ROAD CATEGORY DEPENDENCE OF VARIATIONS IN LONGITUDINAL DRIVING BEHAVIOUR

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ABSTRACT

The paper analyses the parameters and variables used in different longitudinal driving behavioural studies. Furthermore, it investigates the variation of the longitudinal driving behaviour with different road characteristics by using a developed experimental platform (including an instrumented vehicle and advanced data collection and analysis tools). In this study two types of longitudinal driving behaviour are distinguished: car-following (both restricted and non-restricted), and approaching. In addition, longitudinal driving behaviour is measured by control variables, such as vehicle speed, relative speed (between host vehicle and lead vehicle), accelerator pedal release, brake pedal activation, distance headway, time headway, time-to-collision, and gap closing. During two phases, driving behavioural data were collected on different roads of categories in Beijing, and were analysed based on the developed analysis method and data processing programme. The preliminary results show that the longitudinal driving behaviour varies with road characteristics. The results contribute to the design and evaluation of in-vehicle driving assistance systems for improving traffic safety, energy efficiency and traffic harmonisation.

1. BACKGROUND

Road traffic safety, environment and (energy and fuel) efficiency are major issues in the field of traffic and transport. In order to deal with these issues systematically, economically and cost-effectively, an innovative approach could be to implement suitable driving assistance systems (also called ADAS - advanced driver assistance systems), e.g. dynamic speed assistance, (forward) anti-collision (collision warning, collision mitigation and collision avoidance), intersection support, lane keeping assistance, lane change assistance, dangerous spots warning, adaptive cruise control, stop-and-go, and autonomous driving [Lu, et al., 2005]. A hybrid design of in-vehicle dynamic speed assistance (DSA) that adapts to driving behaviour is considered to be the most effective, affordable and easily available system. It is applicable for all road categories, for enhancing road traffic safety, reducing fuel consumption, and mitigating shock waves, and short-term implementation of in-vehicle DSA systems in P.R. China is feasible [Lu, et al., 2010b].

For the design and the evaluation of in-vehicle driving assistance systems, as well as to manage traffic in general, calibration of driving behavioural models is a prerequisite. Longitudinal driving behaviour could be studied by simulation, driving simulator, and/or real world experiment. For the latter, relevant real-world behavioural data need to be collected, e.g. by using an instrumented vehicle test bed [McCall, et al., 2004; Aufrere, et al., 2003; Brackstone, et al. 1999; Gantzer & Rockwell, 1968; Chandler, et al. 1958]. In addition, collected longitudinal driving behavioural data should be analysed, by using reliable and robust tools and by identifying proper parameters and variables.

This paper focuses on the microscopic analysis of longitudinal driving behaviour on (different sections of) three road categories in Beijing: access road, distributor road and flow road. Note that road categorisation corresponds to Geographic Data Files (GDF) Functional Road Class (FC) levels, but that GDF gives no further specification of the classes than the names main roads, first class roads, etc., up to ninth class roads. A more specific typification of the five first and most important classes is: flow road, through road, distributor (or arterial) road, collector road and local access road, for which categories further urban (built-up area) roads and extra-urban (outside built-up area) roads could be distinguished [Lu, et al., 2006]. In a recent study into possible variation of longitudinal driving behaviour with road characteristics, it is concluded that “no effect of road type was found within this research.” [Brackstone, et al., 2009]. However, this conclusion leaves room for argument (for details see the next section). Road characteristics, including elements like functionality, layout, environment, traffic intensity, legal speed limits, and maximum design and real-time actual traffic flow are different for different road categories. Therefore, it is feasible that road category affects longitudinal driving behaviour.

In view of these considerations, the following three research questions are formulated:

1) Why do different (peer reviewed) researches on longitudinal driving behaviour show different results?
2) How to study whether road category affects longitudinal driving behaviour?
3) Are there any differences in longitudinal driving behaviour on different (sections) of the same road category? If so, how can these be explained?

