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Influence of driver characteristics on emissions and fuel consumption

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Abstract

Fuel consumption and atmospheric pollution emissions of vehicles depend on driving conditions, the characteristics of the driver and the car. The influence of driving style on the environmental aspects of a car journey has been investigated. Driver characteristics were determined by a Driver Behaviour Questionnaire and observed acceleration and deceleration behaviour. That results in four types of drivers with similar characteristics within a type group. We measured 56 trajectories of 28 drivers using GPS devices. The measurements were done on a route of 8.4 km in an urban environment in Chengdu (PR China). From the trajectories, the emissions and fuel consumption were determined with the Comprehensive Modal Emissions Model. The results were related to the traffic control along the journey resulting in fuel consumption and emissions per stop and per second idling. There are significant differences in saturation flow, emissions and fuel consumption between different driver types. Cautious, novice drivers have the lowest emission and fuel consumption and give the lowest saturation flow and have the lowest cruise speed; experienced smooth driving drivers give a high saturation flow while keeping fuel consumption and emissions also low. Aggressive experienced drivers have a high saturation flow and fuel consumption / emissions. Therefore, microscopic traffic models that simulate emissions and fuel consumption should take the differences between driver types into account.

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1. Introduction

The determination of fuel consumption and air pollution emissions (shortly: emissions) of road traffic is important for policy making and the management of the driving conditions on the roads.

It is well known that different people behave differently when they drive their car. The performance of a novice driver is different from an experienced driver. Impatient and aggressive driving is characterized by a fast reaction to a changing driving situation, strong accelerations and braking and short headways to a car in front. The applied accelerations and speeds during a trip determine emissions and fuel consumption (e.g. Nam *et al.* 2003).

In previous research, Li *et al.* (2015) analysed different characteristics of drivers (acceleration at different speeds, self-assessment by a questionnaire etc.). Based on factor analysis of 23 personal characteristics they identified four types of drivers. These driver types are given in the following description:

1. Aggressive, macho and unsteady
2. Conservative, careful, novice
3. Professional, smooth going
4. Experienced, speeding.

Drivers with different types behave differently, which has an influence on the fuel consumption and emission of their car.

In urban road networks the traffic control and road characteristics determine for a great deal the driving, deceleration and acceleration of cars. Brundell-Freij and Ericsson (2005) showed that 9 factors are dominant for the fuel consumption and emissions, among which the stopped time, speed changes and the time driven with high accelerations and high engine speed. These factors are especially influenced by traffic control and by the characteristic of the drivers. While Brundell-Freij and Ericsson and Nam *et al.* (2003) determined the characteristics of the drivers that participated in their research ex-post based on their driving performance and a few personal characteristics, we have determined the classification ex-ante based on 23 personal characteristics.

Traffic control can be optimized to reduce fuel consumption, which is normally done by reducing the number of stops. However, the way drivers react on traffic lights is different: some slow down gradually, others use their brakes just on a short distance from the stop line. The acceleration can be smooth or aggressively. Those all have influence on the emissions and fuel consumption. Therefore, the most important factors related to the emissions and fuel consumption for urban trips are the driving pattern as related to the driver type and the traffic conditions. In the research reported in this article we want to show that the ex-ante characterization of drivers is a useful instrument to analyse different driving behaviour and to show that different driver types need different traffic control.

The following section gives a short introduction on the models that can be used to estimate emissions and fuel consumption from trajectories. In order to analyse the influence of the driving behaviour and personal characteristics we measured how 28 drivers in Chengdu (the capital of Sichuan province of China) were driving along a track in an urban environment. This survey is described in the section 3. We have analysed the driving behaviour and the relation with the driver type. That is described in section 4. Finally in section 5 we analysed the traffic control on a part of the test route and investigated whether the optimized traffic control depends on the driver type.

