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Lane density optimisation of automated vehicles for highway congestion control

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ABSTRACT

The rapid development of automated vehicle (AV) technology and increasing deployment in the near future present novel opportunities for congestion control on highways. Collective dynamics of AVs allow for network-wide traffic management, offering more flexible centralised and decentralised control schemes. To capitalise on this technology, control strategies need to be developed to enable traffic management to take advantage of AV potential to manipulate traffic flow dynamics. This paper presents a two-level traffic control method to relieve highway congestion by controlling lateral flows of AVs. The first, a proactive lane density distribution optimisation problem to establish the optimal vehicle density in lanes upstream of bottlenecks. The second, a reactive lane change advisory system to tackle local merging manoeuvres and resolve merge conflicts. The effectiveness of the proposed strategy is demonstrated through microsimulation experiments and comparison to ramp metering strategy. To consider the transition period and gradual uptake of AVs, the proposed control is also tested at various penetration rates of AVs. At moderate to high levels of AV penetration, the control is demonstrated to be superior to ramp metering within a range of traffic demands. The proposed traffic control reduces total travel time of all vehicles and travel time variation among vehicles on the mainline and ramps. The effectiveness is attributed to the delayed onset and severity of congestion and subsequent capacity drop. The success of the proposed strategy is illustrated on a three-lane highway with a single on-ramp and further exhibited on a road network with multiple on-ramps and off-ramps.

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1. Introduction

Through increasing city growth and greater mobility needs, traffic congestion emerges as a widespread urbanisation problem. The demand on existing transport infrastructure is continually growing and straining road networks already near capacity. However, constructing new infrastructure is not a sustainable solution for congestion alleviation since urban development and transportation infrastructure compete for the same space resource. For highway congestion management, control measures such as variable message signs (VMS) (Carlson et al. 2010; Carlson, Papamichail, and Papageorgiou 2011; Tympakianaki et al. 2014), ramp metering (Papamichail et al. 2010; Zhang and Levinson 2010), ramp metering integrated with perimeter control (Haddad, Ramezani, and Geroliminis 2013) and dynamic speed limits (Hegyi, DeSchutter, and Hellendoorn 2005; Hoogendoorn et al. 2013; Han et al. 2017) are extensively investigated to reduce the frequency and impact of traffic congestion.

Potentially with AVs gradually becoming a greater presence on roads, researchers have taken different approaches as to the capabilities of these vehicles. The use of connected vehicles (CVs) to improve traffic performance in urban settings has taken multiple forms such as queue spillback management and redistribution of delays to links with greater storage space (Christofa, Argote, and Skabardonis 2013) and improved signal control strategy with heuristics to modify control algorithms to adapt to varying penetration rates (Yang, Guler, and Menendez 2016). On highways, strategies such as cooperative adaptive cruise control (CACC) are used to increase lane capacity through shorter headways (e.g. Shladover, Su, and Lu 2012; Milanés and Shladover 2014; Sau et al. 2014; Milanés and Shladover 2016; Tuchner and Haddad 2017) or to mitigate traffic oscillations caused by merging, using AVs to sense surrounding driving conditions (Zhou, Qu, and Jin 2016). Talebpour and Mahmasani (2016) developed an acceleration framework distinguishing between CVs and AVs while demonstrating improvements in string stability and throughput. Wang et al. (2016) established a model predictive control (MPC) framework, incorporating sensor and actuator delays to account for mismatch between the system state prediction model and the actual behaviour. Rios-Torres and Malikopoulos (2016) presented an optimisation framework and analytical closed-form solution coordinating CVs and AVs at merging zones.

Longitudinal control using CVs and AVs has been explored, both in standalone applications (Wang et al. 2016; Khondaker and Kattan 2015; Chen, Ahn, and Hegyi 2014) and in conjunction with other control strategies (Han, Chen, and Ahn 2017). It is frequently combined with lateral control, such as the pairing of a VSL controller with a lane change recommendation scheme (Zhang and Ioannou 2017). Roncoli, Bekiaris-Liberis, and Papageorgiou (2017) also proposed a lane changing control by formulating an optimal feedback control problem and solving it in real time to determine the optimal lane assignment of vehicles upstream of the bottleneck in a macroscopic simulation. Baskar, DeSchutter, and Hellendoorn (2012) proposed an MPC approach combining dynamic speed limits, lane allocation and ramp metering, orchestrating AVs into platoons under the assumption of a fully automated vehicle network. Roncoli, Papamichail, and Papageorgiou (2016) developed a hierarchical MPC framework integrating ramp metering, vehicle speed control and lane changing control on a macroscopic level which was then tested in a microscopic simulation showing improvements even at low penetration rates.

The aim of this paper is to alleviate highway congestion by delaying the onset of congestion at recurrent bottlenecks, avoiding capacity drop and consequently increasing the overall throughput. This paper focusses on lateral traffic flow control by developing a two-level control method that integrates a centralised proactive lane distribution optimisation problem and a decentralised reactive lane change advisory system. The strategy assumes AVs are capable of detecting nearby vehicles and have V2V and V2I capabilities to relay and receive information to and from other AVs and roadside infrastructure. The first-level control is a centralised controller formulated as an optimisation problem to control lane change of AVs aiming at optimising the vehicle (AVs and non-AVs) density across lanes proactively prior to an on-ramp merge section to reduce discretionary lane changing and facilitate mandatory lane changing at the merge location. The second-level control is decentralised and presents a rule-based strategy that is active just upstream of the merge location to predict and tackle merging conflicts through the provision of localised lane changing advice. Furthermore, safety considerations of lane changes (i.e. control actions) are integrated within both controllers.

The control strategies are evaluated through extensive microsimulation experiments highlighting the effectiveness of the proposed control for a range of demand levels and the limitations of the control as the demand approaches the capacity of the infrastructure. The scalability of the control is also demonstrated through a multiple ramp case study whereby the same control is extended onto a road network with multiple on- and off-ramps.

A major challenge lies within the transition period whereby conventional vehicles and AVs share the same infrastructure, resulting in mixed traffic flow. AVs can be regarded as actuators while conventional vehicles are unpredictable, managing their own driving behaviour selfishly. Their reactions to control can be regarded as noise and disturbances and potential solutions should be robust and

applicable to this chaotic environment. Due to lack of field data on interaction between AVs and conventional cars, we choose a traffic control structure based on achievable measurements, practical assumptions and fundamental models, and demonstrate the effectiveness of the proposed control strategy with mixed traffic flow. The controller reduces the total travel time (TTT) of all vehicles traversing the mainline and ramps while providing a more equitable operation by reducing the travel time variations among the vehicles on the mainline and ramps.

The paper is structured as follows. Section 2 describes the methodology and the proposed control strategy. Section 3 illustrates the experimental set-up. Section 4 presents the simulation results and evaluation of strategy compared to a baseline no-control case and ALINEA as a benchmark ramp metering strategy. Section 5 concludes the paper.

2. Methodology

2.1. Control strategy structure

When considering the nature of any control strategy, the benefits and drawbacks of centralised versus decentralised control should be examined. Centralised systems offer a much more holistic approach to traffic management due to the ability of the central computer to incorporate all information within the road network and optimise on a system level. This overarching control can easily be modified to suit the characteristics of the road network and, in the case of this paper, the penetration rate of AVs within the network. However, due to the large amount of information, computational load, and spatial and temporal difficulties of real-time measurements, the ability of the controller to apply the control strategy centrally in real time is often a challenging task. In addition, control failures or hardware faults will have extensive degrading impacts potentially affecting the entire system.

Decentralised systems address the above drawbacks by distributing the computational load across multiple processors. Control strategies can be easily implemented in real time and failure in any single node has limited consequence on other parts of the system. There is also increased flexibility as the control follows the processor, enabling the strategies to be employed across many locations without additional investment in infrastructure. However, in regard to AV traffic management, the main challenge lies in the coordination between AVs, compounded by differences in software, manufacturers and attempts to optimise local conditions in preference to an overall strategic goal. Ultimately, control strategies that incorporate elements of each are robust and effective for traffic management.

With this in mind, this paper establishes a two-level control structure comprising two custom controllers, operating sequentially. The first-level control, termed the Proactive Control, considers the road network in a macroscopic sense by optimising the relative vehicle densities in each lane to facilitate merging between the on-ramp vehicles and the vehicles travelling on the main carriageway. The Proactive Controller acts centrally by detecting the number of vehicles in each lane through communication with AVs. An optimisation problem is developed and solved in real time by the Proactive Controller and the control strategy is implemented through lane change advisory communicated to AVs.

The second-level control, termed the Reactive Control, focusses on individual AVs (microscopic level) to address local merging manoeuvres and interactions between vehicles. This control strategy is decentralised in nature and is readily applied without a central controller. AVs travelling on the highway, approaching the merge location, detect the position and speed of vehicles traversing the on-ramp. They then perform calculations to determine potential merge conflicts and subsequently lane change to avoid the conflicts. Cooperative behaviour to facilitate lane changing and gap creation between AVs across multiple lanes is achieved via additional V2V communication between AVs. Minimum front and rear gap sizes are specified to limit the provision of lane changing advice to safe conditions, further minimising the disruption from lateral movements.

