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Environmental Impact of Combined Variable Speed Limit and Lane Change Control: A Comparison of MOVES and CMEM Model

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Abstract: Highway congestion is detrimental to traffic mobility and has negative impact on the environment. Variable speed limit (VSL) control is an approach that aims to reduce the impact of congestion by controlling the speed of traffic along the highway lanes. In this study, we evaluate the environmental impact of a combined variable speed limit and lane change control strategy with two different fuel consumption/emission models: the EPA model MOVES and CMEM developed by the University of California at Riverside. Microscopic Monte-Carlo simulations of traffic on I-710 freeway are used to demonstrate the environment effect of the combined control method. Both environmental models are used to evaluate fuel consumption and tailpipe emissions with and without the combined control strategy. Despite some differences between the two models, the evaluation results of both models confirm the benefits of the combined variable speed limit and lane change control strategy.

Keywords: Highway traffic control, Variable Speed Limit, Lane Change, Environmental impact, Fuel consumption, Tailpipe emissions

1. INTRODUCTION

The rapid growth of traffic demand has long been a great threat to the air quality and sustainable development due to huge amount of tailpipe emissions and fuel consumption. According to National Renewable Energy Laboratory (2013), the ground transportation takes 71% petroleum use and produces 33% of the CO2 emission of the world. Growing traffic demand introduces more congestion on roadways which makes the situation even worse. The travel time and wasted fuel during highway congestion are 5.52 billion hours and 2.88 billion gallons respectively in 2011, and are further predicted to be 8.84 billion hours and 4.5 billion gallons respectively in 2020, see Schrank et al. (2012). Therefore, efficient traffic flow control strategies are needed to avoid or reduce the severity of congestion, hence reduce fuel consumption and tailpipe emissions along the lanes of highway networks. Furthermore, in order to evaluate the environmental impact of potential traffic flow control strategies precisely and efficiently, well-defined emission models are needed to estimate or predict fuel consumption and tailpipe emissions of vehicles under different traffic scenarios in both simulations and field tests.

At highway bottlenecks, there are two basic ideas to save energy and reduce emissions from the perspective of traffic flow control:

(1) *Improving the throughput of the bottleneck.* By increasing the throughput of the bottleneck during congestion, the time spent by the vehicles while waiting in the queue would be reduced. Therefore less emission and fuel consumption are generated, see Lu et al. (2015).
(2) *Smoothing the traffic flow.* Fuel consumption and emissions especially nitrogen oxides are very sensitive to high acceleration, see Zegeye et al. (2009). By maintaining the traffic flow at a constant speed and avoiding the stop-and-go traffic, the emissions and fuel consumption can also be reduced.

Variable Speed Limit (VSL) control techniques have been studied to improve the traffic condition on highway since the 1990s, see Smulders (1990). Most of the existing studies on VSL strategies mainly focus on improving traffic safety and mobility. VSL strategies have been reported to have consistent effect on traffic safety by homogenizing and smoothing the traffic flow, see Abdel-Aty et al. (2006); Allaby et al. (2007). Benefits on traffic mobility of VSLs are also demonstrated in some previous studies, see Carlson et al. (2013); Hadiuzzaman et al. (2012); Zhang and Ioannou (2015). Therefore, VSL strategies have the potential to provide environmental benefits to highway traffic by both improving the throughput of the bottleneck and smoothing the traffic flow.

Some recent studies also evaluated the environmental impact of VSLs on highway traffic with different emission/fuel consumption models, see Zegeye et al. (2009); Khondaker and Kattan (2015); Zhang and Ioannou (2015). It is not possible to measure the emissions and fuel consumption of every vehicle directly either in simulations or field tests, therefore a number of emission/fuel con-

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sumption models are developed and used to estimate the tailpipe emissions and fuel consumption of vehicles. From different points of view, existing emission/fuel consumption models can be classified as follows:

(1) *Macroscopic Models and Microscopic Models.* Macroscopic models estimate the fuel consumption and emissions of all vehicles on a road segment in batch, based on aggregated data, such as the distribution of vehicle population on vehicle types and conditions, average speed of traffic flow, road conditions etc. Typical macroscopic emission models include MOBILE6, MOVES, COPERT III etc. Microscopic models evaluate the fuel consumption and emissions of individual vehicles. These models take the characteristics of an individual vehicle and its second-by-second speed and acceleration profile as input, and return second-by-second emission and fuel consumption values as the output. Typical microscopic models include CMEM, VT-Micro etc. Usually, microscopic models can provide more accurate and detailed evaluation result but require much more computational resources compared to macroscopic models.
(2) *Physical Models and Data-driven Models.* Physical emission/fuel consumption models capture the underlying physical relationship between vehicle characteristics, operating conditions and the emission/fuel consumption rates, while data-driven models learn the relationship from historical data using machine learning and interpolation techniques. CMEM is a typical physical model. VT-Micro and MOVES are data-driven models.