2. Modelling emissions and fuel consumption

In order to get grip on the influence of traffic characteristics on emissions and fuel consumption several models have been developed for the emissions of individual motor vehicles. The U.S. Environmental Protection Agency (2003) developed the MOBILE6 model based on measurements of emissions and fuel consumption of cars in laboratory situations driving the standard driving cycles (Barlow *et al.* 2009). Later, Portable Emissions Monitoring Systems (PEMS) have been used to obtain data on emissions in specific situations like sudden accelerations (Frey *et al.* 2006). In 2006 the Comprehensive Modal Emission Model (CMEM) has become available, which contains a database of various motor vehicles. This model not only gives emissions and fuel consumption in different driving conditions, but also simulates the effect of the age of a motor vehicle, the state of maintenance, ambient air

temperature etc. Also in Europe such kind of models have been developed (e.g. Joumard, 1995, Smit et al. 2005, Hirschman et al. 2010).

Emissions and fuel consumption from automobiles depend on the speed, acceleration, and of course on the engine type, operation mode of the engine, the vehicle type and condition, the temperature etc. The emissions and fuel consumption are found to be determined by the power given by the engine (Jimenez-Palacios 1999). For this vehicle specific power VSP the following formula is applicable for driving on a flat road (Barth et al., 2000, Scora and Barth. 2006):

$$VSP = (M.a + \frac{1}{2} C_d.A.\rho.v + M.g.C_r).v / 1000 \text{ [kW]}, \quad (1)$$

where M is the mass of the vehicle in kg, A is the surface area in m^2 , C_d is the drag coefficient, ρ is the air density, C_r is the rolling resistance coefficient and g is the gravity constant. The quantities in formula (1) that depend on the driver are the speed v (m/s) and acceleration a (m/s^2).

In the Comprehensive Modal Emissions Model (CMEM) manual (Scora and Barth. 2006) a simplified formula is given (4.1 in the CMEM manual):

$$VSP / \text{ton} = 0.132 v + 0.000302 v^2 + 1.1 v.a \text{ [kW/ton]} \quad (2)$$

where constants are filled in in equation (1) that apply to the most common type of car in the USA. Frey et al. (2006) propose a different formula based on their own research with a term v^3 , which is not easy to explain from the physical process of a moving vehicle:

$$VSP = 0.132 v + 1.1 v.a + 0.0003202 v^3 \text{ [kW/ton]} \quad (3)$$

This formula (3) has been used by a few other researchers e.g. Song et al. (2015). In this article we use the functional form of equation (2) which has a close relationship with the physical process of a driving vehicle.

In order to determine the speeds and accelerations needed to calculate the VSP of a trip, the trajectories of cars were measured for different drivers.

3. The data collection

The driving patterns of 28 drivers were measured while they were driving as leader-follower pairs in two consecutive driving cars. All drivers were Chinese, with different background and experience. Test trips were made on a track in the north-west of Chengdu (P.R. China) by drivers using their own ordinary passenger car and were asked to drive as they normally do. The track consisted of ordinary urban roads with 22 signalized intersections and the test trips were executed in normal, uncongested traffic conditions. Cars were moving in pairs and the car following behaviour of the following car was measured. The drivers drove along the route twice and switched position so that we obtained 56 trajectories, 28 of them as leading cars, and 28 as followers. The full set of trajectories was used to determine the VSP .

The data were obtained with portable GPS devices (Garmin 64S) installed in each car. The GPS positions were measured with frequency 1 Hz. This method is similar to the one used by e.g. Song et al. (2015). A check was made of the accuracy of the GPS. The errors in the observations of the position by the GPS were of the order of 2 m, after a 'warming-up' time of 3 minutes. The positions measured by GPS were projected on the digitized track and smoothed by Kalman filtering. This procedure removed the unrealistic extreme accelerations.

The second important aspect of the vehicle trips was the characteristic of the drivers. As far as the authors know, the driver characteristics have not been taken into account in most research on the modelling of emissions and fuel consumption (Li et al. 2013, Hirschmann and Fellendorf. 2010, Song et al. 2015, Shabihkhani and Gonzales 2013). In some studies (e.g. Nam et al 2013 and Brundell-Freij and Ericsson 2005) aggressiveness was used ex-post to explain the fast acceleration pattern of some drivers. Li et al. (2015) developed a classification scheme for drivers. They analysed the driving behaviour, especially acceleration at different speeds, and the self-assessment by a Driver Behaviour Questionnaire (DBQ) of 36 drivers in another city in China (Changsha). Four factors were identified

which explain 75% of the variance of the driver characteristics. The reduction to four factors is possible because there is correlation between the characteristics which makes it possible to combine or ignore some of them.

