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Lane distribution estimation for heterogeneous traffic flows

Femke van Wageningen-Kessels [a,*], R. Eddie Wilson [b]

[a] Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands
[b] University of Bristol, Woodland Road, Bristol BS8 1UB, United Kingdom

Abstract

A new macroscopic steady state theory is proposed to explain how heterogeneous traffic distributes itself over the lanes of a congested highway. Firstly, a model is derived which predicts the speed of a given mixture of traffic within a single lane. The distribution over lanes is then phrased as an assignment problem, where it is assumed that individual drivers choose lanes so as to try to maximise their own speeds. Theory is derived which establishes circumstances in which the assignment matrix and consequent lane speeds can be solved for. Two examples are presented which demonstrate how the theory can be used to inform traffic management that employs either dynamic speed limits or mandatory lane policies. Future research and applications are then scoped.

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1. Introduction

The purpose of this paper is to lay the first blocks in the foundation of a new theory of how heterogeneous traffic flows distribute themselves across multiple lanes of a congested highway. There are a number of practical motivating factors for this work. Firstly, lateral effects in highway traffic are not well studied, yet casual observation during any long highway journey reveals that lane changes are more common than significant longitudinal acceleration events, and moreover, there are patterns in the manner in which different drivers choose to hold different lanes, depending on the type of the vehicle in question, the drivers' personal preferences, and the wider driving norms of the country or region in question. For example, in many European countries, traffic laws instruct drivers to return to the outer lane (left-hand lane in UK, right-hand lane in other countries) after overtaking slower vehicles UK Department for Transport (b). However, this rule is often ignored and in moderately busy conditions, one usually observes that traffic sorts itself into streams of greatly differing speeds, one stream per lane, with very few lane changes between the streams. The recent paper of Farhi et al. (2013), which proposes a simple model for such lane choice based on

* Corresponding author. Tel.: +968-93251057 ; fax: +31-15-2787956.
E-mail address: f.l.m.vanwageningen-kessels@tudelft.nl

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individual drivers' utility, appears to be the only contribution in the literature offering a theory that might help us understand this effect, although Duret (2014) is an other recent related work on lane distribution.

Secondly, Active Traffic Management (ATM) allows the possibility to control traffic on a per-lane basis. A typical set-up (for example, as used in England's Smart Motorways system UK Department for Transport (a)) is to set temporary speed limits by VMS positioned above each individual lane. The usual practice is that all lanes have the same reduced speed limit, but such a system allows in principal that a different speed limit be set for each lane. One might wonder what the effect of such a management scheme would be. In particular, much of the benefit of ATM is thought to derive from an enhancement in stability that results from reducing the variance in the speed of the traffic, both within and between lanes. However, there may be a sub-set of skilled drivers who are able to drive stably at short headways and high speed. Thus if a single lane were to be allowed a higher speed limit, targeted to such drivers, would this increase the capacity of the highway? Other lane management systems work by vehicle class and (for example) include the restriction of trucks to the outermost two lanes of the highway, or alternatively on occasion there may be a lane reserved exclusively for trucks and buses, or indeed one may even set different dynamic speed limits for different vehicle classes.

Thirdly, the introduction of automated vehicles, be they fully autonomous, coordinated by vehicle-to-infrastructure communicated systems, or merely equipped with advanced driver assist systems, is likely to impact significantly on achievable highway capacity in the next 20 years. For example, dedicated lanes for automated vehicles might achieve short headways at high speed (but if this is achieved by taking lanes away from non-automated vehicles, what will the effect on the overall flow be?). Or alternatively, automated vehicles might be instructed by centralised control to penetrate and inter-mix with non-automated vehicles so as to regulate their speed and flow. In which case, what is the optimal way to distribute the automated vehicles across lanes?

Finally, insight into lane choice and (optimal) lane distribution will improve continuum traffic flow models. Some models already take into account multiple lanes and their usage by different types of vehicles (Hoogendoorn and Bovy, 2001; Daganzo, 2002), other models assign fractions of the road to certain types of vehicles (Ngoduy and Liu, 2007; Logghe and Immers, 2008). However, to the authors knowledge, the lane distribution is not discussed explicitly in neither of these multi-class models. We did not consider models for behaviour near ramps or other road inhomogeneities as in this first study we are focussing on the (simpler) case of homogeneous roads. Future adaptations of multi-class continuum models including the lane distribution, will be better able to predict, for example, lane specific speeds and flows. Consequently, they will result in better predictions of congestion and class specific travel time.

In this paper, we consider the development of the simplest possible theoretical framework to address these questions *in general*, leaving the practical details for future work. Our basic set-up is that of a homogeneous unidirectional multi-lane highway, which is populated by vehicles belonging to a small number of discrete classes. The idea is that a single *class* contains vehicles which are identical in both their physical characteristics and in terms of their drivers' behaviours.

The simplified situation that we shall examine is one which is static — that is the macroscopic variables of flows, speeds and densities are independent of both time and distance down the highway. Moreover, we shall assume that there are no lane changes, either because traffic is so congested that they cannot occur, or because the traffic management policy specifically prohibits them. (In fact, the theory presented here could be generalised to allow for lane changes where there is no net flow of any one class from one lane to another. In this case, one would introduce a term that penalises capacity in accordance with lane-changing rates.) In this set-up, it is clear that the average speed of every vehicle in the same lane is the same — and thus if we assume that individual vehicles' speeds are time-independent, then each vehicle in the same lane has the same time-independent speed. (NB in fact oscillatory microscopic dynamics is also consistent with the static macroscopic description, but is beyond the simplified scope of this paper.) However, the vehicles' headways will differ according to their class, and indeed the key behavioural property for each class will be an equilibrium speed-spacing function, from which we derive the speed-density properties of a single lane of mixed traffic (Section 2).

The question is then one of traffic assignment: how does a given mixture of traffic distribute itself across the available lanes? Assuming free (non-automated) drivers, the most reasonable model is a kind of user equilibrium, which is explained in more detail in Section 3. Next, Section 4 continues with the main contribution of this paper: a methodology to solve the user equilibrium problem and calculate the distribution of traffic and the speed of each lane,