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IMPACTS OF REDUCING FREEWAY SHOCKWAVES ON FUEL CONSUMPTION AND EMISSIONS

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ABSTRACT

With increasing public concerns on environmental aspects of traffic, assessment of dynamic traffic management measures should not only focus on throughput, but also on sustainability and livability. This paper focuses on investigating sustainability and livability effects of a freeway shockwave reduction algorithm in the Netherlands. This contribution consists of a method of estimating fuel consumption and emissions at link level. The main idea is to estimate acceleration based on macroscopic traffic data, and calculate fuel consumption and emissions based on speed and estimated acceleration. Results show that potential impacts of the new freeway control algorithm on sustainability are promising.

KEYWORDS

Variable speed limits, shockwave, vehicle trajectory, acceleration estimation, microscopic emissions model

INTRODUCTION

Increasing congestion has been a major problem in freeway traffic. Although different interpretation and classification of traffic jams can be found in literature (Kerner, 2002; Helbing et al., 2009), one common pattern of freeway traffic congestion are shockwaves (Hegyi et al., 2005), or wide moving jams (Kerner, 1996), characterized with jam fronts and tails moving upstream with a constant velocity. Shockwaves can exist for a long time (Kerner & Rehborn, 1996), while keeping their form and parameters. Based on the characteristics of shockwaves, a freeway control algorithm called SPECIALIST (SPEed ControllIng ALgorIthm using Shockwave Theory) has been proposed by Hegyi et al. (2008). Simulation results show that SPECIALIST can improve the outflow and total time spent on the considered road stretch. From September 2009 onwards, SPECLIAST has been implemented on freeway A12 in the Netherlands.

With increasing public concerns on environmental topics, not only the improvements of dynamic traffic management measures on throughput should be considered, but also the potential impacts on sustainability should be investigated. This paper therefore focuses on the research question whether the implementation of SPECIALIST will contribute to reducing fuel consumption and emissions. The contribution described in this paper consists of a methodology to investigate the impact of dynamic traffic management measures on traffic sustainability, using macroscopic data from the inductive loop traffic data collection system MONICA(MONItoring CAsco) system.
This paper is structured as follows: first, the previous work is reviewed and problems are described, followed by a description of the methodology, and the results of the case study. Conclusions and future research are indicated in the last section.

PROBLEM DESCRIPTION

It is generally accepted that speed variations have a significant influence on vehicle emissions and fuel consumption, and mitigating congestion and stabilizing traffic flow can achieve benefits on sustainability. Gense et al. (2001) reported that stop-and-go traffic and high speed driving (faster than 120 km/h) can lead to significant increases of CO, VOC (Volatile organic compounds), PM (Particulate Matter) and fuel consumption, which is mainly caused by many engine load changes or high engine loads, and lowering the speed limit on Dutch motorways can improve emission levels significantly. Barth (2008) found that traffic congestion has a significant effect on CO_2 emissions, and CO_2 emissions can be reduced by traffic flow smoothing techniques that can suppress shock waves and reduce the number of acceleration and deceleration events. Besides, Ahn (2009) indicated that reducing sharp acceleration behavior can significantly reduce fuel consumption and emission rates. Different fuel consumption and emission models are used in the aforementioned studies to explore the relation of vehicle dynamics and sustainability. These models are either macroscopic or microscopic. Macroscopic models developed by testing on different driving cycles use average speed as inputs, and are suitable for application in large networks (Ntziachristos et al., 2009; Pollack et al., 2004). Microscopic models use microscopic traffic variables of speed and acceleration as inputs, and are more appropriate for application at local or link level (Ahn et al., 2004; Barth, 2000). A common problem in using microscopic emission models is the lack of real microscopic traffic data. Fixed detectors (e.g. inductive loops) collect macroscopic traffic variables in aggregated time intervals, which can not be used directly in microscopic fuel consumption and emission models. Zegeye et al. (2009) proposed the VT-Macro model which combines the microscopic emission model with a macroscopic traffic model. In this model, acceleration is estimated as a function of speeds at upstream and downstream boundaries of each road segment. However, application of this method depends largely on the distance of detectors and time interval of loop detector data, which means that this model cannot estimate acceleration with road segments smaller than the spacing of detector stations and with time periods shorter than the intervals of the loop detector data.

METHODOLOGY

This section describes the proposed method to estimate acceleration and calculate local fuel rate and pollutants from macroscopic traffic data. First, we filter the noise and estimate the traffic state using an adaptive smoothing method. Then, the bias of using the arithmetic time mean speed is corrected. After that, the acceleration of vehicle groups is estimated based on reconstructed trajectories. Finally, the fuel consumption and emissions are calculated using a microscopic emission model.

Estimation of traffic state using adaptive smoothing method

The first step in our method is to filter the loop detector data from the Monica database. We use the smoothing method proposed by Treiber and Helbing (2002) and improved by Van Lint and Hoogendoorn (2009) to filter the noise. This method reconstructs traffic states between fixed traffic detectors and it can provide spatio-temporal information on speed and flow at any location (t,x). In the case study presented in this paper, we will use a pre-specified resolution of 100 meters in space and 30 seconds in time to reconstruct the trajectories and to estimate accelerations.

