Integrated lane change and ramp metering control at motorway merges

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INTRODUCTION

Traffic congestion on motorways is a major societal problem and merging sections are one of the common bottleneck sources on motorways. Merging sections are prone to congestion because of the conflicts between the on-ramp and mainline traffic. These conflicts lead to many negative phenomena such as oscillations, increasing travel times for the road users and a drop in the queue discharge rate after the onset of congestion – more commonly known as capacity drop (Bertini & Malik (2004), Ahn & Cassidy (2007). Ramp metering has been extensively used to control the on-ramp flow entering the mainline and avoid or delay the onset of congestion on the mainline. But ramp metering alone is ineffective when the traffic demand is high.

Mandatory and sub-optimal lane changes near merging sections are one of the primary reasons for reduced traffic flow efficiency at merging bottlenecks. This can be improved by encouraging more discretionary and courtesy lane changes in advance of the on-ramp so that the conflicts between mainline and ramp traffic are avoided. By combining a lane change control measure with the existing and well known ramp metering concept, delays on the mainline and on-ramp can be controlled according to the respective demands and prevailing traffic conditions. In this study, we evaluate the performance of an integrated lane change and ramp metering control to reduce the travel times and improve the traffic flow efficiency for a merging section. Lateral flows upstream of the merge on the mainline are controlled to create more space for the on-ramp demand and this is combined with a ramp meter which is used to regulate the on-ramp demand entering the motorway. An optimization based framework is used to determine the lane change rates upstream of the merging area for the lane change control and the well-known ALINEA algorithm (Papageorgiou et al. 1991) is used for the ramp metering. The developed control scheme is evaluated via simulation experiments using an incentive based first order lane-specific traffic flow model.

SYSTEM MODELLING

Lane-specific traffic flow model

An incentive based first-order traffic flow model is used to test and compare the performance of the proposed control measure. The authors refer to Nagalur Subraveti et al. (2019) for a complete description of the model. A brief description is provided here. The starting point of the model is the well-known cell transmission model (Daganzo 1992) which is extended to include the lane change dynamics. A multi-lane motorway subdivided into cell segments, wherein each cell comprises of a number of lanes is shown in Figure 1. The cell segments are indexed i = 1,2,3….n and the lanes as l = 1,2….m.

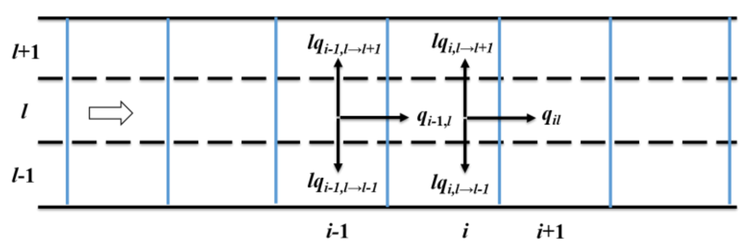

Fig 1: Representation of the discretized motorway

Using the notations from Fig 1, the conservation equation in discrete terms is given by:

$$k_{il}(t+1) = k_{il}(t) + \frac{\Delta t}{\Delta x}\left[q_{i-1,l}(t) - q_{il}(t) + r_{il}(t) + lq_{i,l-1\to l}(t) + lq_{i,l+1\to l}(t) - lq_{i,l\to l-1}(t) - lq_{i,l\to l+1}(t)\right] \quad (1)$$

In equation (1), k and q represent the density and flow of the cell-segments respectively. Δt is the size of the time step and Δx is the length of the cell segment. lq denotes the lateral flow between the cell segments. t denotes the simulation horizon t =1,2,3…..,T where the total simulation time is given by t_{sim} = T. Δt. A triangular fundamental diagram (FD) is used for computing the lateral and longitudinal flows. The fraction of flow with a desire to change lanes is computed as a function of various incentives (I) such as the density difference among lanes maintaining route, keep-right bias and cooperation.

The fraction of flow with a desire to change lane from l to l' is given by:

$$P_{i,l\to l'} = max\left[0, \frac{IK_l - K_{l'}}{K_l + K_{l'}}\right] \tag{2}$$

The model is extended to include the effect of merging location from the acceleration lane to the mainline motorway which is generally not considered in existing macroscopic traffic flow models. Lane changing from the acceleration lane to the mainline motorway is modelled in such a way that a major portion of the merging occurs in the initial half of the acceleration lane as observed in empirical studies such as Daamen et al. (2010) and Marczak et al. (2013).