The Proactive Control is an optimisation method that requires a larger spatial zone and greater proximity from the merge location. This combined with the longer duration between control steps

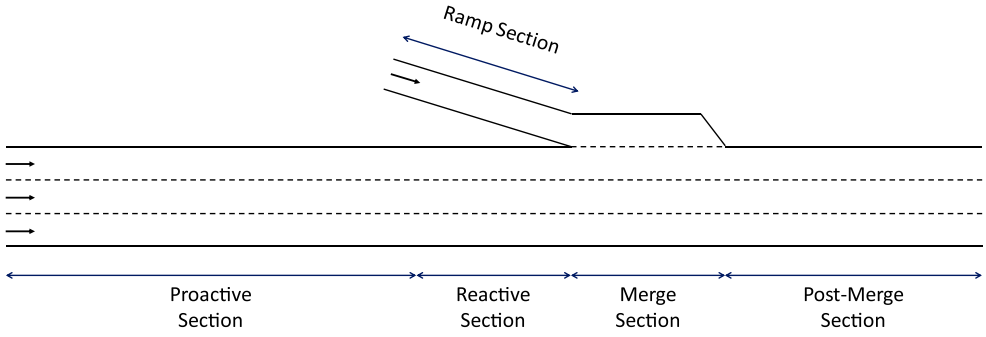


Figure 1. Road network – the two-level control is active in the first two sections of the main carriageway with the sections named after their controllers accordingly.

makes it ideal for centralised control. The Reactive Control works best at a short range and requires rapid detections, estimation and decision making, which is suitable for decentralised control. Figure 1 illustrates the positions of the Proactive and Reactive Controls for ease of understanding. A detailed description of the experimental layout is provided in Section 3. The following sections elaborate the Proactive and Reactive Controls.

2.2. Proactive control

This paper considers a multi-lane highway with one-lane on-ramps. Without loss of generality, the formulation is introduced for a single merge location while the control method can be applied to multiple merge locations. A numerical case study with multiple ramps is presented in the Results section. The main carriageway is composed of $i = 1, 2, \dots, I$ lanes, where 1 is the index of the left-most lane and I denotes the right-most lane (note that the formulation is developed for locations that drive on the left – the methodology is readily transferable where driving is on the right). An on-ramp is present in the road network, linking to the main carriageway via the formation of an additional merge lane before the road returns to I -lanes further downstream.

The Proactive Control is applied in the upstream of merging section (see Figure 2), hereafter referred to as the Proactive Section. This control determines the optimal number of vehicles in each lane by minimising an objective function and provides lane-change advisory to the AVs at various time increments to achieve this optimal density distribution. The main aim is such that the lanes closer to the left of the highway, i.e. closer to the on-ramp, have a reduced vehicle density to facilitate a smoother merging process for the inbound ramp vehicles. By performing lane changing upstream and in conditions less likely to be congested, the amount of lane changing closer to the merge location is reduced, minimising disturbances in the merge section that could lead to less deterioration of traffic flow. The occurrence of capacity drop is thereby delayed, and potentially prevented, reducing the severity of delays experienced.

This optimal distribution represents a trade-off between attaining the ideal vehicle density in each lane and minimising lane change manoeuvres. Due to the nature of the problem, vehicle count is used as a proxy for traffic density. The advantages of using a discrete variable include more accurate instantaneous detection and use as a control parameter when it comes to lane-change advisory. The optimal number of vehicles (including AVs and conventional vehicles) in each lane is governed by the following objective function:

$$\min_{n_i^*(k)} J = \left[\sum_{i=1}^I \alpha_i (n_i^*(k) - n_i^s)^2 + \beta \sum_{i=1}^I i (n_i^*(k) - n_i(k)) \right] \quad (1)$$

$$\text{s.t. } \sum_{i=1}^l n_i(k) = \sum_{i=1}^l n_i^*(k) \quad (2)$$

$$n_i^*(k), \dots, n_l^*(k) \in \mathbb{N} = \{0, 1, 2, \dots\} \quad (3)$$

$$\sum_{i=1}^w n_i(k) \geq \sum_{i=1}^w n_i^*(k) \quad w \in \{1, 2, \dots, l\}. \quad (4)$$

The index of each lane is denoted $i = 1, \dots, l$ with 1 being the left-most lane and l being the number of lanes (and thereby, the right-most lane). The current vehicle count, in the Proactive Section, at time instance k in lane i is represented by $n_i(k)$. The optimal vehicle count in each lane is $n_i^*(k)$ and is determined through the minimisation of the objective function J in (1). The set-point vehicle count in each lane as estimated from the fundamental diagram (FD) is denoted by n_i^s . Equation (2) represents the conservation of number of vehicles. Equation (3) restricts control outputs (vehicle counts) to non-negative integers. Equation (4) ensures that all advised lane changes are right-moving.

The terms in the objective function (1) are weighted by α and β . The first term of the objective function penalises deviations from the set-point count in each lane. Counts which are too low represent underutilisation of the lane whilst counts which are too high reduce the traffic flow (i.e. the decreasing part of FD) and hinder lane changing and merging, leading to the congested condition. This term is squared to not only penalise both under and over-utilisation of the lane but also impose a greater penalty when the counts deviate greatly from the desired values. The weight factor, α_i , is dependent on the lane, enabling greater weighting on critical lanes, i.e. lanes closer to the ramp. The set-point counts (veh) are determined using $n_i^s = \gamma_i(\rho^{cr} - \rho^r)L$ for the leftmost lane (i.e. $i = 1$) and $n_i^s = \gamma_i\rho^{cr}L$ for all other lanes (i.e. $i = 2, \dots, l$), where ρ^{cr} is the critical density (veh/km) as derived from the critical density from the FD, L is the Proactive Section length (km), γ_i is a reduction factor and ρ^r is an estimation of the density of the on-ramp traffic travelling towards the merge section. Note that ρ^r only appears in the left-most lane to consider the inflow from the ramp as this directly adds to the flow of the leftmost lane. In this paper, we take a conservative approach and consider the density of on-ramp traffic, i.e. ρ^r , to associate with the capacity flow of the on-ramp. The set-point counts are adjusted (by reduction factor γ_i , where $\gamma_i < 1$) to be slightly lower than the nominal optimal set-point to establish a buffer, minimising the effects of disturbances and preventing minor control failures from increasing the density to an overcritical point and causing capacity drop. γ_i values are selected so as to create a density gradient across lanes whereby the lanes closer to the left side of the road have lower set-point counts, 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. In our experiments, the FDs are obtained through simulations of the baseline no-control case and ρ^{cr} is assumed to be a unique value for all lanes. For field implementation, the FDs should be observed recurrently and ρ^{cr} can be lane dependent. This is crucial because the penetration rate and configuration of AVs in the traffic stream (e.g. AV platooning) have significant effects on the FD (Ramezani et al. 2017). Dynamic updating of the set-point count values utilising real-time measurements or predictions of the ramp flow is noted as a future research direction.

The second term of the objective function (1) penalises the number of lane changing manoeuvres. Lane changing movements can generate disturbances which trigger the formation of congestion and capacity drop (Zheng 2014; Keyvan-Ekbatani, Knoop, and Daamen 2016). Whilst a number of lane changing movements is necessary to achieve the optimal lane counts, excessive lane changing or over control promotes deterioration of the system through the formation of oscillatory lane-changing behaviour and unsafe driving conditions. The component captured by the second term of J in (1) represents the number of right-moving lane changes as demonstrated by the following.

Let us assume p AVs are advised to lane change from lane a to lane b where $a < b$ and the two lanes are not necessarily adjacent. Then $n_a^*(k) - n_a(k) = -p$ represents a lateral outflow of p vehicles from lane a and $n_b^*(k) - n_b(k) = p$ represents a lateral inflow of p vehicles into lane b . Multiplying this

by the index of the lane, we get $a(n_a^*(k) - n_a(k)) = -ap$ and $b(n_b^*(k) - n_b(k)) = bp$. Combining the two, we derive $a(n_a^*(k) - n_a(k)) + b(n_b^*(k) - n_b(k)) = -ap + bp = p(b - a)$, where p is the number of lane-changing vehicles and $(b - a)$ is the number of lanes traversed by each of these vehicles. Thus $a(n_a^*(k) - n_a(k)) + b(n_b^*(k) - n_b(k))$ represents the total number of lane change movements from lane a to lane b with movements across multiple lanes counted as multiple lane changes. Generalising and extending this to the number of lanes in the proactive section, $i = 1, 2, \dots, l$, we arrive at the second term of the objective function, $\sum_{i=1}^l i(n_i^*(k) - n_i(k))$.

The major assumption underlying this process is that all advised lane changes to AVs are right-moving. This is imposed as, intuitively, the lanes closer to the left will be naturally more congested due to the ramp inflow and subsequent merging. By also only advising lane-changing in one direction, the incidence of oscillatory behaviour whereby AVs move in and out of the same lane is reduced.

