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Mahajan, Niharika; Hegyi, Andreas; Hoogendoorn, Serge; van Arem, Bart

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Optimal lane guidance for improving traffic efficiency on homogeneous freeway sections

N. Mahajan*, A. Hegyi, S. P. Hoogendoorn and B. van Arem

Department of Transport and Planning
Delft University of Technology, The Netherlands
*Corresponding author: n.mahajan@tudelft.nl

1 Introduction

Participation of vehicles in traffic is largely self-interested. This holds also for lateral movements, wherein rational drivers try to make lane changes that maximize their own individual utility, such as keeping a desired speed, lane or route. However, the sum effect of all individual lane changes may not necessarily be optimal for the overall traffic efficiency [Ahn and Cassidy, 2007, Duret et al., 2012]. Intelligent vehicle technologies can be used to design more safe and efficient systems, for individual vehicles but also for the overall system. Specifically, with lane keeping and lane change assistance systems already in the market, modelling and control of lateral behaviour under different driving situations, such as free lane changing, merging and overtaking, has regained attention in traffic research.

From a modelling perspective, the research focus in literature is on microscopic models for lane change decision-making [Hidas, 2002, Kesting et al., 2007], their integration with car-following models [Schakel et al., 2012, Toledo et al., 2007], and on modelling the effects of lateral movements on the dynamics of the subject and surrounding vehicles [Laval and Leclercq, 2008, Schakel et al., 2012]. From a control perspective, different approaches are being developed, some at the operational-level: for planning and tracking reference trajectory for a lane change manoeuvre [You et al., 2015], at the tactical-level: for optimizing lane selection or when and where a lane is performed [Talebpour et al., 2015, Wang et al., 2015], and others at the strategic-level: for optimizing lane distribution for a higher system objective [Roncoli et al., 2016, 2017].

In this work, we are interested in (strategic) lane guidance systems that aim to improve network performance. There are very few studies that aim to do so, mostly because existing lane change models are not suitable for estimating/predicting effects of individual lane changes on overall traffic. Recent work of Roncoli et al. [2016] addresses this gap by developing a macroscopic model for multi-lane traffic with aggregated lateral flows, and a strategy for optimizing traffic distribution over the lanes at freeway bottlenecks. The control mechanism used in their work relates to preventing loss of speed from increasing lane densities. In contrast, we develop a microscopic framework for controlling individual lane change decisions for maximizing traffic throughput on homogeneous freeway sections. The novelty of our control approach is that it takes into account the desired speeds of individual vehicles. Thus, the resulting lane distribution may not necessarily homogenize flow distribution over the lanes but instead distributes vehicles such that the blocking effect from slower vehicles (with relatively lower desired speeds) is minimized. The approach in its current formulation is not applicable to all demand levels, and therefore, the traffic conditions under which it is applicable are also discussed in Section 4.

2 Inefficiency in lane use

The leading incentive for discretionary (free) lane changes relates to the desire of vehicles to travel at their desired speeds. While individual utility gains are expected, the resulting lateral manoeuvres do not always improve the traffic situation for the surrounding vehicles. A typical inefficiency occurs when a lane changing vehicle hinders following traffic on the target lane (after the lane change). This happens when the average speed on the subject vehicle's current lane (before the lane change) is lower than its desired speed, so it is incentivised to change lanes. However, the vehicle's desired speed is lower than the average speed on the target lane, resulting in a blocking effect. Such desired speed-driven lane use behaviour is theoretically examined in Daganzo [2002]. Thus, a system-optimal lane use strategy may require some vehicles to refrain from lane changes that would improve their individual utility but that would be detrimental for overall efficiency. At the same time, it may also require other vehicles to execute lane changes that do not improve their individual situation, for instance by accepting a target speed that is lower than their current speed on the subject lane, for the sake of system benefits.