To answer these questions, some longitudinal driving behavioural studies are reviewed, especially the use of the parameters, and the settings of the control objectives. Furthermore, a developed experimental platform is introduced, including an instrumented vehicle and advanced data collection and analysis tools for comprehensive driving behavioural study. Behavioural data were collected in Beijing, and were analysed based on the developed analysis method and data processing programme. The preliminary results of the comparative analysis of the longitudinal driving behaviour on different sections of each of the mentioned road categories are presented. In addition, a discussion is provided and conclusions are drawn.

2. PARAMETERS AND CONTROL OBJECTIVES FOR LONGITUDINAL DRIVING BEHAVIOUR STUDY

Longitudinal driving behaviour is an essential issue in the area of traffic and transport. The dissimilarities of longitudinal driving behaviour have an impact on traffic safety, energy efficiency, environmental impact and traffic harmonisation. In various researches, longitudinal driving behaviour has been extensively studied from different perspectives, such as psychology (see e.g. [Boer, 1999; Vogel, 2003; Adell1, et al., 2008;]), ergonomics (see e.g. [Van der Hulst, et al., 1998; Van Winsum & Heino, 1996; Van Winsum, 1999; Brackstone, 2000]), physics and traffic engineering (see e.g. [Bexelius, 1968; Gipps, 1981; Minderhoud, 1999; Kerner & Klenov, 2004; Kesting, 2008; Ossen, 2008]).

Two types of longitudinal driving behaviour could be distinguished: car-following and approaching; car-following could be further classified as: restricted (or forced) car-following and non-restricted (or free) car-following [Lu, et al. 2010a]. The microscopic car-following behaviour could be described in different ways, e.g. by using headway [Taieb-Maimon & Shinar, 2001], or TTCi (time-to-collision inverse) [Lu, et al. 2010a]. Note that the term “car-following” is used for the more general term “vehicle following” in this paper.

Parameters that are in general used in the longitudinal driving behavioural study are related to host vehicle speed (V), time headway (THW), distance headway (DHW), time-to-collision (TTC) and relative speed (Vr, between host vehicle and lead vehicle). From the perspective of automotive engineering, additional parameters for specifying longitudinal driving behaviour are, for instance, engine running time, yaw rate, steering angle, lateral acceleration, longitudinal acceleration, brake pedal signal and acceleration pedal position.

Until now, behavioural models concerning psychological factors are still insufficient to cover all different aspects of human behaviour (see e.g. [Van Winsum, 1999]). Furthermore, current assumptions on individual driver behaviour in traffic flow theory and traffic engineering are rather coarse (see e.g. [Toledo, 2007; Boer, 1999]). In general, the main limitation of current traffic flow simulation models is that in many cases they do not adequately capture the sophistication of drivers or the dynamic aspects of driving behaviour [Tampère, 2004]. For the review of parameters in the car-following models see also [Brackstone & McDonald, 1999].

Control objectives that are generally used in the simulation models include: reaching a safe distance or a desired distance to the direct lead vehicle; synchronising speed with the direct lead vehicle or synchronising speed difference with lead vehicles further downstream; reaching a speed in line with distance to the direct lead vehicle, or to leaders further downstream; or reaching the desired free speed. Table 1 summarises the control objectives of various longitudinal driving models, i.e. Gipps (Gipps, 1981), CHM (Chandler et al., 1958), Bexelius (Bexelius, 1968), Tampère (Tampère, 2004), A&L (Addison and Low, 1998), IDM (Intelligent Driver Model) (Treiber et al., 2000), OVM (Optimal Velocity Model) (Bando et al., 1995a, Bando et al., 1995b), and Lenz (Lenz et al., 1999). Note that only in Gipps' model, speed is used as the control variable, and human limitations is included to a limited extent. All other mentioned longitudinal driving models use acceleration as the control variable, without inclusion of human limitations. For model descriptions see also [Ossen, 2008].