At each control cycle, the vehicle counts in each lane, i.e. $n_1(k), \dots, n_l(k)$, are input into the objective function which will then output the corresponding optimal vehicle counts, i.e. $n_1^*(k), \dots, n_l^*(k)$ that minimise the objective function. Determination of the optimal vehicle counts is done through an enumeration of the possible numbers of vehicles in each lane. The computational load is reduced by limiting the solution space for the optimal counts via conservation laws (2) and the assumption that all lane changes are right-moving. The solution space at each control step is $\prod_{i=1}^{l-1} (n_i^{AV} + 1)$, as the number of AVs that can be advised to lane change from each lane ranges from zero to the number of AVs in the lane, i.e. $n_i^{AV} + 1$. No AVs are advised to lane change in the rightmost lane, hence an upper bound of $l - 1$. Given the number of lanes and maximum number of vehicles in each lane, the solution space is relatively small and the enumeration can be done efficiently to guarantee the optimal solution.

When the optimal vehicle counts are determined, the advised number of right-moving lane changes for lane i is calculated as

$$m_i = \begin{cases} n_i(k) - n_i^*(k) & \text{for } i = 1, \\ \max\{0, \sum_{j=1}^i [n_j(k) - n_j^*(k)]\} & \text{for } i \in [2, 3, \dots, l - 1], \\ 0 & \text{for } i = l. \end{cases} \quad (5)$$

For the left-most lane, lateral movements only consist of outflows, hence the number of lane changes equals the difference between the current vehicle count and the optimised vehicle count, i.e. $n_i(k) - n_i^*(k)$. This value is always non-negative due to the constraint set out in Equation (1). The right-most lane always has zero advised lane changes due to no valid target lanes.

When analysing the middle lanes, the inflow of vehicles from all the left-side lanes must be considered. The summation, $\sum_{j=1}^{i-1} [n_j(k) - n_j^*(k)]$, provides the net total outflow from all the lanes prior to the currently analysed lane i . Hence, $n_i(k) + \sum_{j=1}^{i-1} [n_j(k) - n_j^*(k)]$ represents the total vehicle count in lane i after having considered the increase in vehicle count due to inflows from previous lanes. Therefore, $n_i(k) + \sum_{j=1}^{i-1} [n_j(k) - n_j^*(k)] - n_i^*(k)$ illustrates the number of lane changes after adjusting for the inflow from prior (left-sided) lanes. A lower bound of zero is introduced via the max function to prevent negative values which would represent left-moving lane change advisory. As the number of AVs to advise is determined on a lane-by-lane basis, the maximum number of lanes each AV is advised to change at a time is capped at one. Furthermore, AVs are advised to maintain their lane after completing the advised lane change. This results in a maximum of one lane change between control steps and aids in minimising over-control and oscillatory lane changing behaviour.

Determination of which AVs to advise to change lane is based on inter-vehicle gap sizes or headways. Recurrently, each AV measures the lead and lag gaps in their adjacent right lane (i.e. gaps in lane $i+1$ for AVs in lane i) using in-vehicle sensors on the AV. Accordingly, AVs are placed in a list, sorted by the size of their lag gaps. Ranking based on lag gaps as opposed to lead gaps is preferable due to higher uncertainty and caution associated with lag gaps (Toledo, Koutsopoulos, and Ben-Akiva 2007) and lag vehicle speed (Oh, Choi, and Park 2017), hence the space behind them is more critical in determining safety. AVs that have adequate safe lead and lag gap sizes are noted as candidates and are sorted in a descending manner based upon their lag gap (i.e. the AV with the largest lag gap is the

most ideal AV to receive lane-change advice). If the number of candidates are greater than m_i then the best m_i candidates are advised to change lanes. If the number of candidates are less than m_i then all the candidates will be advised to change lanes with the remaining required number of lane changes discarded.

Notably, lane change advisory is communicated to AVs and conventional vehicles still perform their own lane changing which can be left-moving. This represents a disturbance to the optimisation process but with frequent measurements of the system and activation of the proactive optimisation, the number of vehicles in each lane is expected to be maintained close to the set-point values. It is assumed that AVs, as a subset of traffic flow, provide an estimation of the number of vehicles per lane. There is abundant literature on probe vehicle data (car floating data) to estimate traffic flow states such as traffic density and queue size in freeway and urban links (e.g. Ramezani and Geroliminis 2015). Given that each probe vehicle provides information about itself and each AV provides information about itself and its surrounding vehicles, it is expected that the number of vehicles can be estimated easily with use of AVs. In addition, fusion methods using combination of loop detectors and AVs will be sufficient in determining the number of vehicles per lane in the Proactive Section at low AV penetration rates.

2.3. Reactive control

The Reactive Control is the second-level component of the proposed two-level highway traffic flow control and is active in the section immediately upstream of the bottleneck (see Figure 2), downstream of the Proactive Section. The purpose of the Reactive Control is to identify AVs on the main carriageway which potentially could interfere with the merge process of on-ramp vehicles as they enter the highway. These AVs would then be advised to change lanes prior to the merge location to free up additional space in the left-lane for the merging ramp vehicles. These AVs on the main carriageway are termed conflicting AVs.

As vehicles progress down the on-ramp, their position and speed information are detected by AVs. Accordingly, the time for the ramp vehicle to reach the merge location can be estimated using the kinematic equation, $T_r = d_r/v_r$. The distance of the ramp vehicle to the merge location is d_r (m) with speed v_r (m/s), and the time to reach the merge location is T_r (s). For simplicity, the assumption is made that the ramp vehicles maintain their speed from the time that they are detected until the merge point (zero-acceleration assumption).

Having computed T_r , all AVs on the main carriageway in the left-most lane project their position T_r seconds into the future. Their projected position is $d_m = v_m T_r$, where d_m is the projected position and v_m is the speed of the AV on the main carriageway, also assuming zero acceleration. If the projected position of an AV on the main carriageway is within a fixed distance of the predicted merge location (we term this length the conflict window, denoted x , see (6)), then the AV is considered as a conflicting AV.

$$d_r - x \leq d_m \leq d_r + x. \quad (6)$$

The conflict window parameter is adjusted to tone the sensitivity, with larger values representing a more aggressive control. The pseudo code of Reactive Control logic reads as

It is noted that the Reactive controller assumes that the merge point is the beginning of the acceleration lane (i.e. where it is first physically possible to merge). However, in the numerical case studies (i.e. microsimulator), the merging point is not fixed and merging takes place along the stretch of the merge lane. The results show that this assumption is not restrictive and the proposed Reactive Control is beneficial.

Furthermore, underlying the Reactive Control is the assumption that the ramp vehicles and the vehicles on the highway maintain their speed until the merge point. In reality, factors such as preceding vehicles' speeds, nearby lane change movements and road geometry could influence this zero-acceleration assumption. The Reactive Control takes effect in a relatively short section closer to the bottleneck section. The smaller control section and closer proximity combined with the use of the

Algorithm 1 Reactive control pseudo-code

```

for All conventional and automated vehicles on the ramp do
  Determine time to merge ( $T_r = d_r/v_r$ )
  for AVs in left lane of Highway do
    Project future position, ( $d_m = v_m T_r$ )
    if Conflicting with merging vehicle ( $d_r - x \leq d_m \leq d_r + x$ ) then
      Mark as conflicting AV
    end if
  end for
end for

for Each lane except right-most do
  if Vehicle is a conflicting AV then
    if (Lead gap > acceptable safe lead gap) & (Lag gap > acceptable safe lag gap) then
      Advise lane change
    else
      If adjacent vehicle on the target right lane preventing lane change is an AV, mark as
      conflicting AV
    end if
  end if
end for

```

conflict window ensures that accelerations will only lead to minimal discrepancies between the actual distances traversed and the estimated positions. Moreover, extensive microsimulation tests do not demonstrate a significant improvement by considering acceleration of vehicles. Hence to keep the control elegant, the formulation with zero acceleration is adopted.

For the majority of the microsimulation experiments, we consider the scenario whereby there is a complete uptake of AVs (100% penetration rate). The effect of a reduced proportion of AVs and the impact on control strategy performance is also analysed with the assumption that conventional vehicles are unable to receive lane change advisory. AVs continue to measure the information of conventional vehicles as they traverse down the on-ramps. This is not restrictive as, even if AVs are unable to detect ramp vehicles from a distance, loop detectors can locate the presence and speed of all ramp vehicles and, with the aid of communication devices, broadcast this information to AVs. Conventional vehicles will continue with their own lateral movement dynamics, also hindering cooperative lane changing if AVs are attempting to engage surrounding vehicles to change lanes.

