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An optimal variable speed limits system to ameliorate traffic safety risk

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ABSTRACT

Active Traffic Management (ATM) systems have been emerging in recent years in the US and Europe. They provide control strategies to improve traffic flow and reduce congestion on freeways. This study investigates the feasibility of utilizing a Variable Speed Limits (VSL) system, one key part of ATM, to improve traffic safety on freeways. A proactive traffic safety improvement VSL control algorithm is proposed. First, an extension of the METANET (METANET: A macroscopic simulation program for motorway networks) traffic flow model is employed to analyze VSL's impact on traffic flow. Then, a real-time crash risk evaluation model is estimated for the purpose of quantifying crash risk. Finally, optimal VSL control strategies are achieved by employing an optimization technique to minimize the total crash risk along the VSL implementation corridor. Constraints are setup to limit the increase of average travel time and the differences of the posted speed limits temporarily and spatially. This novel VSL control algorithm can proactively reduce crash risk and therefore improve traffic safety. The proposed VSL control algorithm is implemented and tested for a mountainous freeway bottleneck area through the micro-simulation software VISSIM. Safety impacts of the VSL system are quantified as crash risk improvements and speed homogeneity improvements. Moreover, three different driver compliance levels are modeled in VISSIM to monitor the sensitivity of VSL effects on driver compliance. Conclusions demonstrated that the proposed VSL system could improve traffic safety by decreasing crash risk and enhancing speed homogeneity under both the high and moderate compliance levels; while the VSL system fails to significantly enhance traffic safety under the low compliance scenario. Finally, future implementation suggestions of the VSL control strategies and related research topics are also discussed.

1. Introduction

Active Traffic Management (ATM) is a scheme for improving traffic flow and reducing congestion on freeways (Mirshahi et al., 2007). ATM makes use of automatic systems and human interventions to manage traffic flow and ensure the safety of roadway users. This approach seeks to solve the congestion problems through mainline and ramp management strategies for freeway corridors. In addition, ATM is a tool that can maximize safety and throughput, which may be used as an interim strategy to maximize the efficiency of corridors that may ultimately receive major capital investments.

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Among the ATM control strategies, Variable Speed Limits (VSL) is a strategy widely employed in Europe and the US to improve traffic flow and traffic safety. VSL systems adopt signs along the freeways to constantly regulate freeway speeds based on real-time traffic flow information (e.g. speed, lane occupancy, and volume). Speed limits can be reduced when freeway conditions are unsuitable for high speed operation, such as adverse weather conditions (Rämä, 1999). Besides, speed limits can also be lowered when there is an incident or congestion on specific segments in order to reduce the chances of secondary accidents and facilitate a smoother flow of traffic (Sisiopiku, 2012). However, few previous studies have evaluated the use of VSL as a safety proactive strategy to reduce the primary crash risk.

This study proposes an innovative VSL control algorithm which can proactively improve traffic safety. In order to analyze the effects of VSL on traffic flow, an extension of the macroscopic traffic flow model METANET[1] (Carlson et al., 2010a) is introduced. In addition, a real-time crash risk evaluation model is estimated to monitor the hazardousness of crash occurrence. Therefore, with the purpose of minimizing crash risk over the VSL controlled freeway section, optimal control strategies are obtained through solving an optimization problem.

The feasibility of the proposed VSL system to improve traffic safety is investigated for a mountainous freeway bottleneck segment. The chosen mountainous freeway segment features steep slopes, adverse weather conditions, and frequent crash occurrence (Yu et al., 2013). Safety benefits of the VSL are analyzed through microscopic traffic simulations in VISSIM (PTV, 2010). This approach has been utilized in several previous VSL studies (Abdel-Aty et al., 2006a,b; Lee et al., 2006a,b). Five-minute average crash risks and speed standard deviations are utilized as evaluation measures for traffic safety. Moreover, for the purpose of investigating sensitivities of VSL effects on driver compliance, three different levels of driver compliances are tested and compared. Finally, issues regarding future VSL implementations and suggestions for VSL systems' research topics are also discussed.

2. Background

2.1. VSL control strategies

In the abundant VSL literature, system objectives mainly fall into the aspects of traffic safety improvement or freeway operation enhancement. The VSL studies stem from traffic safety aspect (Abdel-Aty et al., 2006a; Lee et al., 2006b) found that VSL systems were capable of improving traffic safety under certain restricted scenarios. Generally speaking, these VSL control algorithms were concluded with microscopic simulation experiments. A certain number of different control strategies were simulated and compared. One or several calibrated crash risk evaluation models were employed as the evaluation measurement of traffic safety improvements.

For instance, Abdel-Aty et al. (2006a) evaluated the effects of a VSL system on freeway safety improvement. A 36-mile freeway section on I-4 that crosses Orlando downtown area was chosen for this study. Two crash risk evaluation models were developed in a previous study (Abdel-Aty et al., 2005) for two distinct traffic regimes (moderate-to-high-speed and low-speed traffic regimes). The simulation study was done in PARAMICS (Quadstone Ltd., 2000) while focusing on four key components of the VSL control strategies: (1) Speed change patterns (Abrupt or Gradual); (2) Upstream lowering and downstream raising distances; (3) Rate of change of speed limits (time step for change and speed step for change); and (4) Gap distances. After numerous test scenarios and comparing the crash risk reductions, the best control strategy was identified.

In addition to the abovementioned VSL studies which adopted an experimental design approach to identify the best control strategies and had a safety objective, other studies focused on traffic flow enhancement and obtained the optimal VSL control strategies by solving optimization problems. Hegyi et al. (2005) proposed an optimal coordination method to resolve the shockwaves with the merit of VSL. A model predictive control (MPC) approach was introduced to predict the network evolution as a function of the current state and a given control input. The macroscopic traffic-flow model METANET was extended to incorporate speed limits' influences. The authors identified VSL control strategies by solving optimization problems: the primary aim was to minimize total travel time and several constraints such as the speed limit change patterns were setup.

As an alternative to the abovementioned algorithm which requires global optimization to locate the control strategies, simplified local optimization VSL systems were also investigated. Popov et al. (2008) proposed a VSL system to resolve shockwaves with distributed controllers; and Carlson et al. (2011) came up with a cascade structure local feedback model based VSL control algorithm. These more localized VSL models were compared to the global optimal control models; results indicated that locally controlled models were able to achieve similar improvements on travel time reductions as the global control models. Besides, locally controlled strategies were claimed as easier to be implemented in-field since no high computational capabilities are needed.

Comparing the two existing approaches to obtain the best VSL control strategies, the experimental design way requires extensive simulation work and the results are not transferable between different facilities; nevertheless, the optimization approach demands real-time computation capabilities and the strategies are easier to be applied to another roadway. However, in the optimal VSL control strategies, safety improvements were not considered as the main objective. In this

[1] METANET: A macroscopic simulation program for motorway networks.