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Lane Distribution Optimisation of Autonomous Vehicles for Highway Congestion Control*

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Abstract

The rapid development of autonomous vehicle (AV) technology present novel opportunities for congestion control on highway bottlenecks. Advancements in AV communication allow for network-wide traffic management, enabling greater coverage and more flexible control strategies. This paper presents two levels of lateral control to relieve highway congestion. A lane distribution optimisation problem to establish the optimal density in lanes upstream of the bottleneck and a lane change advisory system to address local merging scenarios and resolve merge conflicts. The effectiveness of the strategy is demonstrated through microsimulation experiments and comparison to ALINEA ramp metering strategy. The control strategy is shown to significantly reduce total travel time (TTT) and minimise variation in TTT by delaying the onset and severity of congestion and subsequent capacity drop.

1. Introduction

Through increasing city growth and greater mobility needs, traffic congestion emerges as a widespread urbanisation problem, with the demand on existing transport infrastructure continually growing and straining road networks already near capacity. For highway congestion management, control measures such as variable message signs, ramp metering (Haddad et al. 2013) and dynamic speed limits (Han et al. 2017) are extensively investigated to reduce the frequency and impact of traffic congestion.

Zhou, Qu and Jin (2016) focus on the detection technologies in AVs to sense surrounding driving conditions to reduce traffic oscillations caused by freeway merging. Park, Bhamidipati and Smith (2011) introduce a lane changing advisory algorithm to promote lane changing based on gap sizes, noting positive performance only with very high compliance rates. Roncoli et al. (2016a) also proposed a lane changing control by formulating an optimal feedback control problem and solving it in real time.

Others have focused on longitudinal control. For example, by using AVs as actuators for VSL controls (Wang et al. 2016; Khondaker & Kattan 2015) or in conjunction VMS (Han, Chen & Ahn 2017). Baskar et al. (2012) proposed a Model Predictive Control approach orchestrating AVs into platoons. Zhang and Ioannou (2016) paired a VSL controller based on feedback linearization and the Cell Transmission Model. Roncoli et al. (2016b) developed a hierarchical MPC framework integrating ramp metering, vehicle speed control and lane changing control.

This paper focuses on lateral control by developing a method that integrates a proactive lane distribution optimisation problem and a reactive lane change advisory system. The strategy is composed of two parts; an upper-level control aimed at optimising the vehicle density across lanes prior to an on-ramp merge area, and a lower-level control to predict and deal with merging conflicts through localised lane changing advice.

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2. Methodology

2.1. Road Network

This paper considers a multi-lane highway with a one-lane on-ramp. The control strategy developed in this paper is composed of two custom controls. The upper-level control (Proactive Control) considers the road network in a macroscopic sense by optimising the relative densities in each lane to facilitate merging between the on-ramp and the main carriageway. The lower-level control (Reactive Control) focuses on the microscopic level to address local merging scenarios and interactions between individual vehicles. The Proactive Control is an optimisation method that requires a larger zone and greater proximity from the merge location compared to the Reactive Control, which works best at a shorter range.

2.2. Proactive Control

The Proactive Control is applied in the upstream of merging area (see Fig. 1). This control determines the optimal number of vehicles in each lane by minimising an objective function and provides lane-change advisory to the AVs to achieve this optimal distribution.

In this optimised distribution, the lanes closer to the left of the highway will have a reduced vehicle density to facilitate a smoother merging process for the inbound ramp vehicles. In performing earlier lane changing, the amount of lane changing closer to the merge location is reduced, minimising disturbances in the merge area and delaying the onset of capacity drop, reducing the severity of delays experienced.

The optimal distribution is governed by the following objective function:

$$\min_{n_i(k+1)} J = \left[\sum_{i=1}^{I} \alpha_i (n_i(k+1) - n_i^{\mathrm{cr}})^2 + \beta \sum_{i=1}^{I} i\big(n_i(k+1) - n_i(k)\big)\right] \tag{1}$$

$$\mathrm{s.t.} \sum_{i=1}^{I} n_i(k) = \sum_{i=1}^{I} n_i(k+1) \tag{2}$$

$$n_1(k+1), \dots, n_I(k+1) \in \mathbb{N} = \{0, 1, 2, \dots\} \tag{3}$$

$$n_1(k) \geq n_1(\mathrm{k}+1) \tag{4}$$

$$n_I(k) \leq n_I(k+1) \tag{5}$$

The index of each lane is denoted $i = 1, \dots, I$ with 1 being the left-most lane and I being the number of lanes. The current vehicle count, in the Proactive Section, at time instance k in each lane is represented by $n_i(k)$. The optimal vehicle count in each lane in the next time instance is $n_i(k+1)$ and is determined through the minimisation of the objective function J. The critical vehicle count in each lane n_i^{cr} is estimated from the fundamental diagram. The terms in the objective function are weighted by α and β.

