Dynamic Lane Configuration: Bridging Traffic Management and Infrastructure Design

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Extended abstract submitted for presentation at the Conference in Emerging Technologies in Transportation Systems (TRC-30)
September 02-03, 2024, Crete, Greece

April 29, 2024

Keywords: Dynamic lane configuration, Traffic management, Motorway infrastructure, Mixed traffic flow

INTRODUCTION

The surge in transportation demand, combined with the limited capacity of motorway networks, has resulted in widespread traffic congestion. Designing and constructing new road infrastructure is costly, time-consuming, and sometimes not feasible (Keyvan-Ekbatani et al., 2012). Therefore, exploiting the existing infrastructure through traffic management strategies to mitigate congestion becomes of great importance (Papageorgiou et al., 2007). Transportation planning and traffic management, although both aim to improve efficiency, are currently run as separate and independent entities. In other words, transportation planning lacks real-time feedback and flexibility for adjustments based on actual traffic circumstances. Consequently, modern motorway networks' capacity is underutilized daily due to congestion, particularly during rush hours, i.e., when it is most urgently needed.

Two widely used macroscopic control measures for traffic management on motorways that have been extensively studied are variable speed limit (VSL) systems (Hegyi et al., 2005) and ramp metering (Papageorgiou and Kotsialos, 2002). In addition, VSLs have been used with ramp metering as an integrated approach for even further improvement of traffic conditions (Carlson et al., 2010). With recent advances in vehicle and communication technologies in the last decade, leveraging of Connected and Automated Vehicles (CAVs) for microscopic traffic control became a major branch of cutting-edge research toward addressing traffic congestion (Ahmed et al., 2022). Approaches such as hard shoulder running (Geistefeldt, 2012) or the use of reversible lanes (Ampountolas et al., 2020) are also introduced for providing additional capacity via partially infrastructure manipulation. However, the former compromises the safety role of hard shoulders and the latter is only practical with asymmetric demand and in locations where the opposite directions are physically adjacent and not separated by barriers. In the future era of CAV-dominant traffic, dedicated narrower lanes for CAVs (Ghiasi et al., 2020) and lane-free traffic (Papageorgiou et al., 2021a) are proposed for more efficient infrastructure utilization. While these control measures offer significant benefits in the era of CAVs, the need for additional capacity to address heavily congested traffic conditions in motorway networks, with mixed traffic flow with CAVs and human-driven vehicles (HDVs), is vital.

To address this issue, the novel concept of dynamic lane configuration, i.e., dynamic lane width and numbers at each road section, is proposed in this work that provides additional capacity for motorways by bridging the infrastructure design and traffic management. Presently, motorway lanes are designed to be considerably wider than the width of vehicles, primarily for safety reasons during high-speed driving. However, this design leads to a loss of lateral occupancy on the road (Papageorgiou et al., 2021). Thus, additional lateral occupancy on motorways could be realized if lane widths are reduced, assuming a proper traffic control strategy is implemented. Therefore, we suggest that, by actively imposing speed limits, the required lateral gap between vehicles can be reduced, allowing for narrower lanes, and thus, more lanes on the road. This action is intended for application in real time, in response to the prevailing traffic conditions. It is important to emphasize that reducing lane width is only possible with a reduced speed limit to ensure safety. For example, current German regulation allows for lane width of 2.6 m at the speed limit of 80 km/h for work zones where a new lane layout is used temporary, compared to the original width of 3.5 to 3.75 m (German Road and Transportation Research Association, 2021).

Figure 1. Dynamic lane configuration in motorways in response to real-time demand

Dynamic lane configuration suggests motorways' lanes, i.e., the most infrastructure-related element defining the capacity, can be made flexible and dynamic, as illustrated in Figure 1. This concept harnesses infrastructure as a real-time control measure providing different capacity levels at various motorway sections, based on real-time traffic demand, all without the need for physical road expansion.

The developed methodology for macroscopic modeling of traffic flow in the presence of dynamic lane configuration and the proposed control approach is presented in the next section. The methodology is supported by simulation analysis and the promising results indicate the benefit of the proposed approach in congestion mitigation and travel time reduction.