Ramp metering algorithm

The aim of the ramp meter is to restrict the on-ramp demand entering the motorway. The benefits of applying ramp-metering at motorway merge sections in improving traffic flow efficiency and stability has been observed in multiple studies. ALINEA developed by Papageorgiou et al. (1991) is one of the most popular local feedback control ramp metering strategies used. In this study, D-ALINEA is used which uses density as the target variable instead of occupancy. This is a preferable option since traffic densities are the state variables of the traffic flow model. In D-ALINEA, the number of vehicles allowed to enter the motorway is given by:

$$r(t) = r(t-1) + K_R[\hat{k} - k(t-1)] \tag{3}$$

where $\hat{k}$ is the desired density which can be derived from the critical density as $\hat{k} = \xi k_{cr}$ with $\xi \leq 1$. Here, we assume $\xi = 0.9$. The density measurement used in Eqn. (4) is the density on the mainline at the mid-point of the acceleration lane as majority of the merging occurs in the initial half of the acceleration lane and strong congestion is expected at this location. In the simulations, constraints on the maximum (1500 veh/h) and minimum (300 veh/h) allowable flow were set on the ramp-metering algorithm. The flows are metered every 1 minute in this study.

PROBLEM FORMULATION

Objective function and optimization approach

The aim of the optimization algorithm is to find lateral flows which can minimize the Total Travel Time (TTT) of the system. Terms representing delays at the entrance of the mainline and on-ramp are included in the objective function. The objective function is given as follows:

$$J = \int_0^t \Delta N . dt + \int_0^t \Delta N_{q,m} . dt + \int_0^t \Delta N_{q,r} . dt \tag{4}$$

where N is the number of vehicles in the section, dt is the simulation time step, t is the total simulation time and $\Delta N_{q,m}$, $\Delta N_{q,r}$ are the number of vehicles queuing at the origin of the mainline and on-ramp respectively due to limited receiving capacity at the entrance of the section. The first term of the objective function represents the travel time within the section and the second and third terms represents the delay (or time spent waiting) caused by the formation of queues at the entrance of mainline and on-ramp respectively.

The MATLAB implementation of the Sequential Quadratic Programming (SQP) algorithm (fmincon) is used to solve the optimization problem.

Lateral flow control

The optimization algorithm attempts to find ideal lateral flows among lanes in order to minimize the TTT of the system. The lateral flows can be influenced in both directions (i.e. from left to right and right to left). In the case of on-ramps, controlling the lane changes from left to right are not of high importance because vehicles are generally apprehensive to change lanes to the right near merging sections. Hence, for simplicity, only lateral flows towards the left are controlled and lane changes from left to right upstream of the on-ramp are considered to be negligent (zero in this case).

The decision variable chosen for the optimization problem is the fraction of flow wanting to change lane $(P_{l\to l'})$ given by Equation (2). The advantage of selecting this variable is that it directly influences the lateral flow via equations (7) and (8) and the constraints for this decision variable can be easily set as the fraction can only vary between 0 and 1. Lateral flows need to be within the bounds of demand of the origin cell and supply of the receiving cell which are dependent on the dynamically varying density of the cell. If the lateral flow is chosen as the decision variable, then the constraints become dynamic varying with each iteration of the optimization process which can increase the computation time. By choosing the fraction of flow as the decision variable, this problem is easily circumvented.

NETWORK DESCRIPTION AND DEMAND PROFILE

A hypothetical motorway stretch is considered to evaluate the performance of the proposed control measure. The benchmark network is shown in Fig 2. The network is divided into 3 segments. Segment A-B is the mainline section upstream of the on-ramp. Segment B-C consists of 3 mainline lanes and an acceleration lane approximately 280 m long (similar to the lengths of acceleration lanes observed on Dutch motorways). The section downstream of the acceleration lane is labelled as segment C-D. The point where the on-ramp intersects with the mainline motorway is labelled as merging point. The ramp metering installation is assumed to be present at this location. The shaded region in the figure on the mainline represents the LC control zone where the lane changes are controlled.

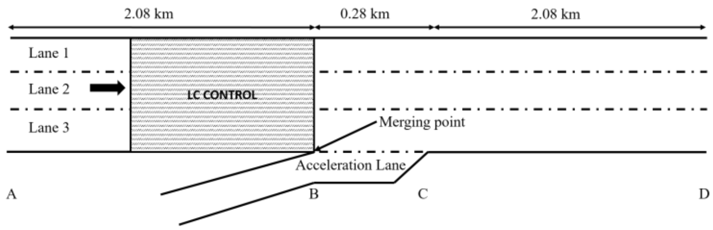

Fig 2: Benchmark network

The demand profile for the mainline and on-ramp chosen for this study is shown in Figure 3. Both demand profiles follow a similar trend. The demand is stopped after 20 minutes and the simulation is run for another 10 minutes to allow all vehicles to exit the section. The overall demand (mainline and on-ramp demand combined) slightly exceeds the capacity during this peak period. Thus, the traffic conditions in this period downstream of the merge point are on the right side of the fundamental diagram and near the top.