Equation 2 represents the conservation of number of vehicles. Equation 3 restricts control outputs (vehicle counts) to non-negative integers. Equations 4 and 5 follow from the assumption that all advised lane changes are right moving.

The first term of the objective function penalises deviations from the critical count in each lane. Counts which are too low represent underutilisation of the lane whilst counts which are too high reduces the traffic flow. The second term penalises the number of lane changing manoeuvres. Lane changing movements can generate disturbances which trigger the formation of congestion. Whilst necessary to achieve the ideal lane counts, excessive lane changing promotes deterioration of the system.

Determination of which vehicles to advise is based on vehicle headways. Recurrently, the lead and lag gaps in the adjacent lane for each vehicle are measured. Vehicles which have adequate lead and lag gap sizes are noted as candidates and are sorted in a descending manner based upon their lag gap (i.e. the vehicle with the largest lag gap is the most ideal vehicle to provide lane-change advice). The required advisory is then provided to these vehicles beginning with candidates with the larger lag gaps.

2.3. Reactive Control

The Reactive Control is active in the region immediately upstream of the bottleneck (see Fig. 1). The purpose of the Reactive Control is to detect vehicles on the main carriageway which potentially could interfere with the merge process of on-ramp vehicles as they enter the highway, and advise them to change lanes earlier.

Ramp vehicles are detected as they traverse down the on-ramp and the time for the vehicle to reach the merge location, T_r, is estimated. All left-lane vehicles on the main carriageway are then projected T_r seconds into the future. If their projected position is near the predicted merge location, then they are advised to change lanes.

An assumption is made that, due to small distances involved, the influences on acceleration are minor and vehicles maintain their speed as they approach the merge section. In reality, factors such as the preceding vehicle's speed, nearby lane change movements and road geometry could influence this zero-acceleration assumption.

To evaluate the performance of the proposed controls, the total travel time (TTT) is chosen as the primary indicator of performance.

3. Experimental Setup

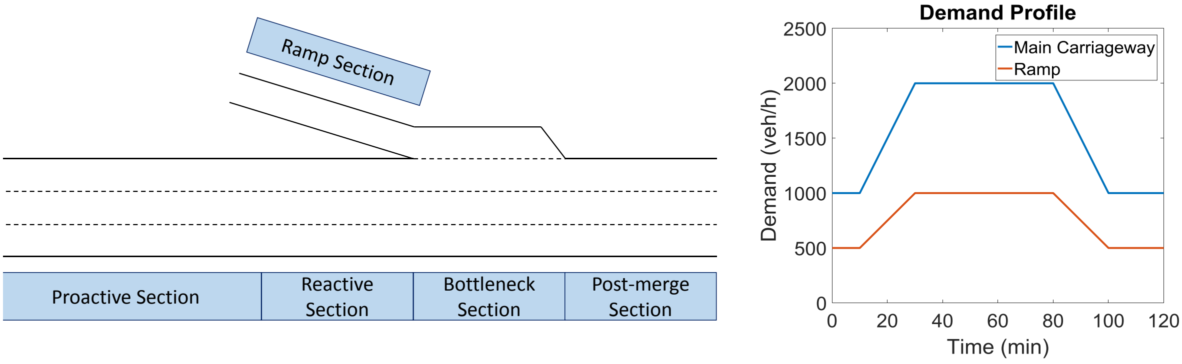
To test and evaluate the performance of each control strategy, experiments were simulated using Aimsun. Initial simulations were run without any external control to establish a baseline case – this strategy will hereafter be denoted as No Control. An ALINEA ramp metering strategy was also simulated to create a benchmark.

