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### Published paper

Marsden, G.R.; Mcdonald, M.; Brackstone, M. (2003) *A comparative assessment of driving behaviours at three sites*. European Journal of Transport and Infrastructure Research, 3(1), pp.5-20

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# A Comparative Assessment of Driving Behaviours at Three Sites

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*Many Intelligent Transport Systems (ITS) that are now under intensive investigation have been designed or assessed with a particular target consumer group in mind. In order for these (and many other) systems to be successfully used around the globe however, some appreciation will be necessary of how behaviours, and hence uses and impacts, may change between different sites and between different countries.*

*This article reports on an instrumented vehicle study designed to assess differences in Motorway driving behaviour between three sites, one in the U.K., one in France and one in Germany. Substantial differences were found between typical car-following headways and time to collisions observed at the sites. The experiment also confirmed that many people drive well below the current recommended safe following distances.*

*It has not been possible through this study to determine why the differences exist between the sites, nor whether they are country specific. However, the findings are important in establishing that significant differences do exist. These differences could impact on the effectiveness of roadside telematics systems as well as for the design of in-vehicle Advanced Vehicle Control and Safety Systems.*

## 1. Introduction

In Europe, considerable emphasis has been placed on Intelligent Transport Systems (ITS) being interoperable, i.e. that they function in the same way irrespective of the country, region or city in which they are being used. (Perrett, 1999). This can be achieved through common architectures, standards and user requirements (Miles, 1997 and Tierolf, 1998). However, whilst there have been many studies of user requirements, often in ways which enable comparisons to be made between countries, regions or cities (eg. Finn, 1997), such

comparisons are usually made at a functional level, without taking variations in local behaviour into account. For the majority of ITS systems and services, any such detailed variability in behavioural response is of little practical relevance. Driver responses to variable message signs may, for example, be different in different countries but this is unlikely to affect the design of the sign itself. However, in some situations, such changes may be of critical importance. One such situation relates to the application of Advanced Vehicle Control and Safety Systems (AVCSS).

AVCSS are designed to increase safety and reduce driver stress by for example, introducing aids designed to maintain a set distance from the preceding vehicle (Adaptive Cruise Control (ACC), eg. Watanabe et. al. (1995)) or warn the driver of potential collisions when the preceding vehicle decelerates (Collision Warning, eg. Hasimoto et. al. (1995)). Systems may use alarms, and/or the actuation of accelerator and the vehicles' brake system. Such systems are designed with specific characteristics in mind, e.g. the typical desired headway to be maintained in the case of ACC, and what constitutes a situation in which the driver should brake in the case of Collision Warning.

Selection of appropriate system values for these characteristics is clearly important. If a driver is confronted with a value that he or she considers too small or unsafe, or equally too large and too conservative, they may switch the device off. Investigations designed to establish norms for these values are now underway around the world (eg. Kuge and Ueno (1995), Lee et. al. (1997) and Kopf and Nirschl (1997)). However, little consideration has been given to differences between these norms, that may be caused by differing enforcement policies or societal attitudes for example. Parameters such as headway following distance for an ACC system can be understood and set by the driver (Richardson et al., 1999). Other parameters such as approach rates, braking levels and system authority are too complicated for the driver to understand and set and a manufacturer-defined value must be used.

A successful deployment of an AVCSS by a U.S. manufacturer into the U.S. market will not therefore guarantee its success elsewhere. Cruise Control, where the driver sets a speed for a car to maintain, has been successful in North America but less so in Europe where inter-urban routes are prone to greater congestion and travelling at a constant speed is more difficult. With virtually all major vehicle manufacturers now relying heavily on international sales, and indeed providing a significant contribution to the economies of other countries (non-U.S. manufacturers produced 20% of the vehicles assembled in the U.S. with a total economic investment of \$43.2 Billion in 1996 alone (OSAT, 1998)), an appreciation of this issue is long overdue.

This article describes a study to examine differences in motorway driving behaviour at three European sites. The experiment examined typical following behaviour with data collected through an Instrumented Vehicle (Brackstone et al, 1999). The next section presents a review of other similar data collection exercises completed to date. The data collection procedures are described before an analysis of differences between typical headway following and approach behaviour. The results show significantly different amounts of time spent by drivers at some sites in close following situations at speeds of above 80 km/hr. The results also offer some insight into classifying different types of driver behaviour. The article concludes with a discussion of the implications of the results for industry, regulators and traffic flow theory.