Table 1 - Overview of control objectives in longitudinal driving models (adapted after [Ossen, 2008])

Control objective	Gipps	CHM	Bexelius	Tampère	A&L	IDM	OVM	Lenz
reaching a safe distance	X							
reaching a desired distance to the direct leader				X	X	X		
synchronizing speed with direct leader		X	X	X	X			
synchronizing speed difference with leaders further downstream			X					
reaching a speed in line with distance to direct leader							X	X
reaching a speed in line with distance to leaders further downstream								X
reaching the desired free speed	X			X		X	X	X

It is remarkable that the results of the study of longitudinal driving behavioural study are not always the same, and may sometimes even be contradictory. For instance, in the study about the influence of the level of traffic flow on a motorway on driver behaviour, [Dijker, et al., 1998] did find that the car-following distance varies with the traffic flow, however, [Brackstone, et al., 2009] found little evidence for this. The latter studied THW on part of the motorway (according to the paper title) based on statistical analysis. The study of [Brackstone, et al., 2009] has several limitations:

- Variables are used rather coarsely. For instance, the use of THW (calculated as the following distance divided by the speed of the following vehicle) as the only parameter cannot sufficiently explain car-following behaviour. THW cannot provide a full understanding of driving behaviour, even for stable following behaviour (defined as "a relative speed of less than 1 ms^{-1}").
- Stable following only, and its definition by using Vr only are insufficient for describing longitudinal driving behaviour, and cannot support the study as stated in the title "Determinants of following headway in congested traffic".

- Only part of motorway and high speed urban arterials do not represent all road types. In addition, only to a very limited extent factors determining road characteristics are taken into account in this study.

Different perspectives, goals, approaches, and assumptions in different longitudinal driving behavioural studies may deduce completely different results. In addition, the verity and representativeness of a research result very much depend on the how well relevant factors are distinguished, how properly various parameters are determined, and how appropriately the experiment is designed. Therefore, the results of longitudinal driving behavioural studies should be interpreted carefully.

3. METHOD

3.1. Experimental platform for comprehensive longitudinal driving behaviour study

In order to gain a good insight of the longitudinal driving behaviour and performance of Chinese drivers, and in addition to obtain human factor parameters for the development of in-vehicle driving assistance systems, we have developed an experimental platform for driving behavioural data collection and analysis [Zhang, et al., 2007]. The platform has two main components: an instrumented vehicle test bed, and advanced data collection and analysis tools (see Figure 1).

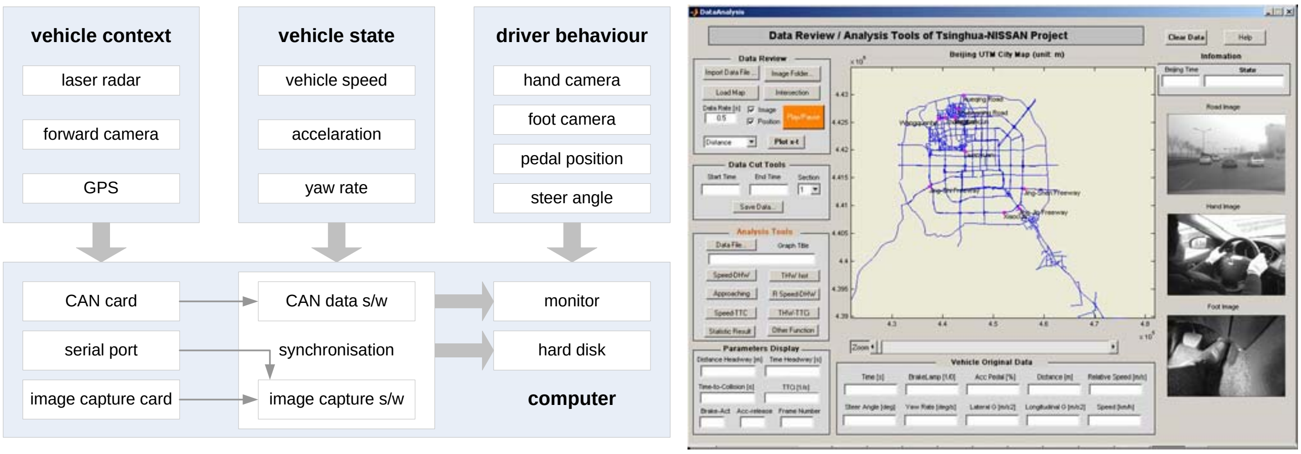

Figure 1 - Architecture of the experimental platform for driving behaviour study (left), and the interface of the behavioural data analysis software (right)

