Increased Consumption in Oversaturated City Traffic Based on Empirical Vehicle Data

Peter Hemmerle, Micha Koller, Hubert Rehborn, Gerhard Hermanns, Boris S. Kerner and Michael Schreckenberg

Abstract. Congestion of urban roads causes extra travel time as well as additional fuel consumption. We present an approach to determine this additional fuel consumption on the basis of empirical vehicle data. We study probe vehicle data provided by TomTom to find the various traffic patterns of urban congestion. We use simulations of these urban traffic patterns based on a stochastic Kerner-Klenov model as input for an empirical fuel consumption matrix compiled from empirical CAN bus signals from vehicles. Our results confirm that in certain congested city traffic patterns vehicles consume more than twice as much fuel as in free city traffic.

Keywords: Urban traffic management, urban congested traffic, traffic signal, empirical fuel consumption, consumption matrix, eco-routing, oversaturated traffic, probe vehicle data, navigation, traffic simulation.

1 Introduction

The commonness of urban congestion and the growing importance of fuel saving create new needs for eco-routing and green traffic management. On the other hand, probe vehicle data from personal navigation devices contribute to a thorough understanding of urban traffic as they allow for the identification of spatiotemporal

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traffic patterns. In this article, we present an overview of the various urban traffic patterns and an approach to determine the additional fuel consumption associated with these traffic patterns. It is important to obtain an algorithm for calculating the fuel consumption due to traffic congestion as an input for traffic management and individual navigation. Our results will be used in an energy efficient routing strategy which is being developed in the project “UR:BAN – Urbaner Raum: Benutzergerechte Assistenzsysteme und Netzmanagement” (Urban Space: User Oriented Assistance Systems and Network Management) funded by the German Federal Ministry for Economic Affairs and Energy [1].

The article is organized as follows. In section 2, we propose a classification method for urban traffic patterns using anonymized probe vehicle data provided by TomTom. Then, in section 3, we explain our approach to compiling a fuel consumption matrix using an archive of recorded CAN (Controller Area Network) bus signals of probe vehicles with combustion engines moving on German highways and in cities. Finally, in section 4, we present some first results for the fuel consumption associated with the various urban traffic patterns.

2 Classification of Vehicle Trajectories

We study anonymized map-matched GPS (Global Positioning System) probe vehicle data provided by the company TomTom. There are both online data (sent directly by the navigation devices) and offline data (the user later connects the TomTom device to a computer), differing in their temporal resolution; offline data is available in steps of one second, and online data in steps of five seconds. However, we do not differentiate between the different types of data in our analysis. The data for each time step consist of timestamp and position (in meters) relative to the beginning of the road section. We use these data to reconstruct the vehicle trajectories and to derive the speed profiles along these trajectories.

The road section in question is a 630m long section of Völklinger Straße in the city of Düsseldorf with a traffic signal at the end and a speed limit of 60 km/h (Fig. 1). We regard this section as suitable because congested traffic is observed there on many days in the data of a stationary video detector [2]. Additionally, no junctions disturb the traffic flow between its beginning and end.

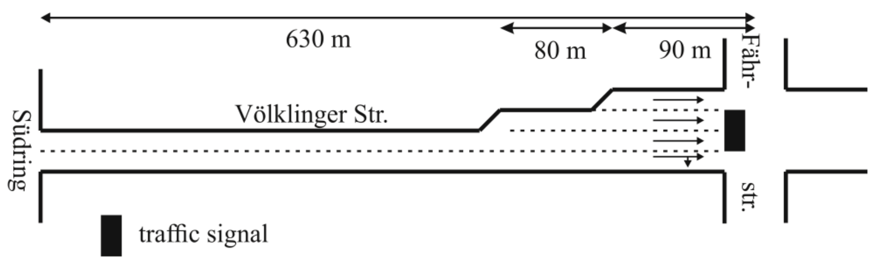

Fig. 1 Road section of Völklinger Straße in Düsseldorf. The speed limit is 60 km/h.

