On the Empirical Parametrisation of a Simulation Model for Platooning on Single-lane Roads

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1 Introduction

On two-lane single carriageway (known as S1) roads, the lack of safe overtaking opportunities results in faster vehicles becoming trapped behind slower ones. We develop and analyse a new parsimonious model designed to investigate the resulting platoon formation and overtaking manoeuvres. The model is microscopic, capturing the key requirement of driver heterogeneity — both in terms of drivers' *desired speeds* and their propensities to overtake. Comparing this model with classic literature from both Wardrop [1] and Daganzo [2] provides evidence that our model retains the required complexity to predict traffic behaviour. We anticipate that the body of theory we present may be used in future to help inform decisions and support policy decisions regarding the dualling of S1 roads.

Three level of service (LOS) metrics are used to measure the complex emergent dynamics in our simulations: i) percentage time spent following (PTSF); and distributions across the vehicle population of ii) average speed and iii) overtaking rates. Roads with high PTSF and low overtaking rates are candidates for dualling.

Other interventions in future might involve the use of connected and autonomous vehicles (CAVs) providing multiple benefits through regulating driver assist functions; and / or centralising the coordination of platoon formation / overtaking opportunities. Platooned vehicles are unable to overtake when the opposing lane is fast-moving with short distances between consecutive vehicles. By proactively forming platoons in the opposing lane, vehicle-free regions appear promoting safe overtaking opportunities. These vehicle-free regions can be further increased with sequences of CAVs that can safely maintain shorter distance headways, reducing a platoon's total spacing. This holistic approach to traffic management reduces the need for new infrastructure (i.e., dualling).

2 Modelling

Our model consists of two parts: i) a longitudinal model — which can be thought of as a kind of first-order car-following model capturing the platoon dynamics; and ii) an overtaking model — capturing the decision making process, propensity to overtake and execution of the manoeuvre itself.

We define a platoon to be a contiguous group of vehicles travelling at the same speed, namely the desired speed of its leader. Thus when a vehicle is following in a platoon, it travels slower than its own desired speed. Whilst there is no single definition of following in the literature, most papers adopt an approach using a single critical time headway that applies to all vehicles — i.e., vehicles with headways less than or equal to the critical value are defined as following. However, some authors [3, 4] argue that the critical time headway is often overestimated and it would be better to take into account the heterogeneity of driver behaviour.

To address this point, we equip each vehicle i with its own invertible speed-spacing function $V_i(s)$, where $v_i^{\max} := V_i(+\infty)$ is its desired speed. The (rear-to-rear) spacing when following is then given by $V_i^{-1}(v_{\text{leader}}^{\max})$, which is the platoon's speed, that is, the desired speed of its leader. In a similar way, V_{leader}^{-1} is used to compute the spacing at which a platoon catches up and merges with a slower platoon and adopts its speed. The speed-spacing function $V(s)$ in our model provides a modelling device for capturing overtaking measurements that are difficult to obtain empirically. Extending the heterogeneity of our model beyond the distribution of desired speeds we are able to capture: i) a good description of traffic patterns on S1 roads; ii) an accurate representation of platoon formation; and iii) realistic frequencies for overtaking.

Our overtaking model supposes each vehicle, when following, overtakes its immediate predecessor according to a Poisson process with rate $\alpha\,(1 - v_i/v_i^{\max})$. This rate function models the propensity to overtake as a function of the degree to which a vehicle's speed is suppressed by following — that is a following vehicle travelling at close to its desired speed $v_i^{\max}$ has little tendency to overtake. Of course, nonlinear rate functions may also be explored in our framework. Note the parameter α (units s^{-1}) scales the overall overtaking rate, and allows it to be calibrated against empirical data, for example in terms of the total number of overtaking events per unit length of road, per