An instrumented vehicle test bed was implemented to measure data on driver actions and vehicle states. The sensors used in this system include three cameras, GPS (Global Positioning System), internal vehicle state sensors and laser radar. The laser radar is used to detect the forward vehicle and measures the distance and relative speed. Images of the frontal road environment are attained by a CCD (charge-coupled device) camera behind the windshield. The position of the vehicle is acquired by using a high precision GPS. In order to observe the driver steering and speed control operation, two CCD cameras have been selected and installed in the vehicle to capture the images of the hands and of the foot movements of the driver respectively. The signals of pedal position and steering angle are also obtained. Basic physical data, collected by the instrumented vehicle test bed, include host vehicle state, host vehicle position, road traffic environment, and the operating actions of the driver. Real-world driving behavioural data are collected on roads of different categories in Beijing.

Data collection software and data analysis software have been developed for a comprehensive study of driving behaviour, which is named "Driver Data Analysis Tools" (DDAT). The software is able to perform the following tasks: data synchronisation, data review (e.g. review of digital data and images, and display of position), selection of usable data and plotting of analysis results. Twenty synchronised data sets that are recorded: (1) running time, (2) brake lamp, (3) accelerator-pedal position, (4) distance to target, (5) relative speed, (6) steering angle, (7) yaw rate, (8) lateral acceleration, (9) vehicle speed, (10) longitudinal acceleration, (11) image number, (12) hour, (13) minute, (14) second, (15) horizontal speed, (16) direct angle, (17) vertical speed, (18) latitude, (19) longitude, and (20) height.

3.2 Research design for studying the microscopic longitudinal driving behaviour

Three scenarios are made for studying the plausible influence of road category on longitudinal driving behaviour. These are:

A. restricted car-following
B. non-restricted car-following
C. approaching

Relevant terms used in this research to determine control variables and to describe longitudinal driving behaviour are listed and defined in Table 2.

Table 2 - Definition of some terms related to longitudinal driving behaviour

Term	Definition
car following	Situation in which the host vehicle is behind a lead vehicle and both vehicles are in motion. *This corresponds to a distance value to the lead vehicle detected by the radar within a certain range, i.e. 0 m and 120 m.* *Note that detection of other objects than the lead vehicle may occur and that data should be well screened using the movie files.*
relative speed	The speed of the host vehicle minus the speed of the lead vehicle.
accelerator pedal release	The accelerator pedal position data has become lower than a set threshold, which is 5% in this study.
brake pedal activation	The driver activates the brake, and the brake lamp signal becomes 1 (on) from 0 (off).
distance headway (DHW)	Distance to the lead vehicle data detected by radar.
time headway (THW)	Distance headway divided by the host vehicle speed.
time-to-collision (TTC)	Distance headway divided by the relative speed.
gap closing	Car-following with positive relative speed, i.e. the host vehicle speed is greater than the lead vehicle speed.
restricted car-following	Relative speed is very low. *Car-following when the absolute TTCi is lower than 0.05, the brake pedal is not pressed, and with a speed threshold dependent on the road category.*
non-restricted car-following	Car following without any restriction on TTCi.
approaching	Scene that gap closing lasts longer than a certain period of time. *Car-following under the following conditions: (1) the duration of gap closing is longer than 5 seconds; and (2) TTC is smaller than 50 seconds.*

For studying whether the road categories affect the longitudinal driving behaviour, the outcome from the data processing programme is used. Besides general statistical results (such as mean, variance and standard deviation of host vehicle speed, DHW and THW, and the first order regression coefficient of host vehicle speed and DHW), the following data can be obtained: distribution of THW and TTCi, relationship between relative speed and DHW at the driver actions, and the relationship between host vehicle speed and TTC at driver actions.