3 Control approach

In this work, we propose a model-based feedback control approach for optimizing lane use on a homogeneous stretch of freeway. The controller uses a parsimonious model for describing the speed of vehicles on a given lane. In this model, the effective speed of a lane is given by the speed of the slowest vehicle driving on it. The model adequately captures the effect of (undesired) lane changes that reduce the average speed on the target lane. However, its accuracy depends on the position of the slowest vehicle and the number of vehicles on a road segment. The assumption is expected to be accurate for a small road section with a few vehicles, where there is a reasonable probability that the slowest vehicle blocks majority of the other vehicles. We will test the accuracy of this model assumption in simulation.

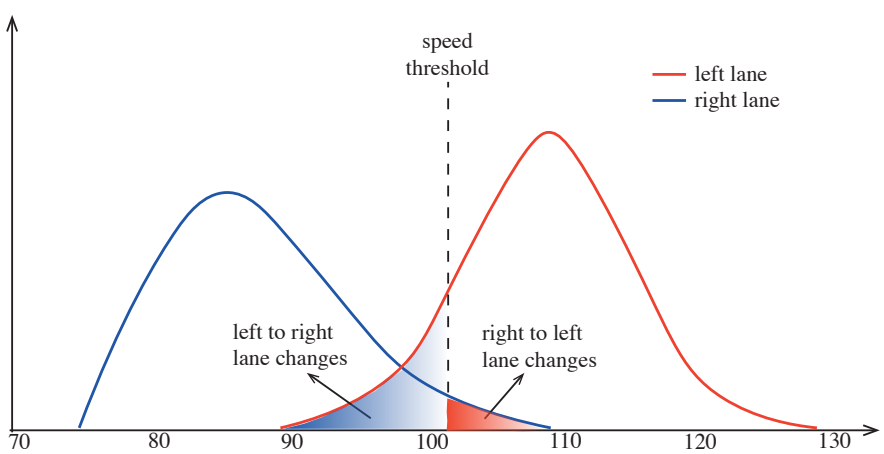

Figure 1: Desired speed distribution functions per lane for a hypothetical 2-lane section, showing the concept of threshold speed.

The control signal of the lane guidance system will be a minimum speed threshold per lane, denoted as $u(k) = [u_1, u_2, ..., u_i, ...u_I][km/h]$. Subscript i is the lane index; the right-most lane has an index 1 and the left-most lane has an index I. The control system is discrete-time, and the optimal control signal u^* is re-evaluated at fixed time intervals. We assume European driving rules, which means that vehicles keep to

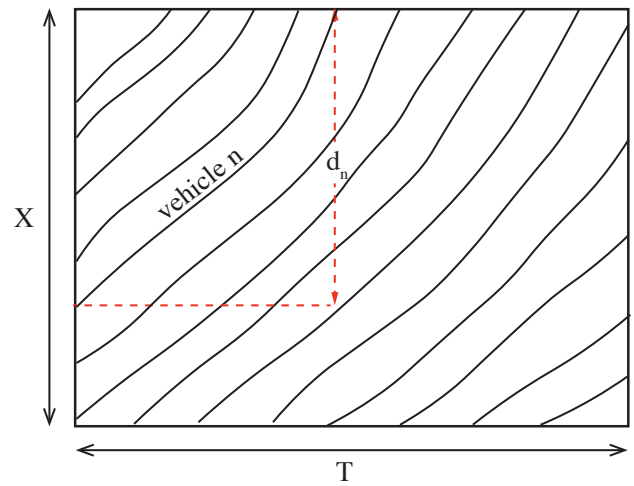

Figure 2: Vehicle trajectories in space-time region (X-T) showing the variables used in Eddie's generalised definition of flow.

the right and use the passing lanes for overtaking and when necessary due to traffic condition. The concept of a lane-specific speed threshold is explained in Figure 1; vehicles on the lane i with desired speed lower than u_i are instructed to changes lanes to the right, and those with desired speed higher than u_{i+1} to change to the left. The threshold values u_1 and u_{I+1} by default take values 0 and inf, respectively. Thus, the optimal speed thresholds (given the current distribution of desired speeds over the lanes) dictate the lane changes necessary to realise the optimal lane use.