## 2. Driver Behaviour Review

The potential impact of differences in driving characteristics between countries as a major factor in the success of ITS has only recently been raised (Ervin et al., 1997). However, few studies have examined differences in driver behaviour. To a certain extent this is due to the nature of the task to be evaluated, where for a detailed understanding to be available, an in-depth study has to be made of a number of factors e.g. driver distance keeping behaviour, lane keeping, factors affecting overtaking and speed.

Studies of driver behaviour during car following have been undertaken since the 1960s (Gazis et al, 1961). However, testing has, until recently, been limited by data capture facilities and sensor technology and much of the data collection was carried out on test tracks. Recent advances in technology have seen the widened availability of a large number of virtual reality simulators and instrumented vehicles across the world (Brackstone et al, 1999). Due to the novelty of the technology, normative understandings of driving styles are only now becoming available in the U.K. (eg. McDonald et. al., 1999), in the U.S. (Allen et. al., 1997, Sayer et. al., 1997), in Japan (eg. Watanabe et. al., 1995) and under initial investigation in Germany (eg. Reiter, 1994, and Bleile, 1997). Each study focuses on a particular aspect of driver behaviour and it is difficult to directly compare results due to differing experimental conditions. However, it should be noted that in a small number of cases some differences have been found between the points at which drivers start to decelerate on the approach to a slower vehicle and those initially suggested for use in a variety of Japanese and U.S. Collision Warning (CW) systems, (Brackstone et. al, 2000).

Table 1 summarises the main driver behaviour and AVCSS studies found from the literature. The table describes the studies objectives (e.g. to investigate braking behaviour), where they were conducted, whether they were conducted using test vehicles or a simulator and a very brief summary of the findings. Whilst the studies were conducted in different countries, there is little overlap of objectives or methodology to allow any direct comparison of results.

Ferrari (1988) hypothesised a reliability model which may be used to predict the instability of motorway traffic, and calibrated this to data from Dutch and Italian motorways, demonstrating clear differences. Relating these differences directly to driver behaviour however is difficult to accomplish. However, from a basic understanding of car following theory (Chandler et. al., 1958), it is easy to conclude that differing population characteristics, in terms of desired distances, response times and scaling factors, will yield traffic streams with differing stability (and hence reliability) characteristics, as found by Ferrari.

Hall et al. (1994) compared macroscopic data on capacity from the UK, US, Canada and Germany. Amongst other issues, the study examined the value of flow on a motorway at which speeds start to decrease (break point). Hall et. al. (1994) tentatively concluding that the flow at the speed breakpoint for congested traffic may be a function of the free flow speed, but were unable to conclude whether the speed at capacity may be a national characteristic. The study also reported significant differences in measurements on some sites on adjacent days.

**Table 1. A Comparison of some of the Differing Experiments conducted so far using the instrumented vehicle methodology.**

Source	Theme	Country	Method*	No. Subjects	Conclusion
Allen et al (1997).	Following Behaviour	U.S.A.	IV	48	Control theory based following algorithm
Hasimoto et al. (1995)	Braking behaviour	Japan	IV	5	Guidelines for a collision avoidance system
Kopf and Nirschl (1997)	Borderline behaviour with ACC	Germany	Sim	40	Conditions under which drivers over-ride ACC
Kuge and Ueno (1995)	Emergency braking	Japan	TV	?	Definition of Emergency Braking Advanced Advisory System.
Lee et al (1997)	Collision Warning	U.S.A.	Sim	64	CW can reduce probability of lead vehicle brake collisions
McDonald et al (1999)	Normative headway behaviour	U.K.	IV	6	Headway highly variable. Non linear following relationship.
Reiter et al (1994)	Headway variation	Germany	IV	15	'Bounds' to following in terms of relative speed
Sayer et al (1997)	ACC use	U.S.A.	TV	35	Can increase headway in certain conditions
Van Winsum and Heino (1996)	Impact of TTC on driving	Holland	Sim	54	Relationships between headway and reaction time.
Watanabe et al (1995)	ACC development	Japan	TV	?	Relationships between headway, braking and reaction times.
Varhelyi et al (2001)	Effect of speed limiters	Finland	TV	68	Effect on speed distributions and headways
Hoedemaeker et al (1999)	ACC usage	Holland	Sim	38	Behavioural adaptations to driving with ACC

\* IV – Instrumented Vehicle, Sim – Simulator, TV – Test Vehicle.