3.3. Research experiment setup

Thirty-three participants were selected in Phase I: 26 male and 7 female drivers; age range from 30 to 69 (mean = 44.94, var. = 116.87, std. = 10.81); driving experience (years of driving) from 1 to 47 (mean = 12.03, var. = 128.28, std. = 11.33). The driver subjects drove the instrumented vehicle on roads of three different categories (flow road, urban distributor road and urban access road) in Beijing, and the behavioural data of each driver were recorded, including vehicle state data and vehicle position data. The road traffic environment and the operating actions of the drivers were captured by the CCD cameras in the vehicle. During the experiment, the relative speed, distance headway and vehicle speed at the follow-up driver actions (in approaching scenarios) can be detected. Two members of the experiment team were accompanying the drivers on each ride. One was sitting in the passenger seat, introducing at the start the experimental rules to the driver, and indicating the direction at intersections, but without any further interference with the driving actions of the driver. Another team member sat in the back and operated the information capturing system. The driver operated the vehicle based on his/her experience and usual practice, and drove for about one hour on each road category.

The legal speed limit on urban access roads, urban distributor roads, and flow roads are 60 km/h, 80 km/h and 120 km/h respectively. In this research, the minimum speed limit conditions are taken into account for data analysis: the vehicle speed must be above 20 km/h on urban access roads, above 40 km/h on urban distributor roads, and above 60km/h on flow roads.

Another twelve driver subjects were selected in Phase II, and the abovementioned experimental procedure was followed by using the developed experimental platform, in the same way as in Phase I. It aims to study the validation of the results of the study of longitudinal driving behaviour acquired in Phase I.

4. RESULT

Statistical results of car-following behaviour, based on the data of Phase I, are presented in tables 3, 4, and 5. The analysis of the results (of the data of the Phase I, by using the developed DDAT) for the three scenarios (i.e. A. restricted car-following, B. non-restricted car-following and C. approaching), are shown in figures 2, 3 and 4.

5. DISCUSSION

In this research, the longitudinal driving behaviour is measured by V, DHW, THW, TTC, Vr, accelerator pedal release, brake pedal activation, and gap closing. The results of Phase I show that the longitudinal driving behaviour varies with road categories. In addition, road categories influence the correlation between the host vehicle speed and DHW in the car-following scenario (Urban access road: $D = 0.56V - 2.06$, Urban distributor road: $D = 0.97V - 33.68$, Flow road: $D = 0.68V - 17.52$); but do not influence the correlation between the relative speed and DHW.

Concerning the validation of the results based on the data analysis of Phase I, we have implemented the same research procedure in Phase II. Only data obtained during clear weather conditions and daytime were chosen and analysed. The results of following variables, based on the statistical data of Phase I and Phase II, are compared:

- mean value of average DHW
- standard deviation of average DHW
- mean value of average vehicle speed (V)
- standard deviation of average vehicle speed (V)
- mean value of average THW
- standard deviation of average THW
- mean value of average TTC accelerator release

- standard deviation of average TTC accelerator release
- mean value of average TTC brake activation
- standard deviation of average TTC brake activation

Table 3 - Statistic analysis of data on urban access roads

	Control variables							
	speed (km/h)	DHW (m)	DHW accelerator release (m)	DHW brake activation (m)	THW (sec)	TTCi (sec^{-1})	TTC accelerator release (sec)	TTC brake activation (sec)
Scenario A:								
Mean	47.14	24.08	-	-	1.83	1.20E-3	-	-
Std	3.82	4.48	-	-	0.32	3.00E-3	-	-
Scenario B:								
Mean	45.68	22.60	-	-	1.78	3.86E-3	-	-
Std	3.95	3.92	-	-	0.29	1.14E-2	-	-
Scenario C:								
Mean	-	-	25.29	22.24	-	-	19.05	14.20
Std	-	-	3.93	3.78	-	-	3.15	3.80

Table 4 - Statistic analysis of data on urban distributor roads

	Control variables							
	speed (km/h)	DHW (m)	DHW accelerator release (m)	DHW brake activation (m)	THW (sec)	TTCi (sec^{-1})	TTC accelerator release (sec)	TTC brake activation (sec)
Scenario A:								
Mean	68.98	33.46	-	-	1.72	2.43E-3	-	-
Std	4.30	6.50	-	-	0.27	3.45E-3	-	-
Scenario B:								
Mean	68.18	31.67	-	-	1.64	8.45E-3	-	-
Std	6.20	6.17	-	-	0.24	1.16E-2	-	-
Scenario C:								
Mean	-	-	33.50	27.37	-	-	21.96	14.68
Std	-	-	6.80	8.02	-	-	3.46	3.35