The data basis of our analysis is probe vehicle data from selected days in November and December of 2011 and in February, March and April of 2013. On all of these 19 days traffic breakdowns have been observed by means of a video detector measuring traffic flow and aggregated speed at the beginning of the section. All in all, data from some thousands of vehicles traced on the road section in question form our data basis.

We set up a classification scheme for vehicle trajectories with the average speed of a vehicle and its number of stops on the road section as the criteria for belonging to a class. The relevance of the average vehicle speed for navigation and routing is obvious due to the drivers' common wish to know the fastest route. The number of stops of a vehicle, on the other hand, plays a part in the fuel consumption of a vehicle. The more often a vehicle stops, the more often it accelerates from speed zero, consuming additional energy in each of these acceleration processes. In our scheme, there are a total of 15 classes, as listed in Table 1.

Table 1 Overview of the 15 vehicle trajectory classes

	Average Speed [km/h]		*Number of Stops*	
Class	*Minimum*	*Maximum*	*Minimum*	*Maximum*
1	30	75	0	0
2	30	75	1	1
3	15	30	0	1
4	15	30	2	4
5	10	15	0	1
6	10	15	2	4
7	10	15	5	6
8	8	10	5	6
9	8	10	7	10
10	6	8	5	6
11	6	8	7	10
12	6	8	11	13
13	3.5	6	7	10
14	3.5	6	11	13
15	0	3.5	13	30

Free flow on an urban road with a traffic signal means that the vehicles move with a speed that corresponds approximately to the local speed limit unless they have to stop at the signal. Whenever a queue is formed upstream of the traffic signal during a red phase, all cars in that queue can pass the signal during the next green phase; the traffic signal is said to be *undersaturated.* Therefore, in urban free flow a car stops zero times or once. Classes 1 and 2 are associated with urban free flow, where we distinguish between drives without a stop (class 1, Fig. 2) and drives with one stop at the traffic light (class 2, Fig. 3). In the case of green wave control we can assume that vehicles can pass road sections without any stops.

In such cases vehicles have almost constant speeds and no stops in undersaturated traffic. From Fig. 2 to Fig. 8 the position of the traffic signal at 630m is marked by a horizontal line in the left-sided figures; the vertical line in the right-sided figures indicates the point in time when the vehicle passes the light signal.

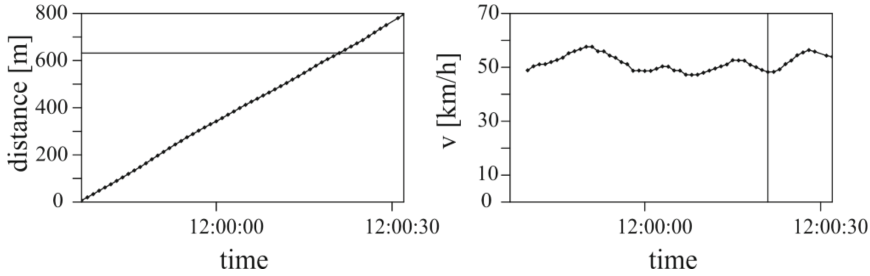

Fig. 2 Representative of class 1 (undersaturated traffic, no stop); vehicle trajectory and speed profile from February 2013

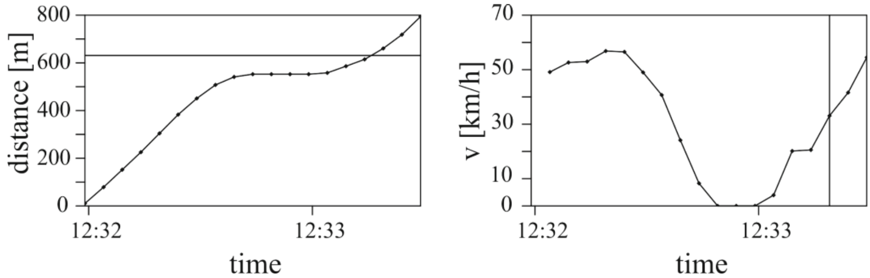

Fig. 3 Representative of class 2 (undersaturated traffic, one stop); vehicle trajectory and speed profile from November 2011

