Integrated control of motorway bottlenecks via flow metering and lane assignment

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In the near future, the appearance of vehicle automation and connectivity will revolutionise the features and capabilities of individual vehicles. Among the wide range of potentially introduced technology, some may be exploited to interfere with the driving behaviour via recommending, supporting, or even executing appropriately designed traffic control tasks, providing unprecedented opportunities to improve traffic control performance [1]. It has been shown that, particularly at bottleneck locations (e.g., lane-drops, on-ramp merges), human drivers usually perform suboptimal lane-changes based on erroneous perceptions, which may trigger congestion, and, thus, deteriorate the overall travel time (e.g., [2], [3]). Furthermore, some of the mentioned empirical investigations indicate that, in conventional traffic, capacity flow is not reached simultaneously at all lanes, a feature that reduces the potentially achievable cross-lane capacity. For these reasons, a promising new feature that may be exploited for traffic management, independently or in combination with other strategies, is lane-changing control.

We address here the problem of maximising the outflow at motorway bottlenecks via a combined exploitation of flow metering and lane-changing control. It is well known that a bottleneck, which is a location where the flow capacity upstream is higher than the flow capacity downstream of the bottleneck location, is activated when the arriving flow is higher than the overall capacity or when the lane-changing behaviour leads to exceeding the capacity in at least one lane. In conventional traffic, in order to avoid or delay the activation of a bottleneck, and the related capacity drop phenomenon, various traffic control measures have been proposed and applied [4]. In the context of automated and connected vehicles, only a limited number of works have considered to exploit optimal lane distribution (e.g., [3], [5], [6]). We presented in [7] an optimal feedback control strategy for lane-changing control, formulated as a linear quadratic regulator, which is highly efficient in real-time even for large-scale networks. The method has been extended in [8] in order to achieve different traffic density distribution for the various lanes at the bottleneck area.

We propose here a novel integrated approach that allows to jointly exploit mainstream (or ramp) flow metering together with lane-changing control, while accounting for unmeasured demand flows and incomplete measurements. The control strategy aims at regulating the mainstream flow, actuated, for example, via variable speed limits, and the lane assignment of vehicles upstream of a bottleneck location in order to maximise the bottleneck throughput. Moreover, the proposed strategy is capable of handling efficiently the case of mixed traffic, where manual vehicles may not receive or may not follow the prescribed lane-changing commands. We first present the formulation of our strategy, which is based on a simplified linear macroscopic traffic flow model, with appropriate augmented dynamics to handle unmeasured flows. The model is employed to design a controller that aims at regulating the flow metered at the motorway entrance together with the lane assignment of vehicles upstream of a bottleneck location in order to maximise the bottleneck throughput, targeting critical densities at bottleneck locations as set-points. Since the critical densities may be a-priori unknown and they may vary over time, we also employ a non-model-based real-time optimisation technique, namely, extremum seeking [9], to identify them, with the aim of minimising a performance index, namely the total time spent over a finite time horizon. Finally, we present simulation experiments, employing a first-order multi-lane macroscopic traffic flow model featuring the capacity drop phenomenon [10], in order to evaluate the effectiveness of the developed methodology and to highlight the different traffic behaviour in terms of generated queues and per-lane flow distribution.

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