3. Experimental setup

The main contribution of this paper is the design of the lane change controller for AVs. Accordingly, the microsimulation experiments are parameterised such that the effectiveness of the proposed controller is measured irrespective of the gains from possible shorter headway and reaction time of AVs compared to conventional vehicles. To this end, the parameterisation of AV and conventional vehicle car-following models is set to be similar. This is a necessity to measure and report the benefit of the AV lane change controller in isolation from longitudinal traffic flow gains. Note that (i) this does not affect the design of the controller and only affects the microsimulation setup and (ii) there is still stochasticity among the parameters of car following models of vehicles where these parameters are drawn from predefined distributions. Evidently, in an integrated system with both longitudinal and lateral controllers for AVs, the model of AV dynamics should differentiate their characteristics from conventional vehicles. This is a future research direction.

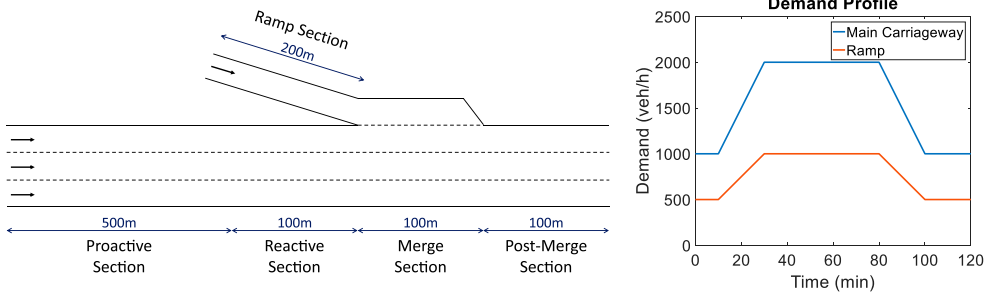


Figure 2. Left: Road network – the two-level control is active in the first two sections of the main carriageway with the sections named after their controllers accordingly. Not to scale. Right: Demand profile – the highway demand and ramp demand increase at the same time to reflect the generation and subsequent dissipation of peak flow.

To test and evaluate the performance of control strategies, experiments are simulated using the Aimsun microsimulator. Initial simulations are run without any external control to establish a baseline case – this strategy will hereafter be denoted as No Control. An ALINEA ramp metering strategy is also simulated to create a benchmark upon which to compare the effectiveness of the proposed traffic flow control measures. Total travel time ($\hat{A}TT$) is used as the primary indicator of performance and is calculated as the summation of the individual travel times of each vehicle that passes through the road network, i.e. vehicles travelling on the mainline and on the ramps.

Figure 2 illustrates the experimental setup. The road network used for simulation depicts a three-lane highway with an 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 sections as indicated in the figure. The speed limit of every section, including the on-ramp is set at 90 km/h. A trapezoidal demand profile is considered 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 2. It is worth mentioning that the lane change of all vehicles is carried out as a continuous movement.

It is noted that the default lane-changing behaviour in Aimsun might inaccurately represent the merging behaviour in a critical flow regime (Chevallier and Leclercq 2009). Under the default calibration, the relative density of the left lane of the highway compared to other lanes is much higher than it would be realistically. Using default parameters, vehicles in the other lanes end up travelling much faster than the left lane vehicles. In reality, drivers in the middle and right lanes upon seeing the congested left lane will take a more cautious and conservative approach and reduce their speed in anticipation of drivers suddenly cutting out of the slow lane. To reflect this behaviour, the two-lane car-following model in Aimsun is recalibrated to represent traffic states on different lanes more similar to observed dynamics.

For each control method, 10 replications are simulated. The seeds used to run each replication are randomly generated for the No Control scenario and then reused for each of the control methods to maintain consistency in vehicle generation. Each replication has a duration of 2 h with zero warm-up time.

3.1. No control

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

3.2. Ramp metering

The ramp metering strategy employed is ALINEA, a local feedback control strategy which attempts to maximise throughput by maintaining a target occupancy downstream of the merge section

Table 1. Proactive control parameters

Parameter	Value	Unit
Minimum Safe Lag Gap	10	metre
Minimum Safe Lead Gap	5	metre
$\alpha_1, \alpha_2, \alpha_3$	10, 4, 1	(—)
β	1	(—)
Set-Point Counts (n_i^s)	10, 15, 20	vehicle
Control Time Step	12	second

(Papageorgiou, Hadj-Salem, and Blosseville 1991). Under this strategy, the output flow is regulated as $r(k) = r(k-1) + K_R[\hat{o} - o_{out}(k)]$, where $r(k)$ represents the ramp flow in the current control step, $r(k-1)$ is the ramp flow in the previous control step, K_R is a regulator parameter, \hat{o} is the target occupancy (%) and $o_{out}(k)$ is the measured downstream occupancy (%).

The target downstream occupancy, \hat{o} , is calibrated at 60% (over the three lanes) since it shows the lowest average TTT of the whole network. The ramp metering strategy is active for the entire duration of the scenario.

3.3. Proactive control

The Proactive Control is active in the first 500 m of the highway. It represents the first-level control strategy that AVs are exposed to and precedes the Reactive Control. Table 1 presents the parameters and the values used for this control. Determination of parameter values is done via an iterative process, where through multiple iterations these parameters are fine-tuned to improve the performance of the control. Note that the parameters remain unchanged in all the numerical experiments.

The minimum safe gaps refer to the minimum acceptable inter-vehicular distance for AVs to perform the lane changing manoeuvre ordered by the Proactive Controller. For each AV, the lead gap is the distance from the front of the AV to the rear of the closest preceding vehicle (in any adjacent lane) and the lag gap is the distance from the rear of the AV to the front of the closest following vehicle (in any adjacent lane). Only AVs with gap sizes greater than the minimum parameter values are considered for lane change advisory, i.e. even if the measured gaps are higher than the minimum predefined values, there is a possibility that an AV cannot change lane because of safety issues. Although not an issue with AVs, during the transition period where there is a mix in traffic composition, consideration of conventional vehicles via awareness of human reaction times and perceptions of safety is done by enacting control advisory which emulates lane change movements similar to those which would be reasonably performed by manual driving. That is, acceptable safe gaps (see Algorithm 1) are increasing functions of the speed of AV and conventional vehicles in the destination lane. The acceptable lag gap is greater than the lead gap to reflect drivers' reduced field of view behind them and hence a greater need to maintain a longer gap for safety.

The α and β values are calibrated to reflect the relative importance of maintaining each lane's density at or under the critical level and balancing this against an acceptable number of lane-changing commands. The α weights are higher in the lanes towards the left to reflect the greater need to maintain the density at an acceptable level due to the influence of inflows from the on-ramp. The Set-Point Counts refer to the optimal vehicle count in each lane, from the left-most to the right-most lane. Initial values for the set-point counts are obtained through analysis of the FDs. These counts are then adjusted to create a density gradient across lanes whereby the lanes closer to the left side of the road have lower set-point counts. This is 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. The frequency at which the Proactive Control is activated is set at 12 s. This value is chosen to ensure that all AVs passing through the Proactive Section would be subjected to the control at least once. This control step size is also chosen to limit the computation load and over-control, while also representing a level of control that would be pragmatically applicable in real time for field implementation.

Table 2. Reactive control parameters.

Parameter	Value	Unit
Minimum Safe Lag Gap	4	metre
Minimum Safe Lead Gap	2	metre
Conflict Window	10	metre
Control Time Step	0.8	second

3.4. Reactive control

The Reactive Control is active in the next 100 m of the highway, downstream of the Proactive Section (see Figure 2). The control region for this control is smaller as this control operates much more frequently, focusses on local merging scenarios and is also sensitive to vehicle accelerations. Table 2 presents the parameters and the values used for this control. Determination of parameter values for this control is via the same methodology as the Proactive Control.

Note the minimum safe gap distances for the Reactive Control are lower than the Proactive Control to reflect the shorter time frame in which AVs are under this control, and hence a greater need to advise lane changes quicker and more aggressively. The conflict window is calibrated at 10 m (i.e. 5 m in front and behind of the merge location). This value provides the appropriate level of aggressiveness in lane-change advisory whilst not over-encouraging lane changing. 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 merge section and consequently follow their own lane-changing dynamics.

The proposed control strategy is formed by integrating the Proactive and Reactive Controls. This strategy is termed the Combined Control. Parameters for both components are kept the same as in their individual configurations.

4. Results

4.1. Single on-ramp case study

The TTT of each control strategy averaged over 10 replications is computed and compared against the baseline scenario (No Control strategy) to evaluate their relative performances. The average results for the scenarios is presented in Figure 3. The Combined Control is the main proposed control strategy in this paper that consists of the Reactive and Proactive Controls. The TTT accounts for all vehicles on the mainline and the ramp.

The baseline scenario TTT is 248.77 h. In comparison, the ALINEA ramp metering strategy TTT is 171.79 h that is 30.9% reduction. Both the standalone Reactive Control and Proactive Control strategies reduce the TTT, accordingly by 37.9% and 13.5%, resulting in a TTT of 154.44 h and 215.20 h. The Combined Control (i.e. the integration of Proactive and Reactive Controls) produces the greatest improvement in TTT of all strategies. The average TTT is 133.68 h, a 46.3% decrease from the baseline case – representing a 22.2% improvement over the ALINEA strategy.