METHODOLOGY

Since the proposed approach is novel and the microscopic and macroscopic behavior of traffic at sections with reduced lane width still need to be investigated based on empirical data, we propose the use of the widely-used CTM (Daganzo, 1995) with the triangular fundamental diagram whose parameters have a physical interpretation and thus are better predictable. Figure 2 illustrates the fundamental diagrams for a given road section with original and modified lane configuration with λ and λ' number of lanes, respectively, where $\lambda \leq \lambda'$.

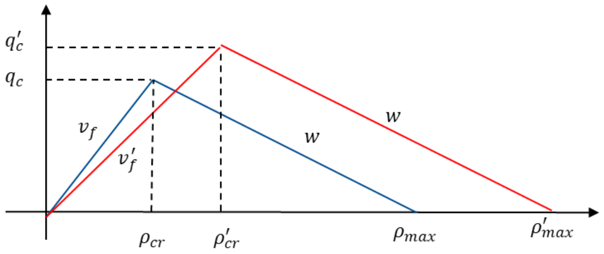


Figure 2. Change in the fundamental diagram with dynamic lane configuration.

The jam density increases linearly with the increment of lane number to $\rho_{max}' = \varepsilon.\rho_{max}$, where $\varepsilon = \lambda'/\lambda$. The variable $\sigma = v_f'/v_f$ is defined, where v_f' is the speed limit applied to the sections with narrower lanes and v_f is the free-flow speed in the original lane configuration. We assuming that the backward wave speed does not change with the reduced lane width, the capacity and the critical density are calculated as $q_c' = \varepsilon w \sigma \rho_{max} v_f/(\sigma v_f + w)$ and $\rho_{cr}' = \varepsilon w \rho_{max}/(\sigma v_f + w)$, respectively. Note that with replacing ε and σ with 1, we get the capacity and critical density for the original lane configuration.

Now, we write the CTM equations for each section i of the network, considering that $k = 0,1, \dots, K$ and $k_c = 1, \dots, K_c$ are model and control time index, respectively, $\varepsilon(k_c)$ is the independent control variable and $\sigma(k_c)$ is the dependent one. The conservation equation reads:

$$\rho_i(k+1) = \rho_i(k) + \frac{T}{L}\left[q_{i-1}(k) - q_i(k) + r_i(k) - \beta_i q_{i-1}(k)\right], \quad i = 1, \dots, n \tag{1}$$

where ρ_i and q_i represent the density and outflow of section i , respectively, r_i is the on-ramp flow and β_i is the exit rate at off-ramp. In addition, n is the total number of sections, T is the model time step and L is the section length. Without loss of generality, it is assumed that the network is divided into homogenous sections with same length. The traffic flows are obtained as the minimum of demand and supply functions, except for the last section where we only consider the demand function. Not that for demand and supply function, we use the extended version of CTM (Kontorinaki et al., 2017) that accounts for the capacity drop effect at on-ramps. Therefore, we have

$$q_i(k) = min\left\{q_{D,i}(k,k_c), \frac{q_{S,i+1}(k,k_c)}{(1-\beta_{i+1})} - \lambda_r r_{i+1}(k)\right\}, i = 1, \dots, n-1 \tag{2a}$$

$$q_n(k) = q_{D,i}(k,k_c), \tag{2b}$$

where

$$q_{D,i}(k,k_c) = \min\left\{\sigma_i(k_c) v_f \rho_i(k),\; q'_c(k_c)(1 + \lambda_d \frac{\rho_i(k) - \rho'_{cr}(k_c)}{\rho'_{cr}(k_c) - \varepsilon(k)\rho_{max}})\right\} \tag{3a}$$

$$q_{S,i}(k,k_c) = \min\left\{w\left(\varepsilon_i(k_c)\rho_{max} - \rho_i(k)\right), q'_c(k_c)\right\}. \tag{3b}$$

In the above equations, $\lambda_r$and λ_d define the capacity drop effect. More specifically, if these parameters are set $\lambda_r = 1$ and $\lambda_d = 0$, no capacity drop is reproduced, as typical for CTM; if these values are set between 0 and 1, a corresponding level of capacity drop is produced by the model.