3.1. Road network/simulation parameters

A trapezoidal demand profile was constructed with peak flows of 1000 [veh/h] on the on-ramp and 6000 [veh/h] on the main carriageway over a period of 120 [min] with a peak period of 60 [min]. An illustration of the demand profile is depicted in Figure 1.

Figure 1 illustrates the experimental set up. The road network used for simulation depicts a three-lane highway with a connecting on-ramp. The length of the ramp is 200 [m] and the total length of the main carriageway is 1000 [m], further divided into the zones as indicated in the figure. The speed limit of every section, including the on-ramp is set at 90 [km/h].

Figure 1: Road network and Demand Profile



For each control method, 10 replications were simulated. The seeds used to run each replication were randomly generated for the No Control scenario and then re-used for each of the control methods to maintain consistency in vehicle generation.

3.2. No Control

Baseline replications devoid of any form of traffic control were established to create the reference for comparison.

3.3. Ramp Metering

The ramp metering strategy employed was ALINEA. The minimum flow rate was set at 700 [veh/h] and the maximum at 1100 [veh/h]. The regulator parameter K_r was set at 70 and the desired downstream occupancy was calibrated at 60%. The ramp meter is located on the on-ramp, 50 [m] from the ramp exit and the downstream detector in the bottleneck section, 20 [m] from the end of the section.

3.4. Proactive

The Proactive Control is active in the first 500 [m] of the highway. It represents the initial control strategy vehicles are exposed to and precedes the Reactive Control.

For this control, the minimum gap for lane change advisory is set at 10 [m] for the rear gap and 5 [m] for the front. The weights for the objective function are calibrated as α_1 = 10, α_2 = 4, α_3 = 1, and β = 1. The critical counts, n_i^{cr}, are 10, 15, 20 for i = 1,2,3 respectively. The control step size is set at 12 [sec].

The minimum gaps refer to the minimum acceptable headways for vehicles to perform the lane changing manoeuvre ordered by the controller.

The α and β values were calibrated to reflect the relative importance of maintaining each lane's density at or under the critical level and balancing this against an acceptable amount of lane-changing advice.

The Critical Counts refer to the optimal vehicle count in each lane. These counts present a density gradient across lanes to account for the fact that inbound ramp vehicles will add to the existing flow and subsequent lane changes will shift more vehicles into adjacent lanes.

3.5. Reactive

The Reactive Control is active in the next 100 [m] of the highway, downstream of the Proactive Section. The minimum gap for lane change advisory is set at 4 [m] for the rear and 2 [m] for the front. These are lower than the gap parameters for the Proactive Control to reflect the shorter time frame in which vehicles are under this control and hence a greater need to advise lane changes quicker and more aggressively.

The Reactive Control performs recurrently due to the low tolerances and time-sensitivity of vehicle information in terms of position, speed and acceleration. After the Reactive Section, the vehicles enter the bottleneck section and consequently follow their own lane-changing dynamics.

The Proactive and Reactive Control were also evaluated together by forming a control strategy using both controls in the same simulation. This strategy is termed the Combined Control.

4. Results

The average total travel time of each control measure was computed and compared against the baseline scenario (No Control strategy) to evaluate their relative performance. The average results for the scenarios are presented in Table 1 and Figure 2 to 4.

Table 1: Total travel times for each control strategy

	No Control	ALINEA	Reactive	Proactive	Combined
Total Travel Time	248.8	171.8	154.4	215.2	133.7
Improvement		31%	38%	13%	46%
TTT standard deviation	49.8	18.5	42.7	67.0	8.0
Improvement		63%	14%	-34%	84%