Classes 3 to 15 cover the various traffic patterns associated with urban congested traffic. For instance, class 3 trajectories have zero or one stops, but the average speed is much lower than in free flow (Fig. 4). Class 4 trajectories lie in the same speed range, but there are two to four stops, as in the example shown in Fig. 5. These additional stops occur due to the emergence of *moving queues* that move upstream from the location of the traffic light. Moving queues are a well-known phenomenon of *oversaturated* traffic signals where not all of the cars in a queue can pass the traffic signal during one green phase. These examples demonstrate how empirical vehicle trajectories can display considerable qualitative differences despite similar average speeds.

It should be noted that the distribution of the vehicle speed shown in Fig. 4 related to class 3 is an empirical example of *synchronized flow* in oversaturated urban traffic the theory of which has been developed recently [3]. In synchronized flow, the speed of a vehicle is considerably lower than the free flow speed the maximum value of which is limited to 60 km/h via traffic regulations on the street

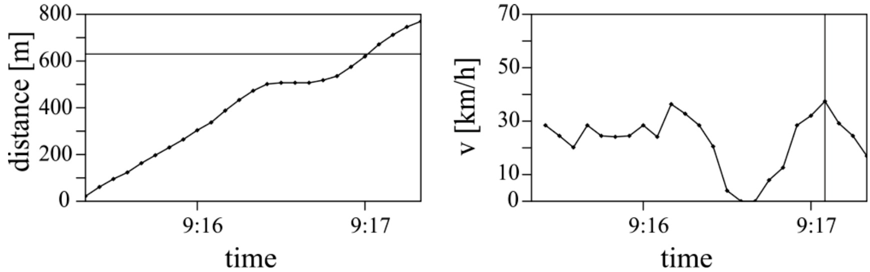

Fig. 4 Representative of class 3; vehicle trajectory and speed profile from February 2013

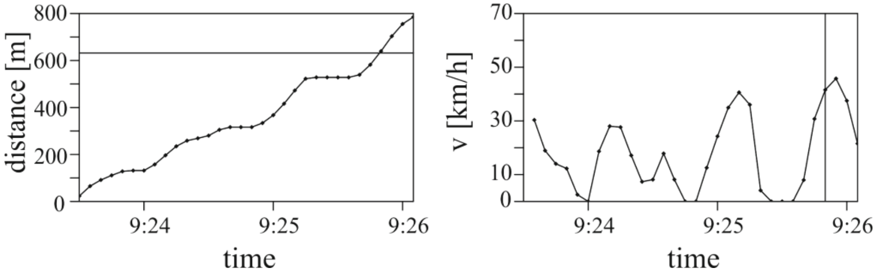

Fig. 5 Representative of class 4; vehicle trajectory and speed profile from February 2013

under consideration. However, in contrast to a vehicle queue within which vehicles are in a standstill and, therefore, traffic flow is interrupted through the queue, there is no flow interruption in synchronized flow [3-9].

Classes 8 and 9 repeat the finding that trajectories with average speeds within the same range can differ with regard to their stops. In the examples depicted in Figs. 6 and 7, not only the numbers of stops are different. Also, the stops are distributed along the road section differently. The representative of class 9 stops three times in the first 200 meters of the road section. In contrast, there is only one short stop in the first 200 meters for the class 8 example, but the vehicle moves with a low speed. On the remaining part of the road section, the stops are considerably longer. This speed profile can be explained with the dissolution of moving queues upstream of the traffic signal and the forming of synchronized flow [3].