Correction of speed bias based on fundamental diagram

Many fixed detectors, e.g. in the Netherlands and UK, collect and aggregate speed using arithmetic time means. Using time mean speed may cause bias in traffic state estimation, because high speeds occur more frequently than slow observations, implicating that time mean speed will be biased towards higher speeds if the instantaneous speed variance is nonzero (Van Lint, 2004). This step is to correct this speed bias using a method proposed by Yuan et al. (2010). This method builds on notions from first order traffic flow theory and empirical flow-density relationships, using only a limited number of parameters.

Estimation of acceleration based on reconstructed trajectory

The third step of our method is to reconstruct trajectories of vehicle groups, and to estimate their accelerations, based on the output of the first two steps and the assumption that vehicles travel with constant speed in each cell.

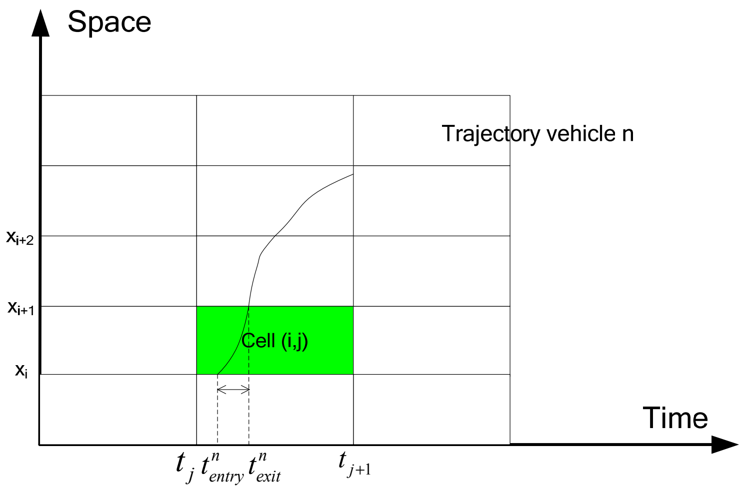

Figure 1: Reconstruction of trajectory

Let us denote *i* and *j* as the index of road segment and time period of spatio-temporal cells respectively. The length of each road segment *L* can be calculated as the difference between the locations of two consecutive loop detectors $L=x_{i+1}-x_i$. The interval of each time period is $T=t_{j+1}-t_j$. We assume that vehicle *n* enters cell (*i, j*) at position $x^n_{entry} \in [x_i, x_{i+1})$ and time $t^n_{entry} \in [t_j, t_{j+1})$ traveling with a speed $v_{ij}(x,t)$, which is a linear function of speed at spatial cell boundaries, and can be denoted as

$$v_{ij}(x,t) = v(x_i, t_j) + (x - x_i)\frac{v(x_{i+1}, t_j) - v(x_i, t_j)}{L} \quad (1)$$

The trajectory of vehicle n in cell (i, j) can then be calculated by solving the differential equation

$$\frac{dx^n(t)}{dt} = v_{ij}(x,t) \text{ with } x^n(t_{entry}) = x^n_{entry} \quad (2)$$

As such, we can approximate the acceleration of the representative vehicle traveling in each space-time cell by dividing the difference of speed with the difference of time between entry point and exit point.

$$\overline{a}_{x_{entry}, t_{entry}} = \frac{v(x_{exit}, t_{exit}) - v(x_{entry}, t_{entry})}{t_{exit} - t_{entry}} \quad (3)$$

Calculating fuel consumption and emissions based on VT-Micro model

Microscopic emission models calculate emissions based on instantaneous vehicle speed and acceleration, and are more suitable for local or link level applications. In this paper, we use a microscopic fuel consumption and emission -VT-Micro developed by Ahn et al. (2004). This model is based on nonlinear multiple regression of typical light duty vehicle fleet. VT-Micro can be used to predict the fuel consumption and emissions on a second-by-second basis for individual vehicles, and is therefore suitable for implementation in analysis of assessing the dynamic traffic management measures at local or link level.

By assuming that the vehicle fleets are the same as light duty vehicles used in the VT-Micro, we can calculate fuel consumption and emissions in each spatio-temporal cell, using speed and acceleration as inputs, and aggregate to derive the total fuel consumption and emissions on a particular freeway stretch.

RESULTS

The considered road stretch is a part of the freeway A12 in the Netherlands and has three lanes and a length of approximately 14 km going from the connection with the N11 at Bodegraven up to Harmelen. SPECIALIST has been implemented in this road stretch. We use data from January to May in 2006 as Before-SPECIALIST situation, and data from September to December in 2009 as After-SPECIALIST situation. The main results of the comparison are shown in Table 1.

Table 1: Before and after comparison of SPECIALIST

Indicators	*Before*	*After*	*Variation*
Average Flow (veh/h)	4761	4991	4,83%
Average Speed (km/h)	91.24	91.75	0,56%
Total Fuel Consumption (liter)	2.2787e+007	2.1524e+007	-5,54%
Total CO emission (g)	6.5541e+008	6.4009e+008	-2,34%
Total HC emission (g)	3.2587e+007	3.1404e+007	-3,63%
Total NOx emission (g)	7.6823e+007	7.3656e+007	-4,12%

CONCLUSIONS

The proposed method provides a way to estimate fuel consumption and emissions using a microscopic emissions model and macroscopic traffic data, and it can be used to evaluate the potential impact of dynamic traffic management measures on livability and sustainability. Application on SPECIALIST using empirical loop detector data shows that potential impacts of reducing shockwaves on livability and sustainability are promising, with a reduction in total fuel consumption and emissions even at a higher traffic flow in After-SPECIALIST situation. Further work needs to be done to improve the accuracy of emission estimation by including multi-vehicle classes.

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