The control optimization problem is formulated to maximize total traffic flow. We use the Eddie's generalised definition of flow (refer to Figure 2), which defines flow for a region in space and time as compared to at a fixed location (as measured by loop detectors). Flow in a region of length X and duration T depends on the distance d_n a vehicle with index n travels, and area of the space-time region:

$$q = \frac{\sum_n d_n}{XT} = \frac{D}{XT}. \tag{1}$$

Therefore, maximising the numerator, i.e. the total travelled distance D, over a chosen optimization horizon will maximize traffic flow. D can be calculated with the vehicle kinematic equations, as a function of vehicle speed v_n and acceleration a_n. Total travelled distance D can then be given as:

$$D = \sum_n \left(v_n T + \frac{1}{2} a_n T^2 \right). \tag{2}$$

For a short control interval T (in the order of a few seconds), the second term in the above equation can be ignored. Note that v_n is the effective speed of the vehicle as determined by the lane speed model. The resulting optimization problem can be mathematically defined as:

$$\begin{aligned} \underset{u}{\text{maximize}} \quad & f(u, v_n) \\ \text{subject to} \quad & 0 < u_i \leq V^{max},\ i = 1, \ldots, I \\ & u_i \leq u_{i+1} \\ & \eta_i \leq \eta_i^{max},\ \eta_i \in \mathbb{Z}^+. \end{aligned}$$

Here, the objective function f is the total distance travelled D given that speed thresholds u are active, and that vehicles can execute the necessary lane changes. The estimate D assumes that the vehicles that are required to change lanes can find a suitable gap to do so. If in reality, some vehicles can not make the necessary lane changes, the (measurement)-feedback controller would keep or give similar speed thresholds in the next time-step. The first constraint limits the threshold values to be positive but below the the legal speed limit V^{max}. The second constraint ensures that the speed thresholds are increasing, from the slowest to the fastest lane. Finally, the last constraint guarantees that the total number of vehicles on a given lane η_i does not exceed the maximum lane occupancy η_i^{max}. In this way, the controller determines the optimal lane-specific speed thresholds at every control time-step, over time resulting in a lane distribution optimized for traffic efficiency.

4 Application conditions

Given the modelling assumptions, the control framework is expected to be effective in near-saturated traffic conditions, and given that there are sufficient gaps in order to realise the recommended lane changes at a future time. When the flows are relatively low, fast vehicles use the right lane, but can still keep their desired speeds by using the left lane to overtake the slower vehicles. In this situation, the controller would still try to segregate the fast moving vehicles from the slow right lane, because of the assumption that the slowest vehicle on a lane dictates its effective speeds. So even though the faster vehicle can drive at their desired speeds (due to sufficient space and overtaking opportunity), our model would have underestimated the vehicles' effective speed. In short, the flow should be high enough that vehicles have car-following behaviour, but not over-saturated that the slowest vehicles can not drive at their desired speeds. The modelling assumptions and the demand range for which the approach is useful, will be evaluated in simulation.

5 Simulation-based analysis

The aim of the simulation-based analysis is threefold: one, to evaluate the potential flow improvement achievable from real-time optimization of lane change decisions for system performance; two, to test the modelling assumptions for estimating the effective lane speed, total travelled distance D, and compliance; and three, to examine the traffic conditions under which the control approach is effective. To that end, the lane advice system will be implemented in VISSIM microsimulation tool. This means that the designed controller will override the desired lane changes determined by the default lane change model in VISSIM. The controller performance will be compared to 2 other microscopic models: (1) VISSIM as the base lane change model, and (2) MOBIL ('minimizing overall breaking induced by lane changes') as the decentralised (local) counterpart of the proposed centralised controller [Kesting et al., 2007]. The latter model uses acceleration of the subject vehicle, weighted using a 'politeness factor' with the accelerations of its current follower and the target follower, to determine the attractiveness of a potential gap. The politeness factor then allows to model cooperative behaviour where the subject vehicle considers the effects of the lane change on its neighbours into its decision-making. Moreover, altruistic lane changes can be modelled by tuning the model parameters properly. Comparison with the MOBIL model then allows to evaluate the performance difference that results from considering the effects of a lane change on all vehicles (in the control region) as compared

to just the immediate neighbours. The results that follow will be a basis for further development of the controller design, and potentially for deriving self-organisation principles for system-optimal lane change decisions.

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