From Figure 3, it can be seen that the majority of the travel time improvements seem to have come from the Reactive Control. There are two reasons for this. First, the Proactive Control requests a very small number of AVs to lane change, based on current vehicle counts, and override their on-board lane-change module. For example, if $n_i(k) = n_i^*(k)$ for every lane, then the controller will not advise any lane changes. In addition, the lane change of conventional vehicles is a disturbance that cannot be controlled (i.e. a suboptimal distribution of all vehicles is expected with low penetration rates). Second, the AVs would follow their individual (and possibly selfish) lane change procedure once they move outside of the Proactive Section which is upstream of the Reactive and Merge Sections. Hence the benefits of the Proactive Control are reduced as an isolated control. The success of the Combined Control

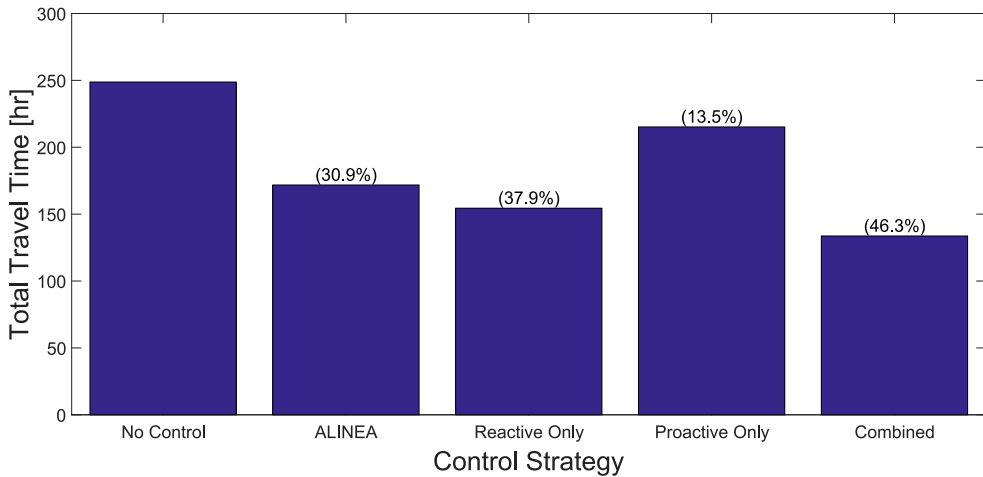


Figure 3. Total travel time of all vehicles (travelling on the mainline and ramp) for each control strategy – the Combined Control is the proposed strategy consisting of the Reactive and Proactive Controls. The values in parentheses represent the percentage improvement over the No Control Strategy.

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 number of lane change control actions from the Reactive Control due to fewer vehicles in the left-most lane. This results in a reduced number of lane changing closer to the merge section, minimising the local disruption to the traffic flow and providing more opportunity for ramp vehicles to merge to the mainline in a smoother manner.

Furthermore, the travel time distribution of individual vehicles for each control scenario is depicted in Figure 4. The replication with TTT closest to the average is selected for representation. The No Control scenario exhibits an average vehicle travel time (TT) of 71.6 s and travel time standard deviation (TTSD) of 32.4 s. ALINEA ramp metering is successful in reducing TT by 22.4% and TTSD by 33.5% with a TT of 55.6 s and TTSD of 21.5 s. The improvement in TTSD can be largely attributed to the controlled inflow of ramp vehicles into the main stream, reducing the variation in the ramp flow. However, it does so at the cost of increased TT for ramp vehicles as illustrated by the long tail of travel time distribution. The Combined Control is the most effective in terms of TT minimisation with a TT of 44.5 s and TTSD of 10.1 s, representing decreases of 37.8% and 68.9% compared to the No Control strategy. Thus the Combined Control not only improves the travel time but does so consistently, i.e. more reliable travel time which is a factor highly valued as low variation in commute times is of essential importance.

Figure 5 depicts the contour plot of lane densities in the No Control case where congestion begins to build up in all lanes around 25 min, coinciding with the increase in flow entering the system. This congestion begins to propagate backwards along the highway, reaching the beginning of the Proactive Section. After 90 min, the traffic demands begin to decrease (Figure 2) and this is reflected in the reduction in density and complete dissipation of congestion.

The effects of ALINEA ramp metering strategy are apparent in Figure 6. The onset of congestion begins at roughly the same time as the baseline scenario but is significantly subdued as illustrated by the lower densities throughout the entire duration of the simulation. However, the improvement in congestion at the bottleneck location is at the expense of larger queues on the on-ramp (a peak queue of 48 vehicles compared to 12). Figure 6 shows that on-ramp queue lengths are significantly greater with an active ramp metering strategy which is highly unfavourable for drivers on the on-ramp due to excessive delays and stop time.

The Combined Control is far superior as seen in Figure 7. Not only it is more effective in controlling congestion compared to ALINEA – demonstrated by significantly lower densities in the contour

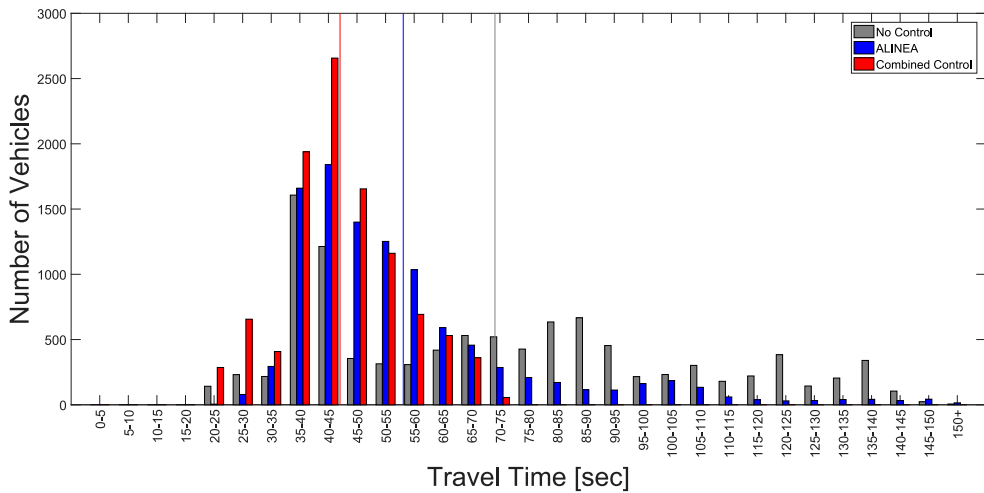


Figure 4. All vehicles' travel time histogram – the vertical lines represent the mean travel times for each control strategy. Note an overall reduction in travel time and travel time variance from No Control to ALINEA to Combined Control.

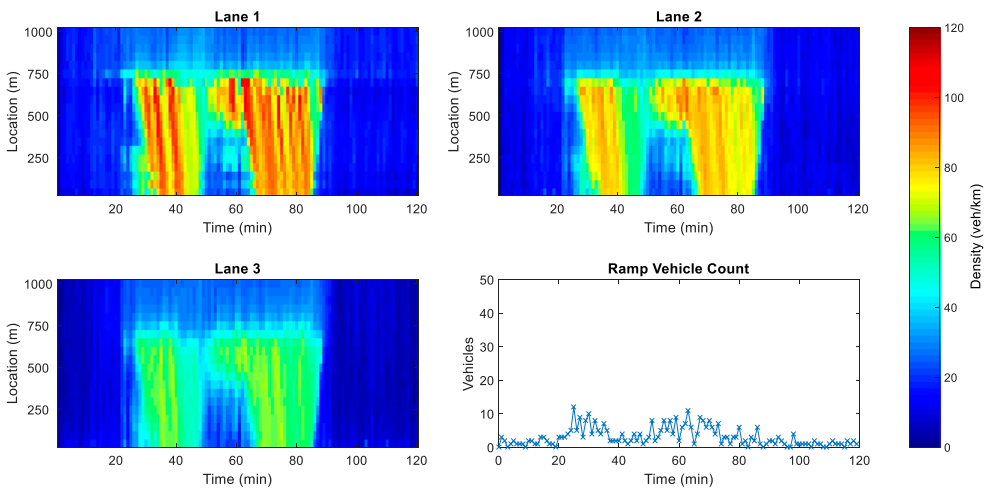


Figure 5. No Control: density contour plot for each lane and the number of vehicles on the ramp.

graph, but it also mitigates congestion without the drawback of creating excessive queues on the on-ramp. The AV lane change advisory is successful in controlling the vehicle density distribution in all lanes, with approximately equal density in every lane. It can also be seen that the right lane (lane 3) presents slightly higher density in comparison to the right lane in ALINEA, demonstrating better capacity utilisation of all available lanes.

The number of lane changes under each control strategy is presented in Table 3 (averaged over the 10 replications) and is divided into three categories: mandatory, discretionary and implemented. Mandatory lane changes only consist of the ramp vehicles which merge onto the main carriageway, hence the number of mandatory lane changing among the control strategies are similar. Implemented lane changes include successful lane changes as a result of lane change advisory provided to AVs. Discretionary lane changing makes up the remaining lane changes that AVs and conventional vehicles perform based on their driving mechanisms.

