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Freeway traffic incident reconstruction – A bi-parameter approach

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ABSTRACT

The paper suggests a novel alternative to generalized traffic incident descriptions within the macroscopic traffic model framework. The contribution of the paper is twofold. First, by extending already existing second order macroscopic conservation laws to characterize off-nominal traffic conditions, we define two main incident parameters such as direct and indirect ones. Physical interpretations of this incident parametrization is provided. These incident indicators are relative in view of the nominal traffic flow model parameters and carries physically meaningful macroscopic content. Second, the paper proposes to use a constrained and nonlinear, joint traffic state- and incident parameter reconstruction method and validates the suggested modeling idea via real traffic measurements fitting. Evaluation of the numerical results demonstrate the effectiveness of the methodology.

1. Introduction

Advanced road traffic control solutions use traffic models such as mathematical abstractions of the real traffic in order to properly predict traffic behavior for management, control, and supervision purposes. Nowadays increased traffic demand and emerging vehicular technology challenge traffic engineers and scientists to elaborate more and more powerful intelligent transportation systems (ITS). We expect more and more functionalities from advanced road traffic control solutions, that invites researchers to focus on the duality of complexity and large-scale traffic control solutions. In terms of functional complexity, one of the most important direction is to create ITS solutions resilient to off-nominal traffic conditions, i.e. to traffic incidents. To embed these features into road traffic control algorithms, proper modeling and reconstruction of effects of traffic incidents are indispensable.

Without giving a complete overview on the various number of traffic incident related literature, we particularly concentrate on macroscopic traffic incident models having direct connection to the presented work. Since, macroscopic traffic quantities such as average speed, density or flow are used for road traffic control, the topic of reconstructing traffic incidents with mean valued variables has obtained a significant research attention. In this line, second order macroscopic traffic flow paradigms of Payne (1971), respectively its appropriately discretized version Papageorgiou et al. (1989) has not only been utilized as a groundwork for alternative road traffic control algorithms e.g. Hegyi et al. (2005), but also for incident recognition, see Wang et al. (2009). The latter note shows an incident parameter and traffic model adaptation through the reconstruction of changing model parameter with the help of extended Kalman filter. The main idea is to address off nominal traffic conditions by adapting the relaxation term through the core equilibrium speed parameters. In Sanwal

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et al. (1996) incident effect is lumped into a time-varying factor as reduction of number of lanes. Both of these approaches directly focus on the effect of incidents causing changes in the infrastructure and disregard the nature of human behavior in incident traffic conditions. However, the average driver behavior used in road traffic flow models is influenced by several key factors. The change in driving strategy is characterized by behavioral variable as *activation level* in Tampère (2004). Different studies have been published to analyze drivers behavior in/before road traffic accidents, see e.g. the microscopic approaches Sheu (2013) and Knoop et al. (2009). In Knoop (2009), it has been found on the basis of real traffic accident analysis that the distribution of drivers' reaction time increases at the bottleneck incident location, modifying traffic flow property. The importance of risk-aware traffic management systems has been concluded as an important future direction for traffic management solutions Dabiri and Kulcsár (2014). To embed driver reaction, Dabiri and Kulcsár (2013) offers a solution as a dynamic relaxation of traffic speed together with modified anticipation term, within the traffic flow framework of Aw and Rascle (2000). In line with the previous researches, this paper addresses incident parametrization in the framework of *second* order traffic flow models by Papageorgiou et al. (1989) with the clear focus on the validation with *real traffic measurements*. One of the main contribution of the paper is to connect incident traffic flow models to driver behavior with the help of novel incident parametrization for macroscopic flow models. Unlike existing solutions (e.g. Wang et al. (2009) and Sanwal et al. (1996) using the traffic flow framework of Papageorgiou et al. (1989)), herewith we classify traffic incidents in two major groups. Incident parameters relative to nominal model parameters are used to model the effect of both *direct* and *indirect* off-nominal traffic conditions. While direct incident model parameters capture the effect of temporal changes in road geometry (relative changes in the relaxation speed, in the corresponding equilibrium speed component), indirect incident parameter describes the changes in the average drivers' perceptions due to abrupt traffic conditions (relative variation in the headway). When incident happens, it modifies traffic flow model parameters. In this concept, incident parameters are defined to describe the divergence due to incident from the given set of nominal model parameters, so they are *relative* quantities to the nominal flow model parameters (unlike e.g. Wang et al. (2009) that proposes to estimate the absolute changes in some core model parameter values). By adequate discretization technique, these relative incident parameters become segment-wise time varying and preserve their physical interpretations. Analysis of these parameters in macroscopic model levels, allows the definition of their upper and lower bounds, i.e. they describe traffic anomalies ranging from nominal condition (incident-free) to complete lane closure. Finally, with the help of on-line parameter observation, one can reconstruct these parameters.

Accordingly, the paper suggests to apply a two-degree of relative freedom incident parametrization (direct and indirect) (Section 3). This concept is tested and verified over the set of real data measurements. Incident free traffic measurements are used for nominal freeway traffic model parameter identification, following the methodology proposed in Cremer and Papageorgiou (1981). Afterwards, an incident corrupted data sequence is selected as a test case for incident parameter estimation. A constrained, nonlinear and rolling horizon scheme Rao (2000) is applied to estimate the effect of incident (Section 4). Evaluation of the obtained results as well as thereof the numerical complexity is provided (Section 5). The paper is concluded by formulating future research directions.

2. Problem formulation

Macroscopic methods for modeling traffic flow involve the evolution of time (t) and space (x) dependent average quantities such as mean velocity or density Whitham (1974). The basic equation in traffic flow dynamics is the conservation of vehicles. If $\rho(x,t)$ is considered as the density of vehicles and $q(x,t)$ as the flux, the conservation equation states that the rate of change of density in $x_1 \leqslant x \leqslant x_2$ is equal to the difference of net flow in x_1 and x_2:

$$\frac{d}{dt}\int_{x_1}^{x_2}\rho(x,t)dx = q(x_2,t) - q(x_1,t), \tag{1}$$

which can be written as:

$$\rho_t(x,t) + q_x(x,t) = 0. \tag{2}$$

The two variables $\rho(x,t)$ and $q(x,t)$ are simultaneously involved in Eq. (2). In the sequel, for sake of simplicity in notation we drop the time and space dependency. In (2), subscripts $\cdot_t$ and $\cdot_x$ denote the partial derivation w.r.t. time and space, respectively. One reasonable option to make use of (2) is to consider a functional relation between q and ρ such as:

$$q = Q_e(\rho). \tag{3}$$

Replacing (3) into (2) results in first order traffic flow models Lighthill and Whitham (1955). Relation (3) is called the fundamental diagram which is indeed a simplistic view of describing a potentially highly complicated dynamics. In Whitham (1974), the effect of the density gradient ρ_x in (3) has been considered in the form of:

$$q = Q_e(\rho) - \eta\rho_x, \tag{4}$$

where η is a positive constant, real scalar. Since $q = \rho v$, from Eq. (4) we have:

$$v = V_e(\rho) - \eta\frac{\rho_x}{\rho}, \tag{5}$$