presence of the ST implies that the demand entering the on-ramp is not exogenous as in the classical ALINEA but it is associated with users' behavior.

B. Route Guidance strategy for METANET-s

The second part of the controller is composed of a route guidance strategy suggesting drivers divert to the ST if the mainstream is congested and vice-versa. In practice, this strategy can be implemented using incentives, e.g., discounts on gas or ancillary services, nudging their behaviors [24], [25]. This controller increases the flow entering the ST during congested periods improving its beneficial effects of congestion reduction.

Such a policy can be effectively modeled as a proportional controller law influencing the value of $\gamma_{m_0,m_1}(k) \in [0,1]$. The splitting rate dynamics read as

$$\gamma_{m_0,m_1}(k) = \gamma^N_{m_0,m_1} - \epsilon k_p\big(\tau_{\text{ml}}(k) - \tau_{\text{st}}(k)\big) \quad (12)$$

where $k_p > 0$ and $\gamma^N_{m_0,m_1} \in [0,1]$ is the nominal split rate reflecting drivers' behavior when no route guidance is

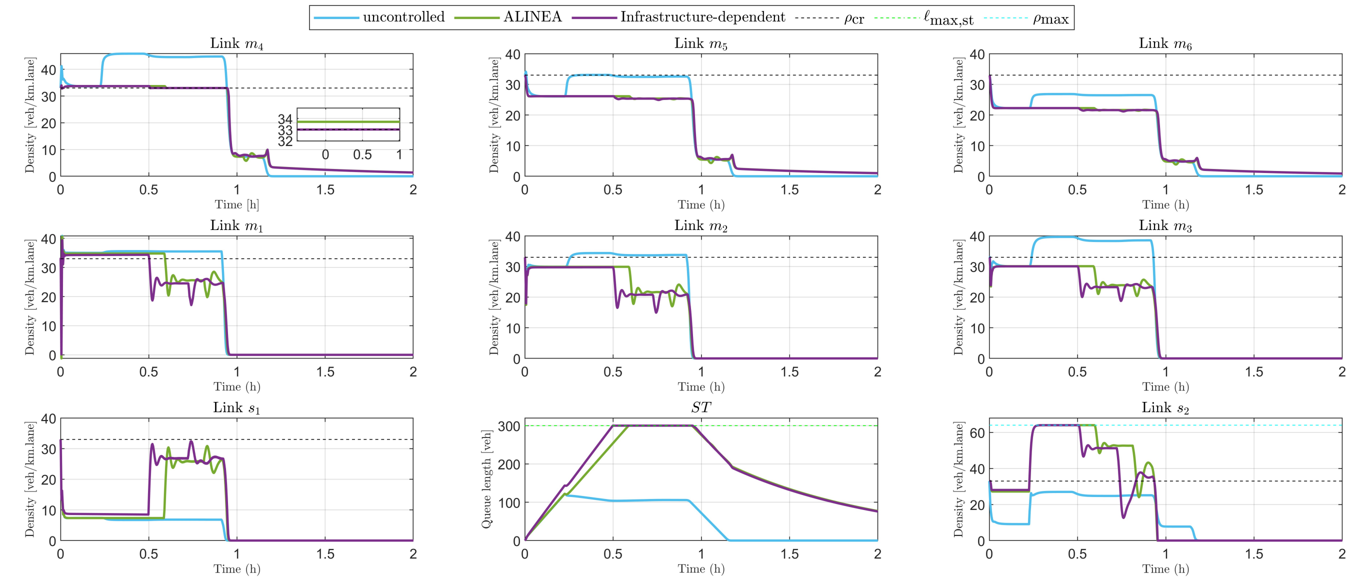

Fig. 3. Infrastructure-dependent control versus no control and ALINEA results with trapezoid shape demand function. First row: density results in downstream links m_4, m_5, and m_6. Second row: density results for upstream links m_1, m_2, and m_3. Third row: density results in ramps s_1 and s_2, and queue length trajectory in the ST.

implemented. The drivers' compliance rate is described by $\epsilon \in [0,1]$ and represents the percentage of drivers actively reacting to the policy. On the contrary to the ramp metering which is a hard policy to which drivers must comply, the route guidance can be ignored since it is implemented via soft policies.