It is clear then that there are few benchmarks against which to judge any differences, and we are additionally hampered in doing so by the ever-present possibility that driver behaviour may be site specific, i.e. geometric differences, or regional variations may in-fact mask any true effect. The only solution to this problem is clearly to conduct exhaustive, in-depth studies on a wide range of roads. In the long term this may become possible, however within the scope of our study we are restricted to providing an initial examination of differences based on three sites.

### 3. Data Collection

Data used in our analysis was collected using an instrumented vehicle (Brackstone et. al., 1999), equipped with three primary measurement suites that compile time series data on driver behaviour at a rate of 10Hz. An optical speedometer provides a high accuracy measurement of speed of the Instrumented Vehicle whilst a radar rangefinder measures distance and the relative speed of surrounding vehicles. The radar was rear-mounted for these experiments so that data was collected on following vehicles as shown in Figure 1.

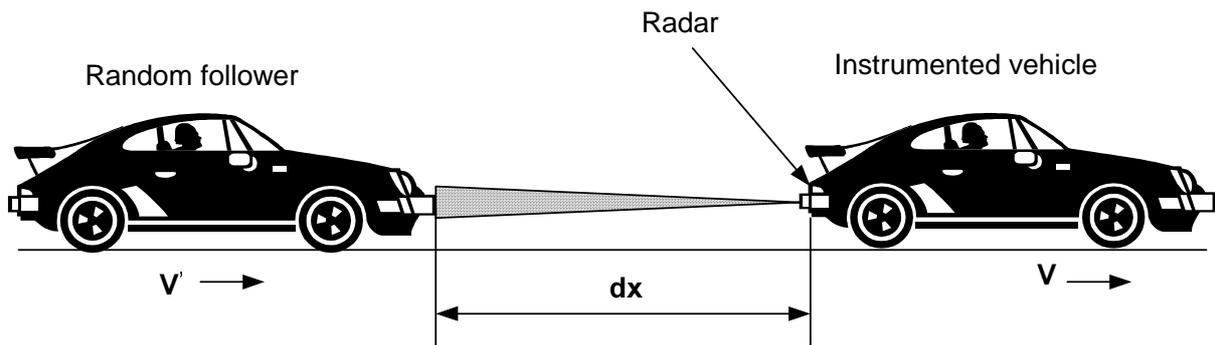


Figure 1. Experimental Layout

A video-audio monitoring system is also integrated into the data collection suite to take a permanent visual record of each experiment with extra comments by the vehicle staff as appropriate. This allows for the further analysis of potentially confusing sensor output and the recording of features not detected through the sensors (e.g. motorway lane). The sensor suite therefore provides first order measurements of the speed of the lead vehicle ( $v$ ), the gap separation ( $dx$ ) and the relative velocity ( $v-v'$ ). Other measures such as time headway and time to collision can also be calculated. An example of a plot of relative velocity against gap separation is shown in Figure 2. A negative relative velocity implies that the rear vehicle is closing on the Instrumented (lead) vehicle.