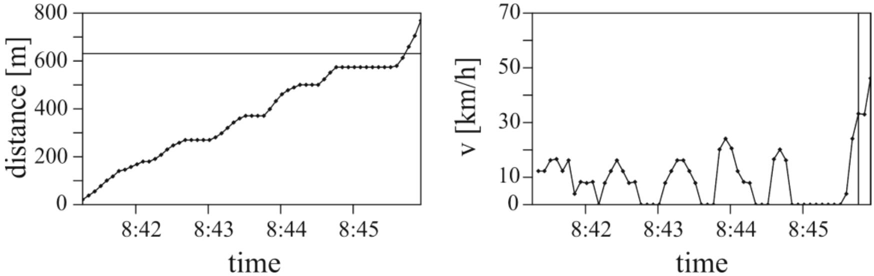

Fig. 6 Representative of class 8; vehicle trajectory and speed profile from November 2011

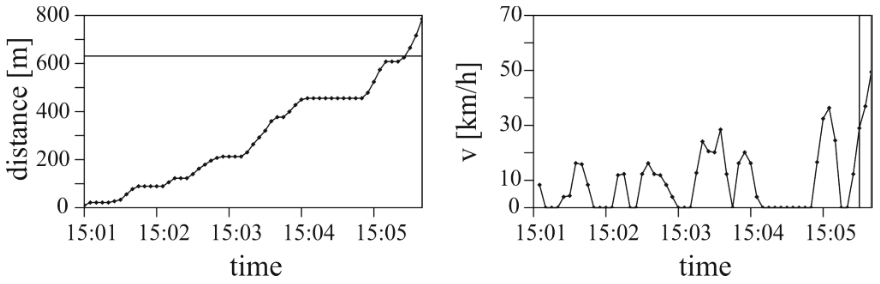

Fig. 7 Representative of class 9; vehicle trajectory and speed profile from February 2013

The highest degree of urban traffic congestion observed in the available data is associated with class 15. An example can be found in Fig. 8, where a sequence of numerous stops and short passages between these stops can clearly be seen.

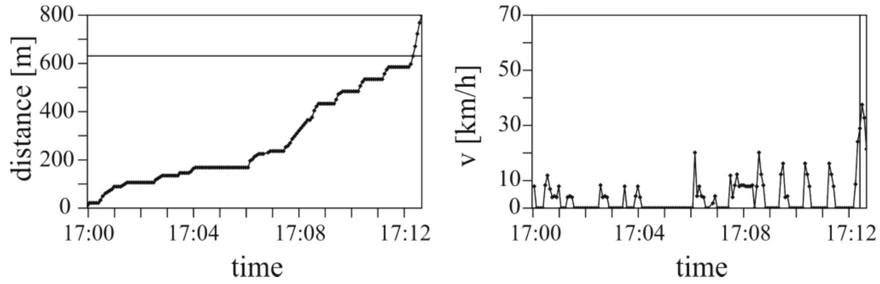

Fig. 8 Representative of class 15; vehicle trajectory and speed profile from February 2013

3 Empirical Fuel Consumption

We examine a recorded archive containing empirical data read from the CAN bus of vehicles driving on German freeways and urban areas. Current velocity, acceleration and instantaneous fuel consumption were recorded multiple times per second. We investigate data of about 90 hours from one vehicle to build a vehicle specific consumption matrix which is shown in Fig. 9. The resolution for velocity is 2 km/h, and the resolution for acceleration is 0.1 m/s². In total, more than 10 million measured data points have been assigned to their corresponding matrix element and aggregated by applying the statistical median operation for each matrix element. Blue pixels indicate consumption values near zero; red pixels indicate high fuel consumption values. A white element in the consumption matrix means that this combination of velocity and acceleration never appears in the data from 90 hours of measurements. As we intend to use the consumption matrix for the determination of the additional consumption caused by specific traffic situations, for instance different patterns of congestion, a normed scale for the fuel consumption is sufficient.