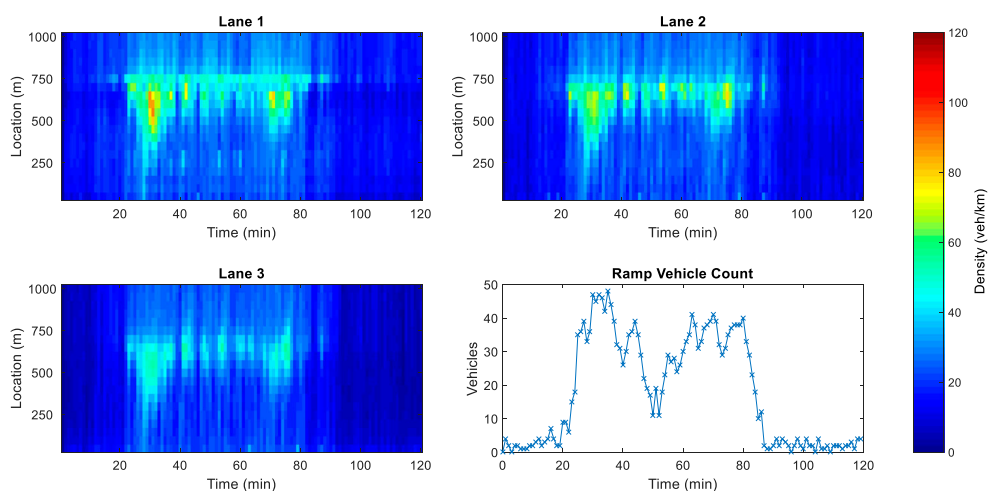


Figure 6. ALINEA: density contour plot for each lane and the number of vehicles on the ramp. Note the high number of vehicles on the ramp during the peak period.

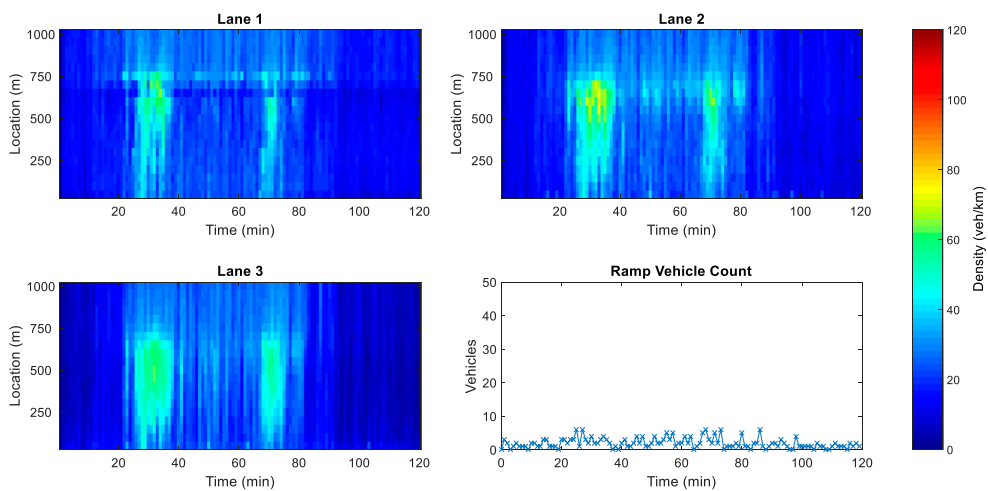


Figure 7. Combined Control: density contour plot for each lane and the number of vehicles on the ramp. Note more similar density profiles among all three lanes demonstrating better utilisation of capacity of all available lanes.

Table 3. Number of lane changes.

	No Control	ALINEA	Reactive	Proactive	Combined
Mandatory	10,997	10,996	10,997	10,999	10,998
Discretionary	6707	8301	7830	7170	8154
Implemented	0	0	530	1149	2099
Total	17,704	19,297	19,357	19,318	21,252

The number of discretionary lane changing is highest in the ALINEA scenario, followed by Combined Control. This can be attributed to the overall improvement in traffic flow, and hence, greater opportunities and space for drivers to perform lane change manoeuvres. The number of implemented lane changes is also higher in the Combined Control scenario compared to the sum of the Reactive Control and Proactive Control scenarios and this can be attributed to the same reasoning.

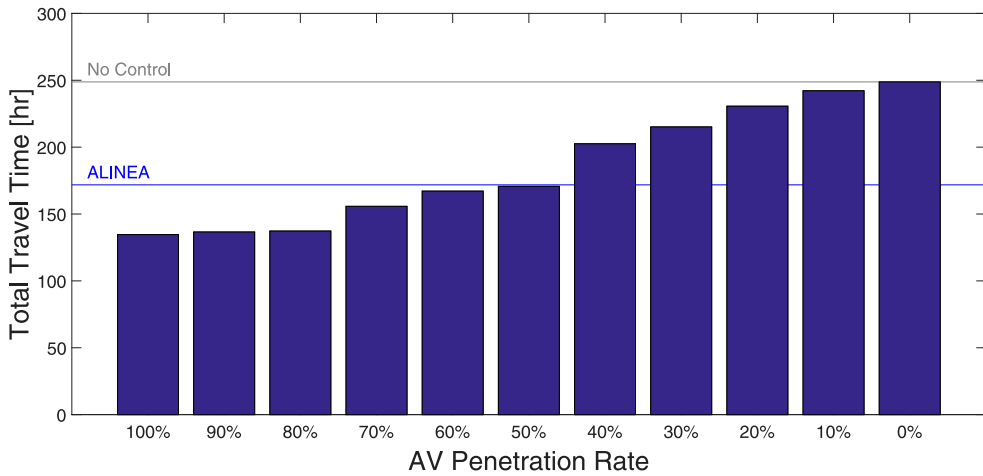


Figure 8. Total travel time for Combined Control strategy under varying penetration rates. For reference, the TTT for the No Control and ALINEA strategies are displayed in grey and blue respectively.

In consideration of the transition period where there is a mix of conventional vehicles and AVs on roads, the proposed control strategies are evaluated under varying AV penetration rates. For the Proactive Control, an estimation of the number of vehicles in each lane is possible, however, only AVs will receive and follow the lane change advisory. The central controller performs the same function as before but with a smaller group of candidates. For the Reactive Control, AVs continue to pre-emptively lane change accordingly. Conventional vehicles are unable to perform the control nor will they be able to engage in cooperative lane changing if AVs in the adjacent lane seek a lane change into their lane.

The Combined Control strategy is evaluated under varying penetration rates and the results are illustrated in Figure 8. For high levels of penetration, the control is still very effective. An average penetration rate of 80% results in an increased TTT of just 2%, from 134.60 h to 137.24 h, compared with 100% penetration rate. As the average penetration rate decreases further, the control starts to deteriorate, with increase in TTT.

In addition to daily traffic peak periods, overall traffic demand can vary greatly, influenced by factors such as seasonality, intra-week fluctuations and special events. To test the robustness of the control strategy and to assess the impact of varying demand levels, experiments are carried out with demands ranging from 10% less to 10% more in relation to the base demand levels outlined in Section 3 (see Figure 2). The ramp demand and highway demand are modified by the same percentage changes so that the ratio of ramp demand to highway demand is always constant. The TTT (h) is used as the measure of performance and the comparisons are presented in Figure 9.

As the demand decreases, the differences between the control strategies diminish. The Combined Control continues to present an improvement over the No Control scenario, with a 4.7% improvement in TTT for the 10% decreased demand. This improvement generally increases as the demand increases towards the base level.

As the demand continues to increase, the performance of ALINEA further improves in relation to both the No Control scenario and the Combined Control. From demand increases of 3% up to 10% (with the exception of 4%), the ramp metering strategy presents lower TTT compared to the Combined Control, with TTT improvements over the No Control scenario ranging from 43.2% to 58.5% and TTT improvements over the Combined Control from 1.1% (at a demand increase of 3%) to 40.6% (at a demand increase of 10%). These results highlight the limitations of the Combined Control at higher demand levels, due to lack of space for effective lane changing. With excessive demands, constraining vehicle inflow may be an imperative requirement to prevent overcrowding of the network.

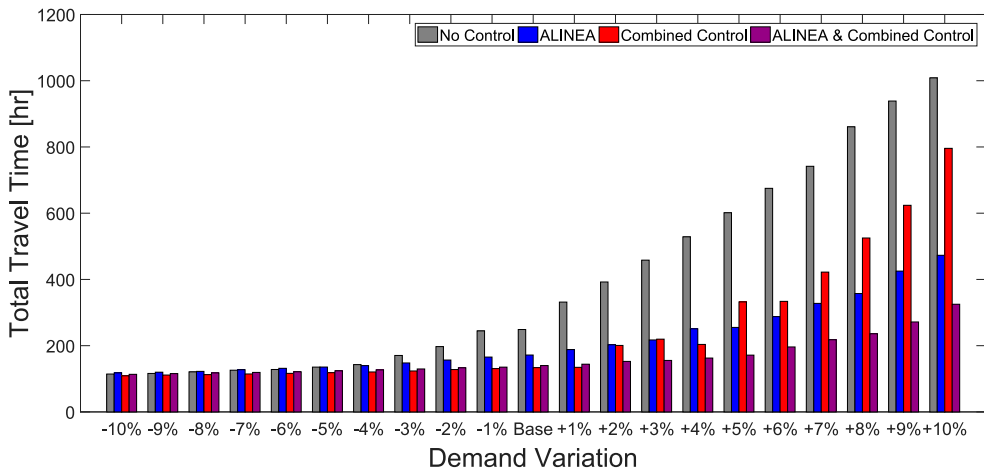


Figure 9. Total travel times for the No Control scenario (grey), ALINEA (blue), Combined Control strategy (red), and ALINEA & Combined Control (purple) with varying demand levels from 10% reduction to 10% increase.