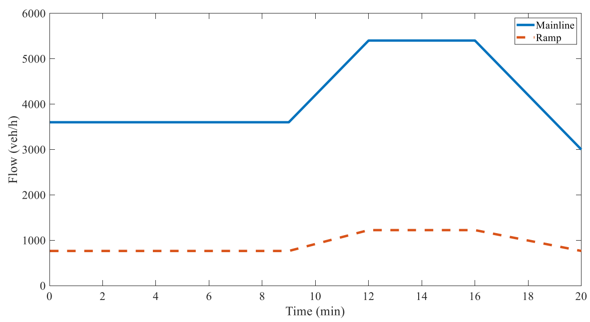

Fig 3: Demand Profile

RESULTS AND DISCUSSIONS

The solutions for the lateral flow obtained from the optimization framework are combined with the ramp metering algorithm described in the previous section. Integration of the lane change control with ramp-metering leads to a minor reduction (~0.6 %) in the TTT of the system compared to the no control case. However, the interesting point of observation is the distribution of delays across the mainline and on-ramp. Fig 4 shows the comparison of the delays observed on the two traffic streams.

The total delay in this case was observed to be distributed evenly on the mainline and on-ramp. The integrated control takes into account the distribution of delays and the fairness between the mainline and on-ramps. In the integrated setup, the ramp meter controls the inflow to the mainline while space for this metered flow is created via the lane change control where the mainline flow on the right lanes are directed to the left lanes. For the chosen demand profile, as the ramp and mainline demands increase simultaneously at the same rate, the lane change rates obtained via the optimization framework and the RM settings lead to approximately similar delays upstream of the mainline and on-ramp. However, the delays across the mainline and on-ramp can be controlled in this integrated setup by changing the parameters of the ramp metering control which can change the distribution of delays.

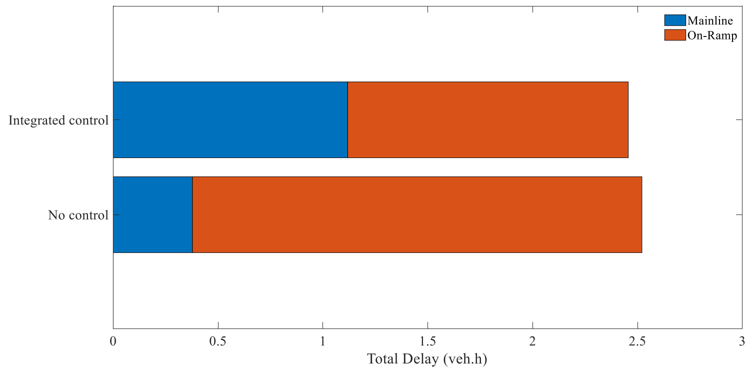

Fig 4: Comparison of delays on the mainline and on-ramp

For example, higher values of the regulator parameter can lead to the metered flow from the on-ramp to be reduced leading to a comparatively higher delay and queue length at the entrance of the ramp. But this leads to a decrease in the number of lane changes on the mainline resulting in lower delay on the mainline. Similarly, increasing the number of lane changes towards the left lanes can cause higher delays on the mainline but this creates gaps on the shoulder lane leading to smoother merging process for the on-ramp demand.

Fig 5 shows the variations of the delays on the mainline and on-ramp for different K_R (regulator parameter in the feedback equation) and lateral flow values. The values on the horizontal axis represent the percentage contribution of delay over each section to the total delay. In the first plot, it can be seen that as the value of K_R increases, more on-ramp demand is metered leading to queue formation upstream of the merge point on the ramp and consequently, higher delay. As the flow entering from the on-ramp is heavily metered, flow entering on the mainline is greatly reduced which causes the delay on the mainline to decrease due to less conflicts with the incoming ramp vehicles.

In the second plot of Fig 5, the vertical axis represents increasing lane change rates towards the left lanes with 1 representing the optimal solution. The lane change rates are varied by multiplying the optimal rates with an increasing factor. When lane change rates towards the left are increased, the delay on the mainline is increased due to the high lane changing activity. This however creates enough space on the right-most lane for the on-ramp demand to merge easily. This leads to the delay on the on-ramp to reduce.

Figure 6 shows the flow that is in queue upstream of the merging point on the ramp due to the onset of congestion on the mainline and acceleration lane. It can be seen that during the peak demand, the flow in queue is high in the no control case. In the ramp metering case, queue formation starts earlier and reaches the same peak value as in the no control case. However, in the integrated control scheme, though the queue length is for a comparatively longer duration compared to the no control case, it is never too high which can be beneficial in controlling the queue length on the on-ramps.

Thus, based on the incoming demand on the two traffic streams, the lane change and ramp-metering control can be tuned accordingly to avoid heavy congestion on either stream. If the demand on the ramp is high, lane change control can be used to direct flow away from the right lanes and create space. And when the mainline demand is high, ramp metering can be used to control the flow entering the mainline. The integrated lane change and ramp-metering control presents opportunities for the road authorities to control the distribution of overall delay across the two traffic streams.