Different emission/fuel consumption models have different properties. It is inconvenient to compare the evaluation results on the environmental benefits of VSL with different models directly since we cannot tell whether the difference comes from the controllers or the evaluation models. Therefore, it is important to compare the performance of VSL controller with different emission models in order to identify possible differences between models and verify that the benefits obtained do not differ at least qualitatively by using different emission models.

In Zhang and Ioannou (2015), a combined variable speed limit and lane change (LC) control method is proposed to relieve congestion at highway bottlenecks. The study shows that one of the main causes of capacity drop is forced lane changes in the queue. By providing appropriate lane change recommendations to upstream vehicles, more efficient lane changes can be performed hence capacity drop can be removed. The authors showed that by applying combined variable speed limit and lane change control strategy, the traffic flow can be increased due to the removal of the capacity drop and smoothness of vehicle density.

In this paper, we studied the environmental benefits of the combined VLS and LC controller proposed in Zhang and Ioannou (2015), including fuel consumption and tailpipe emissions. We evaluate the fuel consumption and emissions with two different emission models: the Comprehensive Modal Emissions Model (CMEM) developed by University of California at Riverside (An et al. (1997)) and the Motor Vehicle Emission Simulator (MOVES) developed by Environment Protection Agency (EPA) (U.S. Environmental Protection Agency (2014)). The similarities and differences of the two models and their evaluation results are also compared and analyzed in this paper.

Some existing research work assessed the environmental benefits of different VSL strategies. In Zegeye et al. (2009), a VSL strategy based on model predictive control (MPC) was proposed using a car-following model to reduce both total time spent (TTS) and total emissions. The environmental impact was evaluated with macroscopic COPERT III model, which showed that a reduction of TTS alone may not reduce the total emissions.

In Khondaker and Kattan (2015), a MPC-based VSL controller was proposed to improve traffic safety, mobility and the environmental impact simultaneously in a connected vehicle (CV) context. The environmental impact was evaluated with VT-Micro. The study showed that in case of 100% penetration rates of CVs, optimizing for safety alone is enough to achieve simultaneous and optimum improvements in all measures. However, in case of lower penetration rate, higher collision risk was observed when optimizing for only mobility or fuel consumption.

Some previous studies compared existing emission models. In Rakha et al. (2003), MOBILE5a and MOBILE6, which are pre-versions of MOVES, CMEM and a microscopic emission model VT-Micro developed by Virginia Tech were compared. The authors concluded that MOBILE6 and VT-Micro is more accurate than CMEM since the evaluation result is closer to field data. However, in this study, the database used to validate the models is the same one which is used to develop VT-Micro and MOBILE6, therefore the result is not persuasive.

In Chamberlin et al. (2011), CMEM and MOVES were compared under different intersection control strategies. This study showed that the evaluation of NOx by the two models are similar, but significant discrepancies were observed in evaluation of CO.

2. DESCRIPTION OF COMBINED VSL AND LC CONTROLLER

In this section, we briefly introduce the design of the combined VSL and LC controller developed in Zhang and Ioannou (2015).

2.1 Configuration of VSL and LC Control System

VSL & LC control facilities can be deployed at upstream of lane drop sections, merging points and incident-prone sections etc. An example of combined LC & VSL control system is shown in Fig. 1. The highway segment upstream the bottleneck is divided into N sections with similar length. LC control uses overhead signs to make lane change recommendations at the beginning of M sections at upstream of the bottleneck, i.e. section $N-M+1$ through section N.

To help improve the flow rate at the bottleneck, VSL controller tends to maintain reasonable density in discharge section. VSL signs, which are used to inform drivers of the enforced speed limits, are deployed at the beginning of section 1 through section $N-M$. It is assumed that