Table 5 - Statistic analysis of data on through roads

	Control variables							
	speed (km/h)	DHW (m)	DHW accelerator release (m)	DHW brake activation (m)	THW (sec)	TTCi (sec^{-1})	TTC accelerator release (sec)	TTC brake activation (sec)
Scenario A:								
Mean	94.65	47.86	-	-	1.80	2.51E-3	-	-
Std	8.25	9.74	-	-	0.36	3.32E-3	-	-
Scenario B:								
Mean	91.49	45.19	-	-	1.77	9.26E-3	-	-
Std	13.16	9.41	-	-	0.32	8.66E-3	-	-
Scenario C:								
Mean	-	-	44.60	34.16	-	-	20.04	14.64
Std	-	-	7.65	9.16	-	-	2.59	5.71

No obvious differences were found between the results of the two experiments in Phase I and Phase II respectively. Therefore, the result of Phase I is confirmed, i.e. road category does affect the longitudinal driving behaviour. However, there are some factors are different between the two experiments in the two different phases, e.g. the number of drivers in Phase II is lower than in Phase I; there are more experienced drivers in Phase II in relative sense; the traffic Beijing environment in Phase II showed more congestion than in Phase I. All these factors may influence the analysis results and deserve further study. For a study of how longitudinal driving behaviour varies with the driving style and driver characteristics, see also [Lu, et al., 2010a].