Based on the developed concept, the goal is determination of the time(s) and sections where the lane configuration should be changed. To this end, the objective function to be minimized is defined as follows:

$$J = T\sum_{k=1}^{K}\sum_{i=1}^{n} L_i\rho_i(k) + w_1\sum_{k_c=2}^{K_c}\sum_{i=1}^{n}\left(\varepsilon_i(k_c) - \varepsilon_i(k_c-1)\right)^2 + w_2\sum_{k_c=1}^{K_c}\sum_{i=2}^{n}\left(\varepsilon_i(k_c) - \varepsilon_{i-1}(k_c)\right)^2 \tag{4}$$

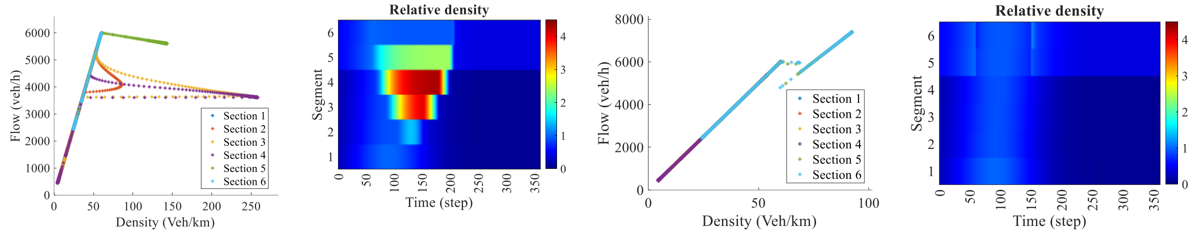
The first term is (4) represents the TTS (total time spent). Minimization of TTS induces reducing the delay, thus increasing the traffic efficiency resulting from the action of the proposed control measures. For the practical implementation, it is important to minimize the number of switching of lane configuration with respect to the time and the neighboring sections. Therefore, the second and third terms are introduced in (4) with the proper weighting factors to account for switching frequencies.

This formulation leads to a nonlinear and nonconvex mixed-integer programming that is hard to solve. Therefore, a heuristic global optimization algorithm (Nezamabadi-pour et al., 2008) is used. To this end, a binary auxiliary decision variable $x_i(k_c) \in \{0,1\}$ for each section is defined. $x_i(k_c) = 0$ represents the original lane configuration with $\varepsilon, \sigma = 1$ while $x_i(k_c) = 1$ indicates modified lane configuration with $\varepsilon = \lambda'/\lambda$ and $\sigma = v'_f/v_f$. Thus, the goal is finding the optimal values of $x = [x_i(k_c)]$ minimizing the objective function J, where the densities are obtained based on (1)-(3).

RESULTS AND DISCUSSION

The developed methodology is tested on a stretch of motorway with six sections with one on-ramp at section 5 and one off-ramp located at section 2 with the same demand profile and other simulation parameters as used in (Malekzadeh et al., 2021). In contrast, as the proposed approach is designed for mixed traffic, a longer control time step of 300 seconds is assumed in this work. In addition, the speed limit of 80 km/h is assumed for the sections with modified lane configuration.

Two cases are considered and simulated. In the first case, all lane configurations are fixed whereas in the second case, the lane configurations are dynamic, and change based on the defined optimal control problem. The achieved results are illustrated and compared in Figure 3. Since each section with the dynamic lane configuration might have different jam density, all densities are normalized with respect to section critical density and thus the relative densities are used for better comparisons.



a- Fixed lane configuration b- Dynamic lane configuration

Figure 3. Flow-density curves and spatiotemporal relative density evolution in two scenarios.

The flow-density curves and relative densities of the two cases indicate the significant improvement in the traffic conditions. While initially four sections experience different levels of congestion, with the additional capacity provided for only sections 5 and 6, the congestion is avoided. In fact, the TTS reduced from 147.70 to 89.38 $veh.h$ with only two switchings for two sections.

The promising initial results highlight the efficiency of the dynamic lane configuration and the proposed control approach. In the full paper, we further implement the method on different network topologies and test it with several demand patterns. In addition, as mentioned earlier, the driving behavior, e.g., headway, in the reduced lane width and thus its macroscopic effects such as backward wave speed needs to be further investigated. Therefore, a sensitivity analysis will be carried out on the effect of different values of backward wave speed and speed limit on the achieved capacity and traffic improvement.

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