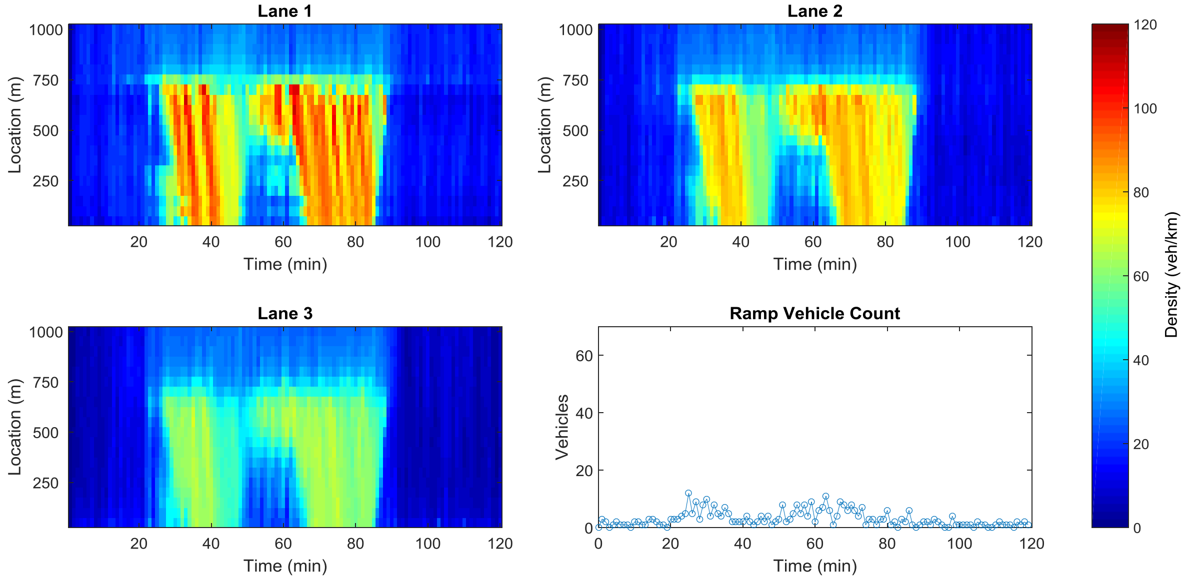
The baseline scenario TTT is 248.8 [hr] with the standard deviation of the 10 replications computed as 49.8 [hr]. In comparison, the ALINEA ramp metering strategy was successful in decreasing the TTT by 31%, resulting in a TTT of 171.8 [hr]. The variation of travel times scenario was also lower with a standard deviation of 18.5 [hr]. This can be largely attributed to the controlled inflow of ramp vehicles into the main stream, reducing the variation in input flow from the ramp.

The Combined Control produces the greatest improvement in TTT. The average TTT was 133.7 [hr], a 46.3% decrease from the baseline case; representing a 23.8% improvement over the ALINEA strategy. In addition, the TTT across scenarios were very consistent, presenting a standard deviation of only 7.97 [hr], an 84.0% improvement over the baseline case.

The success of the Combined Control can be attributed to the synergistic action of the Proactive and Reactive Controls. The Proactive Control reduces the density in the left lane which aids in minimising the required amount of control action required from the Reactive Control due to fewer vehicles in the left-most lane. This results in reduced lane changing closer to the merge, minimising the local disruption to the traffic flow in the bottleneck region.

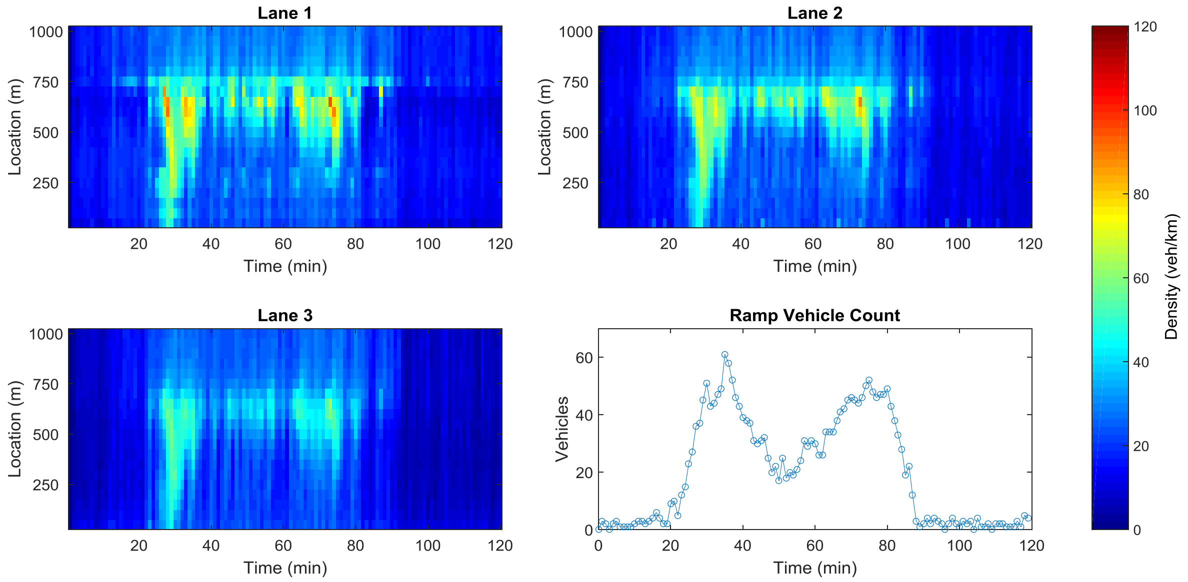
The density contour plot in Figure 2 illustrates the formation of congestion and subsequent propagation upstream along the highway for the No Control scenario