In (12), $\tau_{\text{ml}}(k) = \sum_{\ell=1}^{3} \frac{\rho_{m_\ell}(k) L_{m_\ell}}{q_{m_\ell}(k)}$ is the instantaneous travel time to travel through the mainstream central links $\{m_1, \cdots, m_3\}$. On the contrary, $\tau_{\text{st}}(k) = \frac{\ell_{\text{st}}(k)}{q_{\text{st}(k)}} + \sum_{\ell=1}^{2} \frac{\rho_{s_\ell}(k) L_{s_\ell}}{q_{s_\ell}(k)}$ is the travel time for drivers stopping at the ST hence using the links $\{s_1, \text{st}, s_2\}$. Notice that for calculating $\tau_{\text{st}}(k)$ we are not factoring in δ since during that period drivers are actively taking advantage of the facilities. The split rate from equation (12), $\gamma_{m_0,m_1}(k)$, ensures that drivers increase the flow towards the ST only if it is convenient for them in terms of travel time. In fact, the route guidance acts as follows

$$\begin{cases} \gamma_{m_0,m_1}(k) = \gamma^N_{m_0,m_1} & \text{if } \tau_{ml}(k) = \tau_{\text{st}}(k) \\ 0 \leq \gamma_{m_0,m_1}(k) < \gamma^N_{m_0,m_1} & \text{if } \tau_{ml}(k) > \tau_{\text{st}}(k) \\ \gamma^N_{m_0,m_1} < \gamma_{m_0,m_1}(k) \leq 1 & \text{if } \tau_{ml}(k) < \tau_{\text{st}}(k) \end{cases} \quad (13)$$

and (6) prevents an unfeasible traffic flow to the ST since it constraints it by the maximum storage capacity $\ell_{\text{max,st}}$.

IV. Simulation Results

In this section, we conduct numerical studies to assess the performance of the proposed infrastructure-dependent control for the METANET-s. The highway stretch considered is organized as in Figure 1. The traffic condition after link m_6 is assumed uncongested, i.e., $\rho_{\text{boundary}} = 0$. The length of each link is 0.3 [km], while the ST spans 1.2 [km]. Assuming that the average length of the vehicles is about 4 [m], the maximum storage capacity of the ST is set at $\ell_{\text{max,st}} = 300$ [veh]. Furthermore, for all the links, we select the following features: free-flow speed $\bar{v}_m = 102$ [km/h], critical density $\rho_{\text{cr},m_\ell} = 33$ [veh/km lane], and maximum density $\rho_{\text{max},m_\ell} = 65$ [veh/km lane]. We simulate a 2 [h] interval with $T = 0.01$ [s] and the time interval ranges $k \in [0, 7.2 \times 10^4]$. Initially, we assumed that 20% of the total demand travels through the ST and stops there for a time interval $\delta = 15$ [min], while the remaining 80% continues along the mainstream. Hence, the nominal split rate is $\gamma^N_{m_0,m_1} = 0.8$. The control gains k_r and k_p are selected equal to 10 and 20, respectively.

A. Infrastructure-dependent control

We employ a piece-wise linear trapezoidal demand to simulate a typical peak-hour traffic pattern, we define it as

$$d_o(k) = \begin{cases} 2500, & \text{if } 0 \leq k < a \\ \frac{2500}{b-a}(k-a) + 2500, & \text{if } a \leq k < b \\ 5000, & \text{if } b \leq k < c \\ \frac{-5000}{d-c}(k-c) + 5000, & \text{if } c \leq k < d \\ 0, & \text{if } d \leq k \leq 72 \times 10^3 \end{cases} \quad (14)$$

while a, b, c, and d are equal to 9×10^3, 11×10^3, 16×10^3, and 22×10^3, respectively.

Initially, the freeway stretch is assumed to be congested, i.e., $\rho_{m_\ell}(k) = \rho_{\text{cr},m_\ell}$ for all $\ell = \{1, \cdots, 6\}$. We compare three different scenarios referred to as:

(I) Uncontrolled: where no control is applied to the ST;

(II) ALINEA: where only the ramp metering control is applied to s_2;

(III) Infrastructure-dependent: where both ALINEA and the route guidance are applied.