This is when a combination of ramp metering and lane changing presents the most effective control. Experiments with both the ALINEA ramp metering strategy and Combined Lane Change Control are simultaneously run with no changes in parameter settings. At demand increases of 2% and higher, this new control displays substantial improvements in TTT. An improvement of 61.1% over the No Control case at 2% increased demand is observed, and this generally increases as demand increases with a 67.8% improvement over the No Control at 10% increased demand (a 31.3% improvement over ALINEA and 59.1% improvement over the Combined Control). This highlights the flexibility of the proposed lane changing control strategy and the potential for it to be integrated with existing strategies to further increase the effective capacity of the road and prevent the onset and severity of congestion.

4.2. Multiple ramps case study

The Combined Control strategy is also tested on a highway with five on-ramps and four off-ramps. Figure 10 illustrates the network setup and the demand profiles for the highway entrance and each of the ramps. The demand levels are constructed to create two active bottleneck locations, one at the middle of the road network and another towards the downstream end of the road network. At each of the off-ramps, 10% of vehicles exit via the off-ramp while the rest continue along the highway. The controller parameters for the single ramp network remain the same for the multiple ramp network. A baseline scenario is constructed (No Control) and ALINEA is again used for reference where the target downstream occupancy, \hat{o} , is decreased from 60% to 50% for better performance.

The TTT of each control strategy is computed and compared against the baseline scenario (No Control strategy) to evaluate their relative performances. The average results (over 10 replications) for the scenarios are presented in Figure 11.

The baseline scenario TTT is 1021.84 h. In comparison, the ALINEA ramp metering strategy is successful in decreasing the TTT by 36.9%, resulting in a TTT of 644.97 h. Both the standalone Reactive Control and Proactive Control strategies reduce the TTT. The Reactive Control reduces the TTT by 39.5%, resulting in a TTT of 618.46 h and the Proactive Control reduces the TTT by 15.7%, resulting in a TTT of 861.32 h. The Combined Control (i.e. the integration of Proactive and Reactive Controls) again produces the greatest improvement in TTT of all strategies. The average TTT is 587.99 h, a 42.5% decrease from the baseline case – representing a 8.8% improvement over the ALINEA strategy.

The travel time distribution of individual vehicles for the multiple ramp case is depicted in Figure 12. The No Control scenario exhibits an average vehicle travel time (TT) of 243.1 s and travel time standard

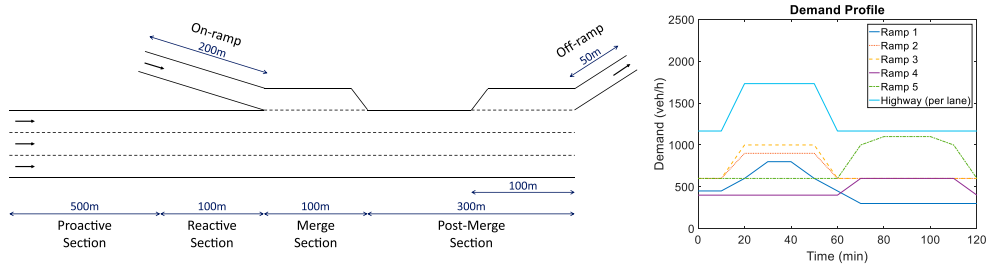


Figure 10. Left: Multiple-ramp road network – The network is the above illustration repeated five times. The last downstream section has no off ramp and continues as a three-lane highway (see the single ramp road network case). Not to scale. Right: Demand profile – the demand on ramps 1, 2 and 3 increases with the highway demand to create the initial bottleneck, demand on ramps 4 and 5 increases later in the experiment to create the second bottleneck downstream.

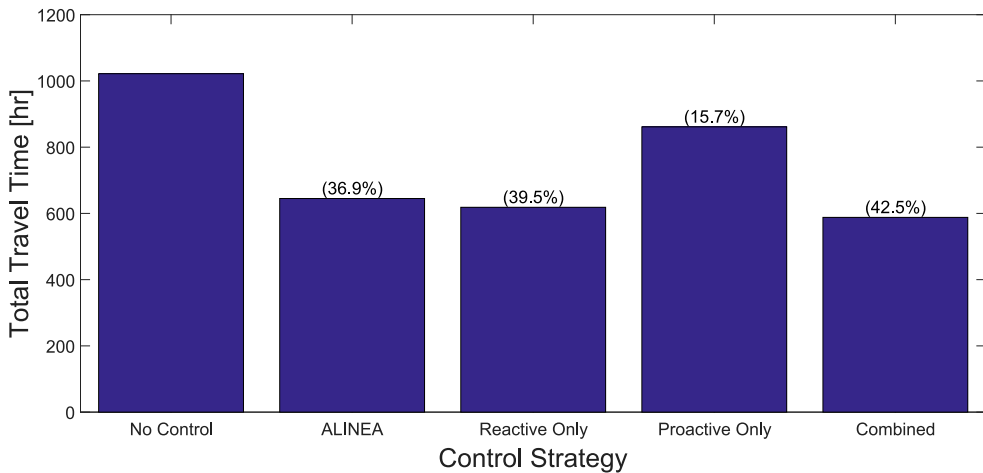


Figure 11. Total travel time for each control strategy for the multiple ramp case study – the Combined Control is the proposed strategy consisting of the Reactive and Proactive Controls. The values in parentheses represent the percentage improvement over the No Control Strategy.

deviation (TTSD) of 161.7 s. ALINEA ramp metering is successful in reducing TT by 36.9% and TTSD by 57.2% with a TT of 153.4 s and TTSD of 69.3 s. The Combined Control is the most effective with a TT of 140.4 s and TTSD of 70.2 s, representing decreases of 42.3% and 56.6% compared to the No Control strategy. The results are consistent between the single ramp case study and the multiple ramp case study. Overall, the Combined Control continues to display the greatest decrease in TTT, illustrating the scalability of the control to more complex road network.

Figures 13–15 present the density contours and vehicle counts on each on-ramp for the multiple ramp case study. In the No Control scenario (Figure 13), two areas of congestion are observed. The first instance of congestion begins to develop on the main carriageway near the third ramp, approximately 35 min into the simulation, propagating upstream of the network. A second area of congestion develops approximately 60 min in, albeit smaller, and propagates only one section upstream. It is also noted that an extremely large queue (up to 126 vehicles in size) forms on the last on-ramp. ALINEA is successful in reducing congestion as illustrated by the significantly lessened density. However, similar to the single ramp case, the trade-off of increased ramp queues arises as a result of the control. There is increased queuing on the second and third ramps, with maximum queues of 43 and 75 vehicles respectively. There is also queuing on the fifth ramp but it is much less compared to the No Control scenario with a maximum queue of 30 vehicles, illustrating the successful operation of ramp metering. The Combined Control is also successful in delaying and preventing the onset of congestion, while also

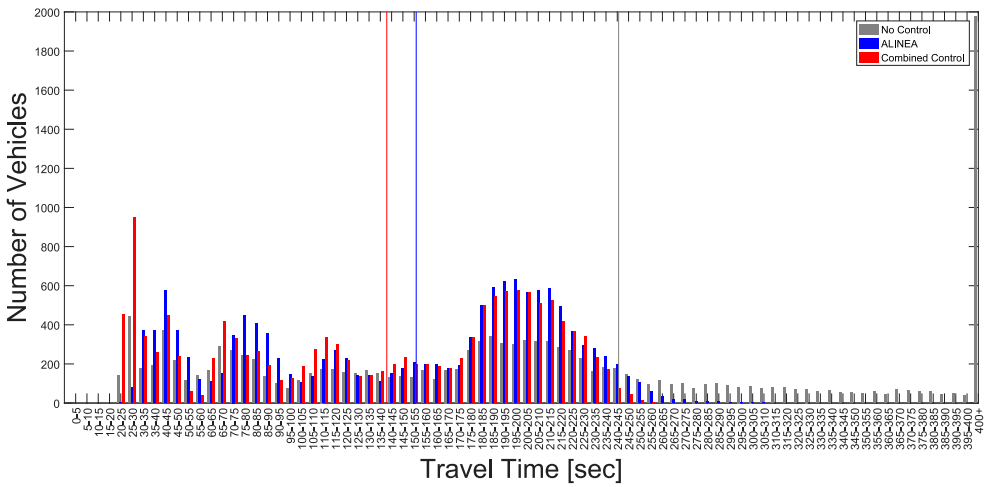


Figure 12. All vehicles' travel time histogram for the multiple ramp case study – the vertical lines represent the mean travel times for each control strategy. Note an overall reduction in travel time and travel time variance from No Control to ALINEA to Combined Control.