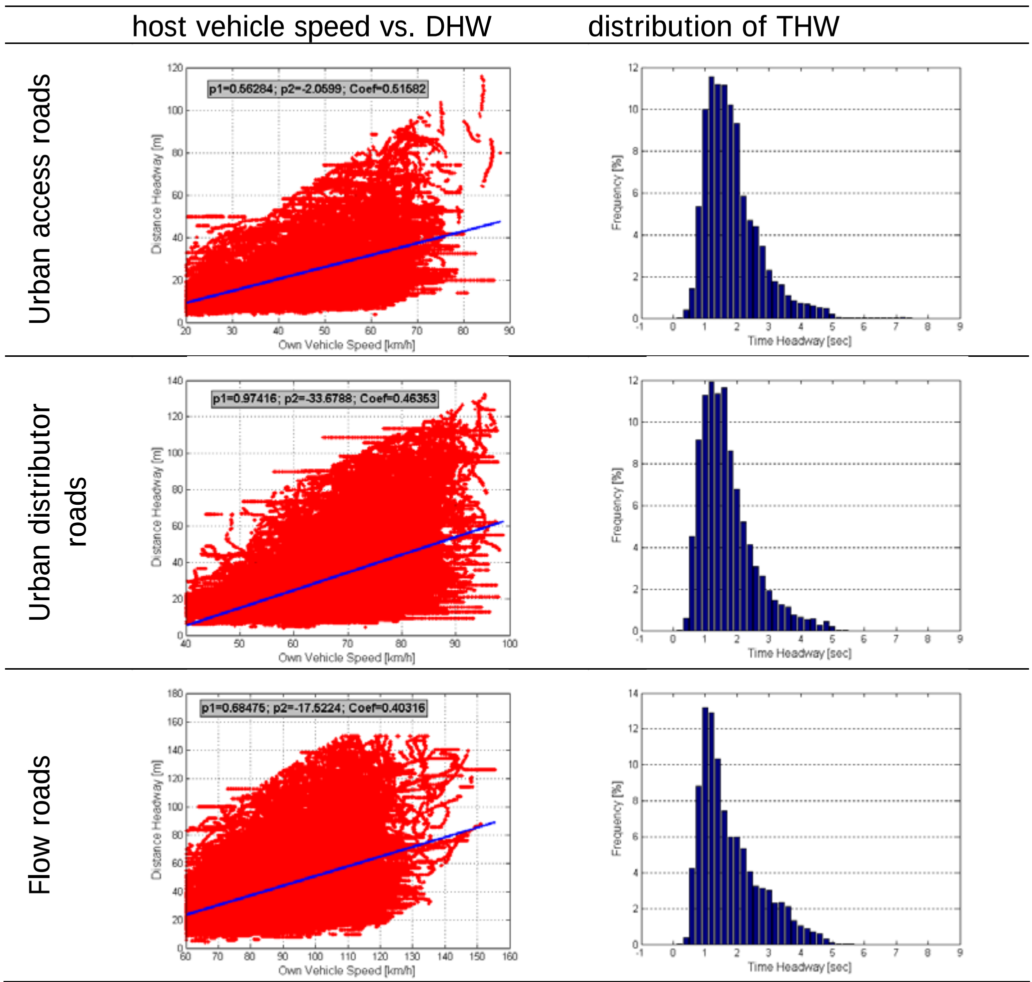

Figure 2 - Results for scenario A restricted car-following behaviour, on three road categories: host vehicle speed vs. DHW, and distribution of THW

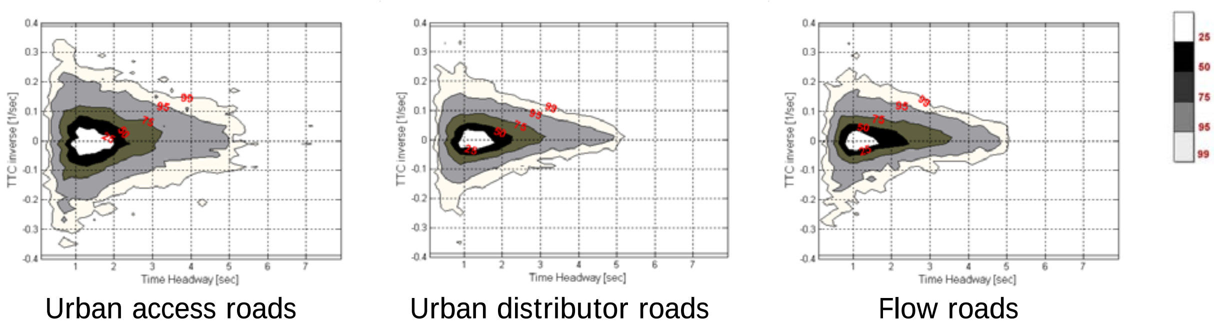

Figure 3 - Results for scenario B non-restricted car-following behaviour, on three road categories: THW vs. TTCi