From the DBQ an aggressiveness score was determined based on actions such as ‘crossing stop-line during the red phase’, ‘offences in the last year’, etc. as given in the answers to the DBQ. This score appeared to be an important explanatory variable for the driving behaviour. In total 23 characteristics of drivers were determined, such as:

- DBQ aggressiveness score;
- Gender (78.6% male, 21.4% female);
- Age (21 to 60, average 38.0 years, standard deviation 8.7);
- Driving experience (1 to 20 years, average 8.4, standard deviation 5.5 years);
- Experienced traffic density during the test driving (derived from number of stops and average speed);
- Mean acceleration and its standard deviation at low speeds (< 10 km/h);
- Mean acceleration and its standard deviation at higher speeds (> 10 km/h);
- Mean deceleration and its standard deviation at low speeds;
- Mean deceleration and its standard deviation at higher speeds.

The same classification scheme that was developed for drivers in Changsha was used for the 28 drivers involved in the survey done in Chengdu. Factors analysis applied to the 28 sets of driver characteristics showed that there are 4 factors that explain 67% of the variance of these characteristics for these 28 drivers in Chengdu. These factors are combinations of the original characteristics and characterized as:

1. F1 related to deceleration and acceleration at low speeds (< 10 km/h);
2. F2 related to accelerations at all speeds;
3. F3 related to aggressiveness score and decelerations at higher speeds;
4. F4 related to accelerations at very low speeds (<10 km/h) and driving experience.

The following typology was identified (Li, 2014) and characterized as follows:

1. Aggressive, macho, unsteady (High F2, High F3);
2. Conservative, careful, novice (Low F2, Low F3, Low F4);
3. Professional, smooth going (High F1, High F4);
4. Experienced, fast driving (High F2, Low F3, High F4).

Age and gender did not have a significant influence on the classification.

The fact that the drivers have different acceleration and deceleration behaviour makes it necessary to deal with them specifically in microscopic simulation programs. The acceleration and deceleration behaviour influences the emissions and fuel consumption and also the saturation flow (Li 2015), so the assumption of a single driver type that is implicitly used in the specification of most simulation programs is not appropriate.

4. Driver specific fuel consumption and emissions

We compared the *VSP* by applying equation (2) for the trajectories for every driver. The speed per second was used as input for the *VSP* calculation. The average *VSP* per meter were aggregated per driver class. Table 1 shows the results. The conclusion is that the hypothesis H0 that driver type 1 has the same average *VSP* as type 2 is less probable than 1% and should be rejected, also the hypothesis that type 1 and 3 have the same *VSP* is less probably than 1% and for the comparison between type 1 and 4 the probability that the *VSP* values are the same is less than 1%. The difference between driver type 3 and driver type 4 is significant at $P < 1\%$. Driver type 2 is not significantly different from driver type 3 and 4

Table 1 Comparison of the average Vehicle Specific Power for 56 trips and the standard deviations

| Driver type | Number of measured trips | Mean <i>VSP</i> /ton/m | Standard deviation |
|-------------|--------------------------|------------------------|--------------------|
| 1 | 10 | 1.632 [kW/ton/m] | 0.027 [kW/ton/m] |
| 2 | 28 | 1.571 | 0.026 |
| 3 | 10 | 1.598 | 0.055 |
| 4 | 8 | 1.571 | 0.026 |

The 56 trips were different even though they were made over the same track. Some drivers had to wait more often and longer than others at the signalized junctions. A closer analysis was done for the trajectories between the grey lines in Figure 1 with a length of 1800m with 4 signalized intersections. We determined the number of stops and idling time for each trajectory.