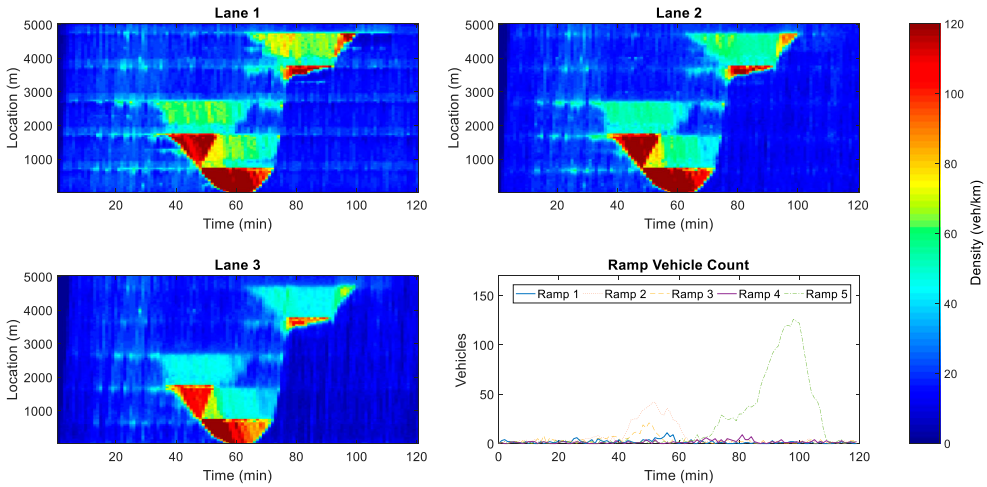


Figure 13. No Control: density contour plot for each lane and the number of vehicles on each of the on-ramps.

maintaining small on-ramp queues (maximum of eight vehicles over all ramps). Hence this demonstrates that the proposed control strategy can readily be applied to a network with multiple ramps. Further refinement of the strategy to cater for varying traffic characteristics between each on-ramp is a future research direction.

5. Summary and future research direction

This paper presents a two-level lane changing control strategy utilising the emerging capabilities of automated vehicles to improve traffic flow on highways in case of active bottlenecks such as on-ramps and lane drops (e.g. work zones). The strategy is composed of a first-level centralised control aimed at optimising vehicle density across lanes to balance the traffic flow among lanes and to reduce lane changing closer to the merge location. An optimisation problem is established and solved in real time to identify AV candidates to receive safe lane change advisory upstream of the merge section.

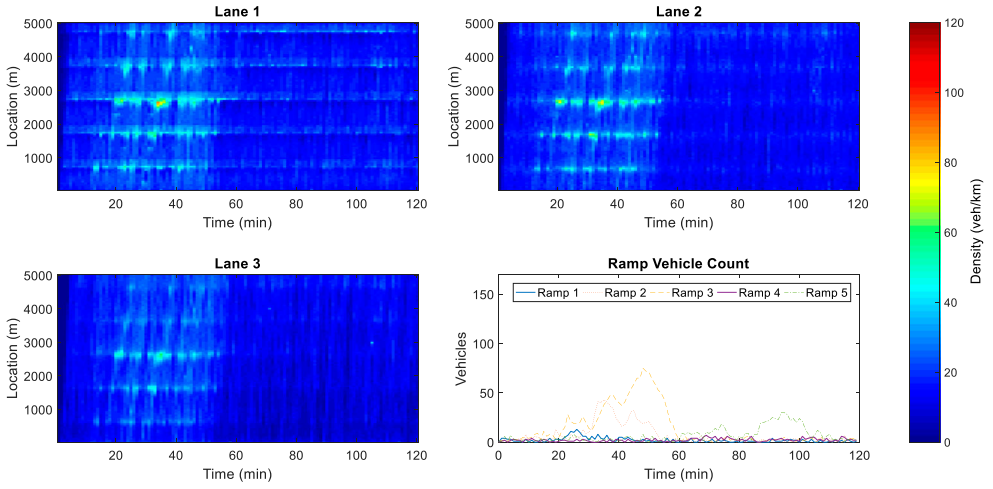


Figure 14. ALINEA: density contour plot for each lane and the number of vehicles on each of the on-ramps.

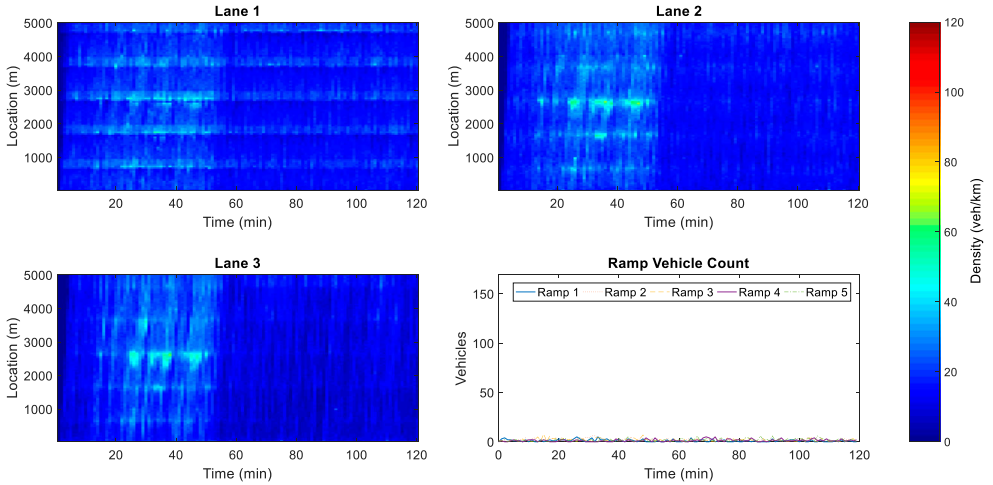


Figure 15. Combined Control: density contour plot for each lane and the number of vehicles on each of the on-ramps.

A second-level decentralised control is developed to predict and tackle merging conflicts via localised lane changing. This strategy facilitates merging onto the main highway stream through eliminating merge conflicts between ramp vehicles and AVs on the mainline and gap generation via targeted lane change advisory for AVs. The onset of congestion is delayed and mitigated with no increase in delay on the on-ramp.

The proposed control strategy provides a novel way of addressing and relieving congestion on highways using the enhanced capabilities of automated vehicles over conventional vehicles. The control strategy presents improvements in traffic flow compared to the baseline scenario and against ALINEA ramp metering strategy in the form of reduced total travel time and travel time variation among vehicles travelling on the mainline and ramps. It is worth mentioning that the proposed control outperforms ALINEA at the base demand level and for minor increases in demand, effectively increasing the potential capacity of the infrastructure. However, as the input demand exceeds the enhanced capacity, ramp metering displays superior performance as the input demand is constrained below the maximum capacity of the highway.

With mixed traffic, composed of both AVs and conventional vehicles, the control strategy continues to exhibit improved performance over the baseline case, illustrating the potential of this strategy in the early stages of AV uptake. The control strategy is also tested on a road network with multiple on-ramps and off-ramps. A similar result is observed, with ramp metering strategy successful in mitigating congestion by constraining on-ramp inflow and subsequently increasing ramp queues, and the proposed control strategy successful in mitigating congestion whilst also maintaining acceptable ramp queues.

The proposed AV lane change control strategy reduces congestion on the highway, irrespective of the characteristics of AVs and conventional vehicles. Avenues for future research include integrating the proposed lateral traffic control strategy with longitudinal control methods (analogical to variable speed limit methods, e.g. SPECIALIST (Hegyi et al. 2008), at the scale of individual AVs) to achieve further improvements. However, this integration may lead to complex and intertwined changes to traffic dynamics at both micro and macro levels (e.g. variations in FD characteristics with different AV penetration rate and configuration of AVs in the traffic stream; Ramezani et al. 2017). Nevertheless, these changes in traffic dynamics can be modelled and estimated with real-time measurements.

For the Proactive Control, the set-point counts are determined offline via a conservative assumption of the ramp density corresponding to peak ramp flow. The control strategy can be improved by augmenting predictive capabilities to the control strategy and through dynamic updating of the current ramp flow to predict more realistic set-point counts and further minimise lane changing in the Proactive Section. Second, it may be worthwhile to explore the combination of multiple strategies such as ramp metering or longitudinal control with this lateral control to improve the performance of the control for a wider range of demands. Finally, this paper assumes that the detection of AVs is perfect. Experiments incorporating a noise element whereby the number of AVs differ from measured values will make for a more robust and adaptable control.

Disclosure statement

No potential conflict of interest was reported by the authors.

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