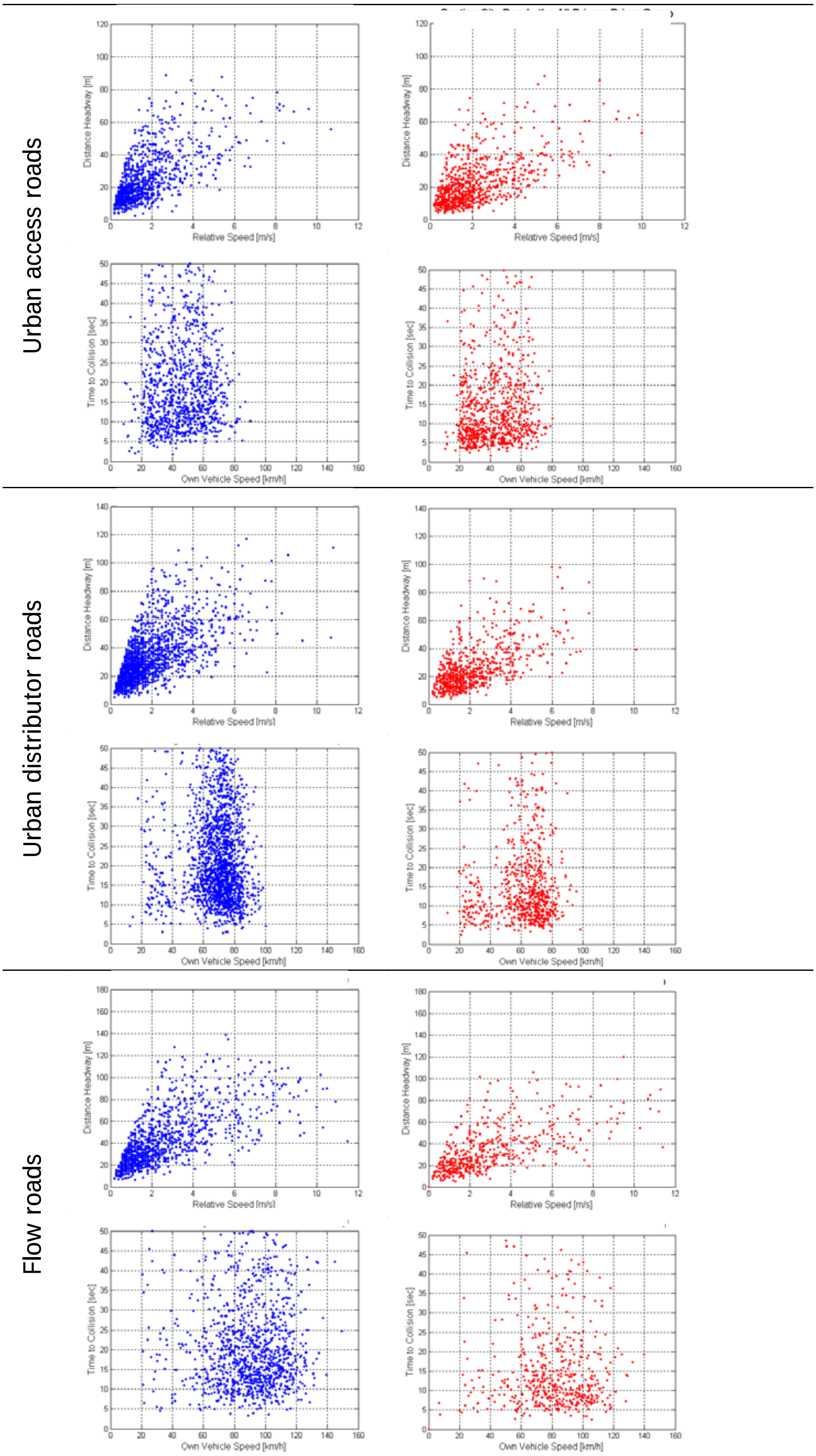

Figure 4 - Results of the analysis of scenario C approaching behaviour, on different road categories: relative speed vs. DHW, and host vehicle speed vs. TTC (Note: The blue points present the data at the first accelerator pedal release from start of the approaching, and the red points present the data at the first brake pedal activation from start of the approaching.)

Concerning the question whether car-following behaviour varies with road characteristics, the result deduced from this research is different from that stated in [Brackstone, et al., 2009], which only focuses on stable following behaviour. In this research, Scenario A is equivalent with stable following, which, however, it is defined, from the perspective of a system and control perspective, which different from the definition in [Brackstone, et al., 2009]. The main reason for the difference in the results of these two studies is due to the use of different approaches for the study of longitudinal driving behaviour, including differences in the selection and the definition of parameters, and the experimental design.

6. CONCLUSION

There is a need for proper behaviour modelling to evaluate and improve the design of driving assistance systems. An application of the developed experimental platform was used to study longitudinal driving behaviour on different road categories in Beijing. In total, thirty-three drivers participated in the experiments. It was found in this study that longitudinal driving behaviour is different for different road categories, and these differences are quantified by using a data processing programme. In addition, it was found that the lower the host vehicle speed, the shorter the distance headway (DHW) is. However, the change of the host vehicle speed is not always in the same direction as the change of the time headway (THW), which can be explained from the fact that drivers tend to be inconsistent in their choice of headway (see also [Brackstone, et al., 2009]). Due to different perspectives, goals, research approaches and variable settings, the results in this research could be different from other studies. One should be careful with interpretation of the results.

The results provide supports for the development of the algorithms of safety-oriented in-vehicle driving assistance systems, especially for the dynamic speed assistance with different feedback models that can adapt to driving behaviour. The results can also contribute to traffic simulation modelling, and theoretical research of driving behaviour. In a follow-up project, the dissimilarities of longitudinal driving behaviour will be further studied for the design of control algorithms, as these are seen as potential determinants for traffic safety, fuel consumption and traffic flow harmonisation.

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