From these trajectories we analysed the relation between fuel consumed and the number of stops. The software of the CMEM (Scora and Barth. 2006) converted the trajectory positions into speeds and accelerations and used that to estimate the fuel consumption. The same could be done for emissions of HC (Hydro carbons), CO₂ (carbon dioxide) and NO/NO₂ (nitrogen oxides). The results differ between the driver types. Figure 2 shows the relation between the number of stops and the fuel consumption over the trip of 1800 m. For each additional stop the vehicle consumed 8.83 grams additional fuel for the aggregated driver population. The disaggregated presentation of the relative fuel consumption of stops shows that per stop results in 9.1075 grams (driver type 4) to 18.764 grams (driver type 1). Table 2 shows the additional fuel consumption and emissions per stop for every driver type.

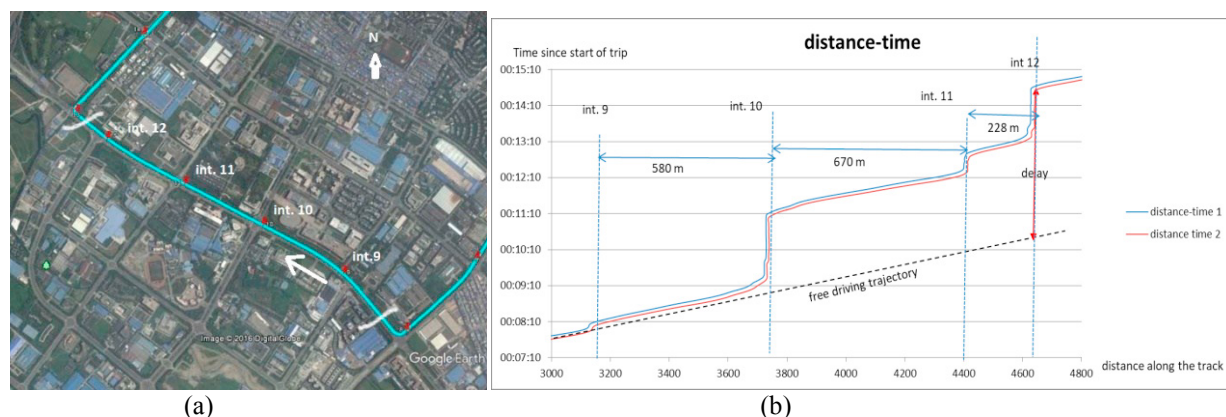


Figure 1 (a) The Xixin Road for which the detailed trajectory analysis has been executed; (b) example of a trajectory of a leading and a following vehicle showing the delay and number of stops at the signalized intersections

Table 2 Estimated fuel/ emission per stop for each driver type. HC emissions per stop are not significantly different from 0 for driver type 3 and 4

| driver type | 1 | 2 | 3 | 4 |
|----------------------------|--------|--------|-----------|-----------|
| Fuel grams/stop | 18.764 | 16.477 | 16.421 | 9.1075 |
| HC grams/stop | 0.0675 | 0.0147 | Not sign. | Not sign. |
| CO ₂ grams/stop | 52.677 | 51.739 | 53.742 | 29.182 |
| NO _x grams/stop | 0.087 | 0.0318 | 0.0122 | 0.0033 |

This analysis shows that driver type makes a significant distinction in fuel consumption and emissions. Driver type 4 can be characterized as the most environmentally friendly in terms of emissions and fuel consumption. The distinctions between 1 and 3 are insignificant.

5. Consequences for traffic control

Traffic control is an instrument to manage the use of the road space at intersections. In most practical situations traffic safety and the management of the road capacity are the most important criteria for the optimization of the signal schemes. The management of the road capacity is in general optimized by minimizing the sum of the delays of all road users that have to pass over the intersections. Also emissions and fuel consumption can be used as evaluation criteria (Chamberlin *et al.* 2011, Hirschmann and Fellendorf 2010, Scabikhani and Gonzales 2013). The relevant knowledge needed for this evaluation is the relation between traffic control and fuel consumption /

emissions. Until now, only Li et al. (2015) collected data that show the role of the type of drivers. In this research we compare several factors related to traffic control for different driver types.