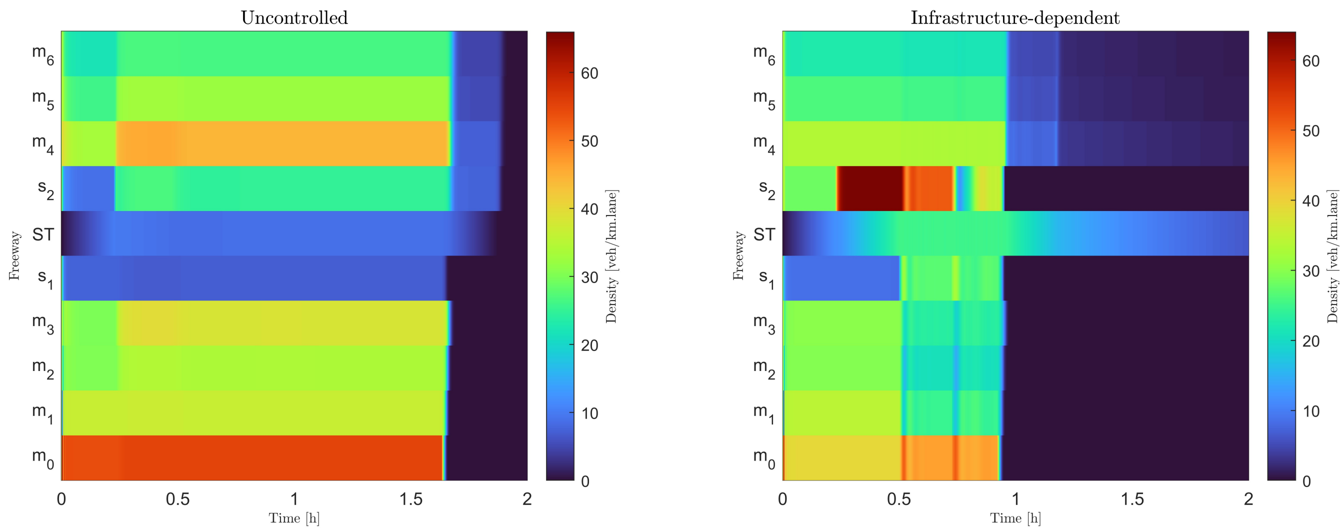

Fig. 4. The traffic density evolution with infrastructure-dependent control versus no control through METANET-s model.

According to Figure 3, in scenario (I) heavy congestion occurs at $t = 0.25$ [h] when both flows $q_{s_2}(k)$ and $q_{m_3}(k)$ try to access link m_4. This congestion propagates downstream, affecting links m_5 and m_6 as can also be seen in Figure 4. Furthermore, as the external demand $d_o(k)$ increases to its maximum value, it leads to congestion also in links m_1, m_2 and m_3.

In scenario (II) ALINEA eliminates almost completely the congestion in m_4 and consequently throughout the whole mainstream. To achieve this result it creates a traffic backlog in s_2, extending backward into both the ST and s_1. Between $t = 0.5$ and 1 [h], the number of vehicles in the ST reaches $\ell_{\text{max,st}}$. Then, the queue of vehicles waiting to exit the ST decreases when ρ_{m_4} goes below ρ_{cr,m_4}.

The infrastructure-dependent controller in scenario (III) effectively manages traffic flow in both sub-streams. In response to congestion forming in the mainstream links from m_1 to m_4, the route guidance control advises drivers to utilize the ST to bypass potential congestion in the mainstream, given that $\tau_{\text{st}}(k) < \tau_{\text{ml}}(k)$. Consequently, after $t = 0.5$ [h], as $\rho_{m_4} < \rho_{\text{cr},m_4}$, the augmented outflow from s_2 enables ρ_{s_2} lower below ρ_{cr,s_2} faster than in scenario (II). Figure 4 depicts the evolution of traffic density in scenarios (I) and (III). By implementing the infrastructure-dependent control, the traffic congestion dissipates across all links, including the ST, by approximately $t = 1$ [h]. In contrast, in the uncontrol case traffic congestion persists until $t = 1.75$ [h].