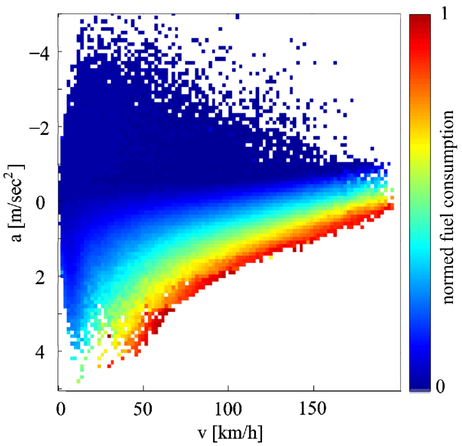

Fig. 9 Visualization of an empirical consumption matrix with the parameters acceleration *a* and velocity *v*

4 Increased Consumption in Urban Oversaturated Traffic

Empirical TomTom data do not easily allow a precise determination of the acceleration profiles of vehicles because the devices do not measure acceleration directly (it must be derived from the GPS signal with its impreciseness). Thus, the empirical trajectories and speed profiles described in section 2 cannot directly be used as input for the consumption matrix introduced in section 3.

To close this gap, obtain realistic acceleration values and make a large variety of vehicular congested traffic patterns available, we use a microscopic simulation of vehicular traffic based on a stochastic Kerner-Klenov three-phase traffic flow model [4-6]. The choice of simulation parameters aims at an accurate qualitative reproduction of the empirical vehicle trajectories. Therefore, the classification scheme for empirical vehicle trajectories can be applied to the simulated vehicle trajectories as well. We calculate the fuel consumption for each trajectory by means of the consumption matrix. We denote the average fuel consumption per traffic class N as C_{classN}. The average additional fuel consumption C^{RA}_{classN} relative to class 1,

$$C^{RA}_{classN} = \frac{C_{classN}}{C_{class1}}, \tag{1}$$

is depicted for the first 11 classes in Fig. 10. A gap between classes 1 and 2 of undersaturated traffic can clearly be seen, hinting at the additional fuel consumption caused by a stop at the traffic light. However, the gap between classes 2 and 3 is much larger. The latter gap and the increase in consumption from class 3 to class 11 illustrate the extent to which oversaturated city traffic causes additional fuel consumption. In an oversaturated traffic situation corresponding to class 11, a vehicle with a combustion engine consumes more than twice as much fuel as in the ideal traffic situation corresponding to class 1.

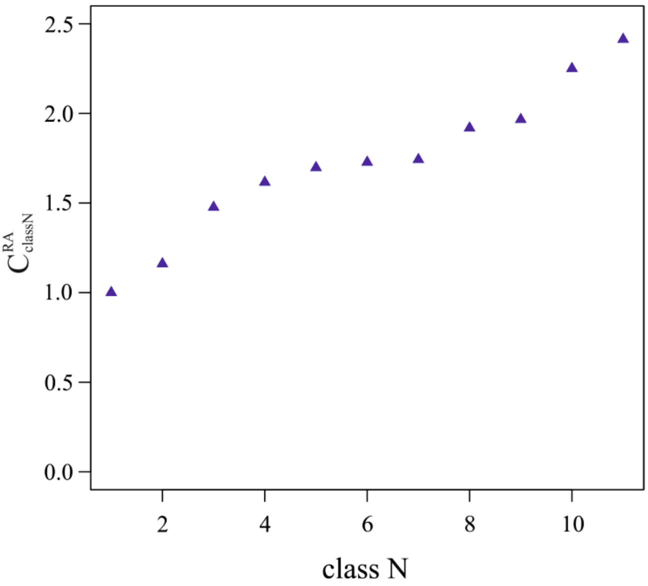

Fig. 10 Average fuel consumption for the first 11 traffic pattern classes as a multiple of the average fuel consumption of class 1

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