For the evaluation and optimization of traffic control not only the characteristics with respect to emissions and fuel consumption are important, but also the saturation flow and the cruise speed. The following subsections discuss these issues.

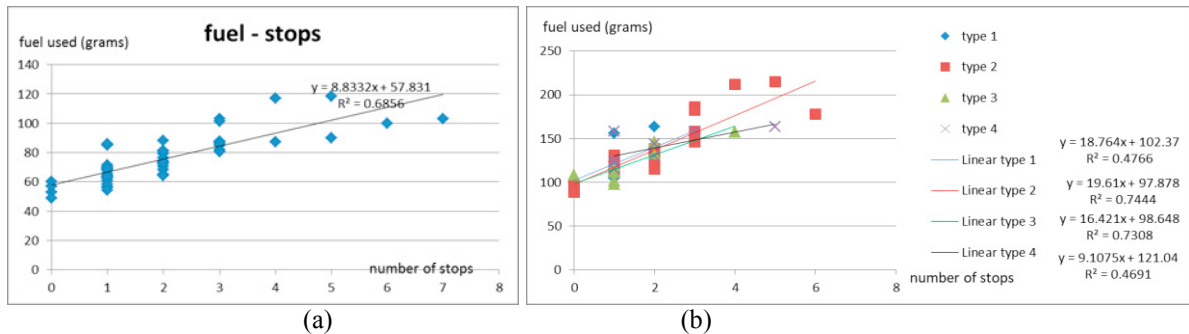


Figure 2 Relation between number of stops and fuel consumption; (a) for all trips, (b) disaggregated per driver type

5.1 Saturation flow

One of the most important parameters in the optimization of traffic control is the saturation flow, i.e. the maximum number of standard passenger cars [pcu] that can pass a stop line during an hour green. In fact this is measured on much shorter time intervals than an hour, a period of 10 to 20 seconds during the green phase while there is still a waiting queue. The saturation flow is inversely proportional to the minimum headway between vehicles driving at low speeds (HCM 2010). These headways have been determined for every driver when he/she was following the car in front. A significant difference was observed between the four driver categories.

The headway was determined from the headway distance between the leading and the following car at low speeds divided by the speed of the following car as:

$$h = \frac{L}{v_F} [s] \quad (4)$$

Where L is the headway distance between the leading and the following vehicles [m]; v_F is the speed of the following vehicle [m/s].

From the distribution of the headways the most likely value was selected (an average value was not suitable because the distribution has a long tail in the high headway values). The statistical analysis of the headways was made for every driver type as shown in Table 3.

The headway for drivers of type 2 is significantly longer than the headway for the drivers of other types. That means that drivers of type 2, i.e. novice, cautious and conservative drivers give a lower saturation flow rate than the other drivers. There is also a significant difference (at $P=5\%$ level) between drivers of type 4 (experienced and speeding drivers) and drivers of type 3 (professional and smooth going) (at $P=10\%$ level). The differences between types 1 and 3 and between types 1 and 4 are not significant.

The conclusion is that the distinction of drivers in types according to the factor analysis is meaningful when we look at saturation flow rates. For the calibration of microsimulation models the distinction should be made at least between unexperienced, conservative (type 2) and the other drivers.

5.2 Cruise speed

Another relevant characteristic of traffic flow in traffic control is the cruise speed, i.e. the speed that drivers keep when they can choose their speed without constraints of queues and traffic control. In Table 3 the cruise speeds for the different driver types are shown. It is obvious that drivers of type 2 drive significantly slower than the drivers of the other types. The differences between the other driver types are less strong: only between driver types 1 and 4 the significance of the difference is above the 1% level.

The consequence of this difference in cruising speeds is that coordination between intersections or a green wave should be different for different driver types. Especially driver type 2 has a significant lower cruise speed which has a consequence for the optimal coordination on corridors with through going traffic and signalized intersections.