Figure 2: Contour plot - No Control



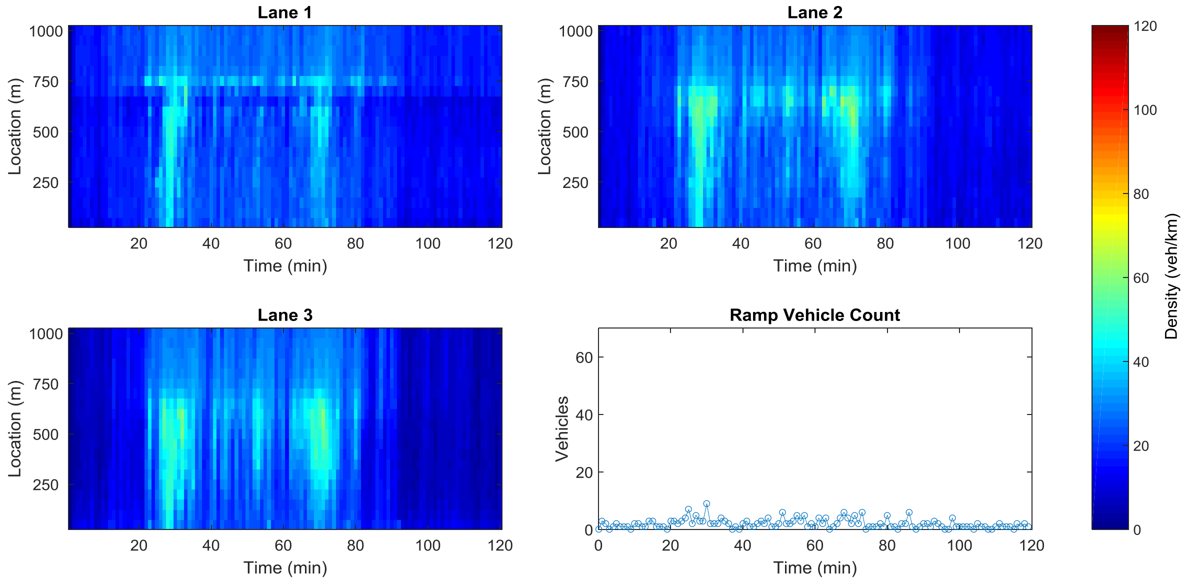
The effects of ALINEA ramp metering strategy are apparent in Figure 3. The onset of congestion begins at roughly the same time as the baseline scenario but is much more subdued. The improvement in congestion along the highway is at the expense of larger on-ramp queues.

Figure 3: Contour plot - ALINEA



The Combined Control, in Figure 4, is more effective in controlling congestion compared to ALINEA, demonstrated by significantly lower densities in the contour graph. It also mitigates congestion while avoiding the creation of excessive queues on the on-ramp. The lane change advisory is successful in preventing the formation of congestion and following capacity drop.

Figure 4: Contour plot - Combined Control



5. Summary

This paper presents a lateral control strategy utilising autonomous vehicle communication capabilities. The strategy is composed of an upper-level control aimed at optimising vehicle density across lanes and a lower-level control to predict and tackle merging conflicts through localised lane changing advisory. The proposed control strategy provides a novel way of addressing and relieving congestion on highways using the enhanced capabilities of autonomous vehicles over conventional vehicles.

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