The overall traffic conditions can be evaluated by calculating the Total Time Spent (TTS) throughout the network, i.e., $TTS = T\sum_k \Big[\sum_{\ell=0}^{6} \rho_{m_\ell}(k)L_{m_\ell} + k_m T q_{m_\ell}(k) + \sum_{\ell=1}^{2} \rho_{s_\ell}(k)L_{s_\ell} + k_m T q_{s_\ell}(k) + \big(\ell_{\text{st}}(k) + k_m T q_{\text{st}}(k)\big)\Big]$, where $k_m T$ is the constant delay to reach the exit point of a link starting from the entering point.

As shown in Table I, the use of the infrastructure-dependent controller achieves a remarkable reduction in TTS of the 10% compared to the uncontrolled case and outperforms the sole use of ALINEA of 5.8%. This enhancement in performance can stem from the ability of this controller to anticipate both congestion and decongestion trends in the highways.

Scenarios	(I)	(II)	(III)	(IV)
TTS $[h]$	660.02	632.95	593.71	621.45
Improvement	–	-4.2%	-10%	-5.8%

TABLE I

TTS AND IMPROVEMENTS UNDER: (I) UNCONTROLLED, (II) ALINEA, (III) INFRASTRUCTURE-DEPENDENT CONTROL (IV) VARIABLE COMPLIANCE RATE.

B. Compliance ratio

Next, we explore a scenario (referred to in Table I as (IV)) where not all drivers comply with the route guidance strategy, hence $\epsilon = 0.5$ while in the previous section, we assumed perfect compliance. As expected and shown in Figure 5, this leads to a behavior that is in between scenarios (II) and (III). Thus, the traffic density in the mainstream is higher and s_2 takes more time to reduce its density below the critical one compared to (III). Yet, we achieved beneficial results compared to (II) where only ALINEA was employed.

V. CONCLUSIONS

The control of a ST on a highway stretch can effectively reduce the traffic congestion in the mainstream. We have shown that the proposed infrastructure-dependent control scheme, including ramp metering and route guidance, is an effective control strategy to reduce traffic congestion. More precisely, we leverage the METANET-s to design the control scheme and show via a numerical example that it can reduce the total time spent up to 10% and allows for a smoother merging of the vehicles back to the mainstream.

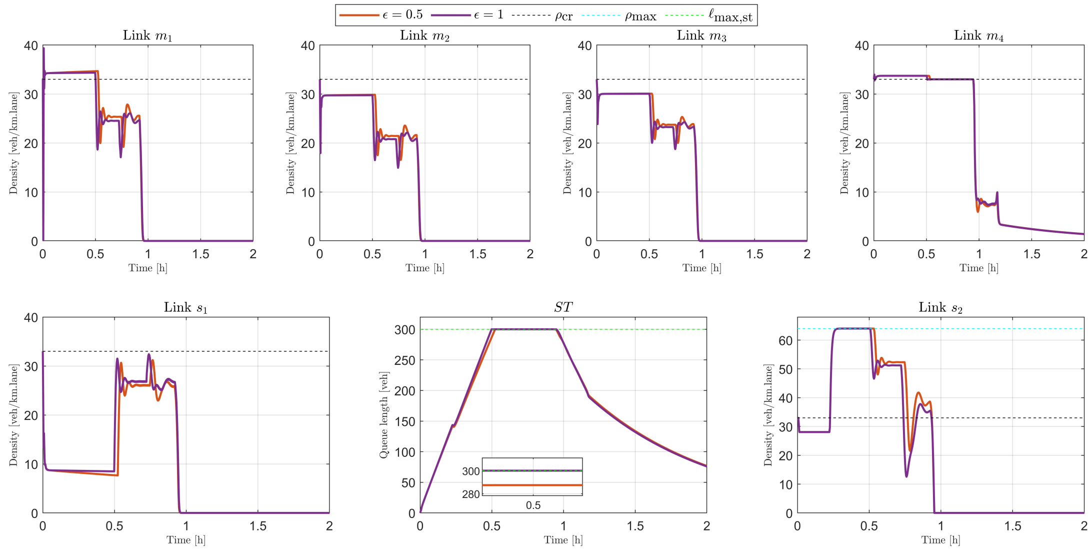

Fig. 5. Infrastructure-dependent control in METANET-s model with 50% compliance ratio compared to full compliance. First row: density evolution in links m_1 to m_4. Second row: density evolution in ramps s_1 and s_2, and queue length in the ST.

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