Table 3 Mean headway and mean cruise speed per driver type of accelerating drivers at low speed (<5 km/h), distinguished with respect to the driver classification.

| Driver class | Number of drivers | Most used headway (s) | Standard deviation (s) | Saturation flow [pcu/h] | Cruise speed (km/h) | Standard deviation (km/h) |
|--------------|-------------------|-----------------------|------------------------|-------------------------|---------------------|---------------------------|
| 1 | 5 | 2.47 | 0.65 | 1457 | 55.8 | 3.3 |
| 2 | 14 | 3.5 | 0.83 | 1029 | 48.2 | 3.5 |
| 3 | 5 | 2.41 | 0.47 | 1494 | 54.0 | 4.6 |
| 4 | 4 | 2.83 | 0.49 | 1272 | 51.1 | 2.9 |

5.3 Weighted optimization

A common way to optimize traffic control is to minimize a linear combination of delay and stops (e.g. Robertson 1969). For networks the cycle times of the intersections, the structure of the control scheme, the green splits and coordination can be chosen to minimize an objective function of a weighted sum of stops and delay. The weight of one stop with respect to one second delay can be chosen as the ratio of the emissions /fuel consumption for one stop, compared to that for one second delay. The measurements of the trajectories done in this research and the processing using CMEM give the ratio between one stop and one second waiting time is shown in Table 4.

Table 4 Ratio of fuel /emission per stop and per second idling

| driver type | 1 | 2 | 3 | 4 |
|-----------------|----------|----------|----------|---------|
| fuel | 51.27 | 45.02 | 44.87 | 24.88 |
| HC | 0.06 | 0.01 | 0.00 | 0.00 |
| CO ₂ | 10750.41 | 10558.98 | 10967.76 | 5955.51 |
| NO _x | 321.03 | 117.34 | 45.02 | 12.18 |

The ratios for fuel consumption, CO₂ and NO_x are very high. Some trials with the signal optimization program TRANSYT (Robertson et al. 1969) to use these weights in the optimization of the signals timing result in unrealistic settings where side roads get very short green times leading to oversaturation and long waiting times while traffic on the main road get coordination and long green phases to reduce the number of stops. Of course, the signal settings are different when they are calculated for different driver types.

Even in the case that the optimization of the signals were not done for the weights as shown in Table 4 the settings were different for the four driver types since the saturation flows – important for the cycle time optimization – and cruise speeds – important for the coordination between intersections – differ.

6. Conclusions

The measurement of the trajectories of the 28 drivers on a track consisting of urban roads in Chengdu shows that there are important differences between drivers. The drivers were categorized in 4 types according to a methodology that was developed for a group drivers in Changsha. Within each of these 4 types the drivers behave rather homogeneously. The differences are visible in acceleration, deceleration and speed patterns. Processing of the trajectories with the Comprehensive Modal Emission Model shows that the differences in driving performance have impact on the emissions and fuel consumption. Conservative, novice drivers of type 2 differ significantly from the other drivers with respect to fuel consumption and emissions. Furthermore, the analysis of the driving behavior shows that the cruise speed is lower and headways at low speed are longer. Drivers of type 4 (experienced drivers with preference for faster speed) give also a relative lower fuel consumption and emissions but without having

longer headways and lower cruise speed as those from the conservative, novice drivers of type 2. The other groups of drivers (aggressive / unsteady of type 1 and smooth driving of type 3) are not significantly different for most aspects and had a worse performance for fuel consumption and emissions.

Since in China nearly 40% of the drivers have less than 3 years driving experience (Traffic Management Bureau 2012), the type 2 drivers form a large group of the road users. It can be expected that gradually a shift will occur from type 2 to the other types. Continuing driver education could stimulate that this shift goes into the direction of type 4 and especially type 1 drivers will not become the most common in the future.

The fact that drivers have different behaviour has the consequence that simulation programs should have different driver types. The trajectory data that have been obtained in this research will be used to calibrate driving models so that different parameters can be determined to characterize the car following behaviour in simulation models.

It is likely that the results are applicable in other Chinese cities, but due to the specific driving culture in Chinese cities, the results in other countries might be different. Still the distinction of drivers in several types is probably also a valid approach in other countries. The common assumption that there are just two driver types: aggressive and non-aggressive, is too simplistic.

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