CONCLUSIONS

The main objective of this study was to evaluate the performance of an integrated lane change and ramp metering control for high demand scenarios at motorway merges. An optimization problem was formulated to determine the lane change rates upstream of the merge area on the mainline of a multi-lane motorway. This was combined with the density based ALINEA which used the density downstream of the merge area as the measured variable. The control scheme was evaluated via simulation experiments using an incentive based lane-specific traffic flow model. It was observed that the integrated case resulted in a slight reduction in the total travel time of the network. But the manner in which the total delay upstream of the merge was distributed varied from the no control case. Considering similar rate of increase in the demands on the mainline and on-ramps, the integrated control lead to similar delays over the two traffic streams. However, these delays could also be regulated by changing the parameters of the integrated control measure. The findings reveal an potential insights into the possibility of controlling the distribution of total delay over the two traffic streams and the choice in terms of prioritizing between mainline and on-ramp control based on their respective demands.

There are multiple interesting future directions which include investigating the robustness of the integrated control setup for a variety of demand profiles and traffic conditions as well as consider mixed traffic involving Connected Autonomous Vehicles (CAVs). Furthermore, the study is currently restricted to isolated merges and extensions to multiple on-ramp sections with coordinated lane change and ramp metering will be explored.

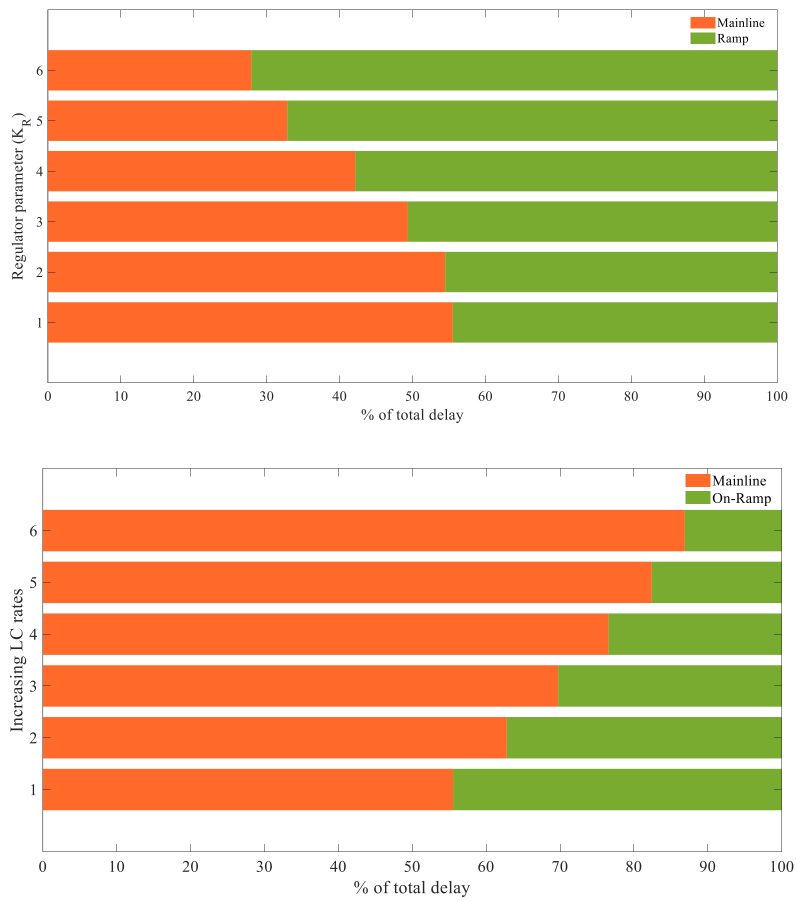

Fig 5: Variation in delays with changing control parameters

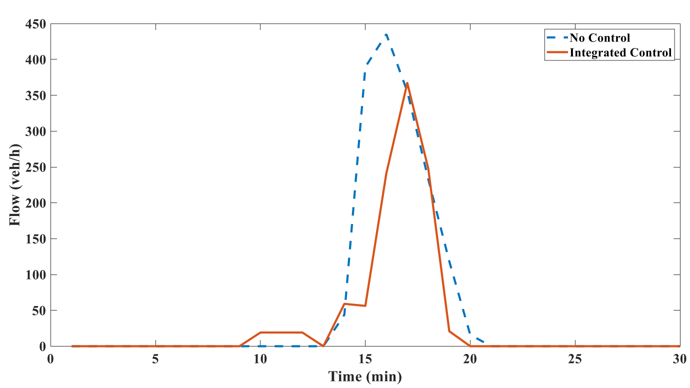

Fig 6: Flow in queue upstream of the on-ramp

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