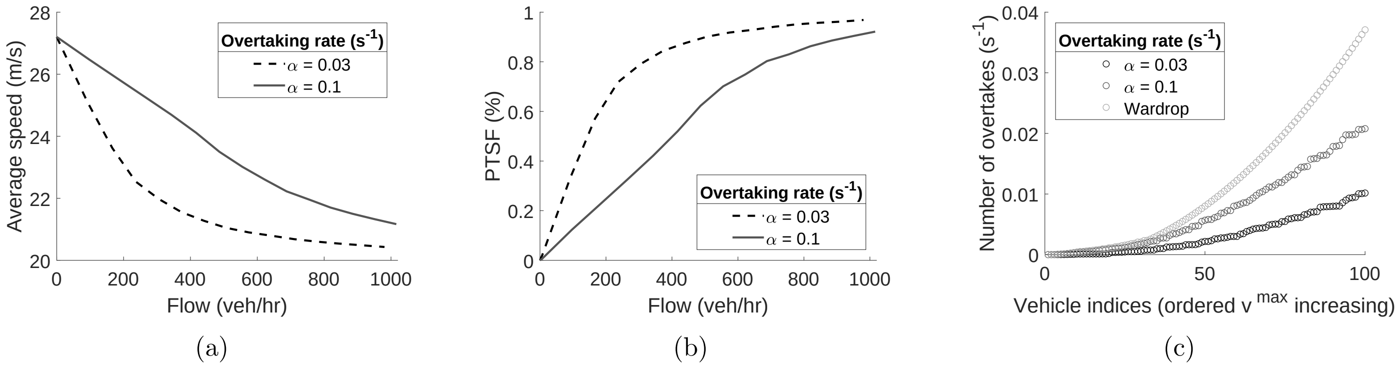

Figure 1: Plots of the LOS metrics for varying values of the overtaking rate parameter α. Non-ANPR derived α used.

unit time. We may distinguish between overtaking events i) within a platoon (when the two vehicles concerned swap their order) and ii) when the platoon leader is overtaken and the overtaking vehicle forms a new singleton platoon. Finally, note that although the overtaking model is highly simplified, it forms a framework within which more complicated effects, such as modelling the opposing flow direction, can be incorporated.

The parameter α should be empirically determined: i) either according to the average number of lane-changes experienced on a multi-lane highway (1 lane-change per 2km) — recognised as unrealistic; ii) or, in our case, according to empirical ANPR data from the A9 road (Scotland). Overtaking rates were inferred from the ANPR data and estimated as functions of the flows in both the travelling and opposing directions. To achieve this, Edie's definitions [5] have been applied on simply connected regions $\Delta t \times \Delta x$ built from the road segments between ANPR sites (length Δx) and varying time blocks (duration Δt) to obtain generalised flows. By calculating α according to real-world data, opposing flows may now be included explictly in our model.

3 Results

We have built a time-stepping simulator of our model. For this paper we simulate a ring-road set-up, in which the time-average statistics of LOS metrics are independent of position on the road, which thus may also be averaged over. The simulations adopt initial conditions in which vehicles are positioned randomly on the road according to a prescribed density — which is one of the key parameters of interest. In this paper, the proportion of slow vehicles (SVs) is fixed at 20%. We suppose SVs (essentially HGVs) have a PCU of 3.5, and combining with our various other parameters, this implies a maximum density of $\rho^{\max} = 0.0227\text{PCUs/m}$. In addition to varying the density, we investigate the effect of the overtaking rate α.

Sample results are shown above in Fig. 1. In Figs. 1(a) and 1(b), for $\alpha = 0.03\text{s}^{-1}$ we observe a change of state where vehicles become highly platooned above flows of around 200veh/hr. A greater overtaking rate α gives flow rates that are significantly higher for the equivalent levels of average speed and PTSF (around 600veh/hr). The value of $\alpha = 0.1\text{s}^{-1}$ corresponds to an overtaking event per vehicle every 2km. In this example, providing only a slight increase in opportunities for overtaking results in a much higher LOS.

We compare our overtaking rates with Wardrop's theoretical upper bound for friction-free overtaking [1]. In Fig. 1(c) we can see that the slowest vehicles make almost no overtakes, since they are usually the heads of platoons. We also see that for fast vehicles, almost double the number of overtakes occur by increasing overtaking opportunities.

References

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