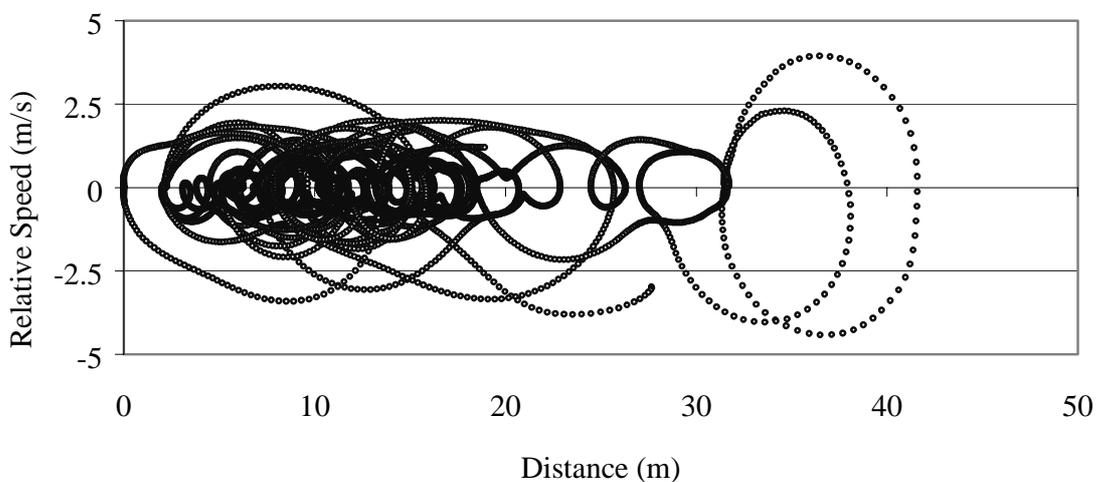


Figure 2. Relative velocity against gap separation

The database itself consists of measurements taken at three sites from three different countries, details of which are shown in Table 2. The first part was collected during 1997 in France during the course of a round trip from the port of Calais to Paris over a three day period, with data being collected at two test sites. At the first of these, the A25 near Lille in the North of the country, data was collected during two evening peak periods with laps being performed of a test course between junction 8 of the A25 and junction 18 of the A1, a total of 32 Km in each direction. The second data collection session was performed on the Boulevard Peripherique (B.P.) which circles Paris. However, this data has been excluded from the analysis due to the severe congestion conditions encountered which prevented the collection of free-flow following data. In total, following data was collected on 41 drivers, averaging a little under three and a half minutes each.

**Table 2. Data Collection Trials**

Date	Site	Approx. times	Weather	N° of following events
14/10/97	France, A25	17:00-19:00	Dry and dull	15
16/10/97	France, A25	17:00-19:00	Dry and sunny	36
22/10/97	U.K., M3	07:30-08:30	Dry and sunny	9
23/10/97	U.K., M3	07:30-08:30	Dry and sunny	11
24/10/97	U.K., M3	07:30-08:30	Dry and dull	10
02/6/98	Germany,	08:00-10:00	Dry and sunny	21
02/6/98	Germany,	16:00-17:40	Dry and overcast	2
03/6/98	Germany,	07:20-09:30	Dry and cloudy	22
03/6/98	Germany,	15:20-17:30	Dry and cloudy	26
04/6/98	Germany,	07:25-09:50	Dry and cloudy	21
04/6/98	Germany,	16:00-19:00	Dry and cloudy	32
05/6/98	Germany,	07:25-11:20	Dry and cloudy	38

The second part of the database was also collected during 1997, on the M3 3-lane motorway in the U.K., just to the South-West of the M25 circling London. Data was collected during three morning peak periods, with laps of a test course between junctions 2 and 4a (a total of 22 Km in each direction), yielding data on 30 drivers, averaging a little under four minutes each.

The last part of the database was collected in Germany in spring 1998, on the A1 around the south east corner of Hamburg in the North of the country. In total, data was collected on 162 drivers, averaging a little under three minutes each.

#### **4. Experimental Constraints**

Experiments involving floating cars have a limited but important application. Where people are aware that they are part of an experiment, there is evidence (e.g. the 'Hawthorne effect', Mayo (1933)) that they adapt their behaviour. However, such experiments can be organised to enable the same or similar conditions to be set before the range of subjects. In this instance however, the intention of the experiment was to capture a random sample of following sequences on three different test sites. The equipment was on board the lead vehicle of the following pair and the driver following was unaware that data was being logged. This meant that the location of the following sequence was random (along the given area of road being

examined) as was its duration. Each following sequence captured only a short period of following for every driver and no details were available of the age, sex and driving history characteristics of the drivers.

The vehicle concerned was a UK car, right hand drive with UK number plates. Whilst it is not possible to say whether the use of a foreign car on French and German roads influenced the experiment, great care was taken to mitigate any such effects. The same driver was used for the vehicle at all times. The following events were always undertaken in conditions where other traffic was in close proximity, both on near-side lanes and preceding the instrumented vehicle. In this way, the vehicle formed part of an 'enclosed' traffic event and was not blocking progress of the rear vehicle.

The purpose of the experiment was to collect a series of following sequences, to analyse trends in the data and compare differences between sites. The design proposed cannot provide clear statistical evidence of between site differences. The surveys would have to be supported by more detailed data capture techniques including the use of road mounted inductive detector loops. However, such loops are normally only available at the sort of intervals required on urban motorways. Paradoxically, these motorways contain high levels of weaving to leave and enter the traffic streams and continuous following data is more difficult to collect. This comparative analysis of this experiment has largely been limited to data collected at speeds above 80 km/hr in order to remove some of the flow-density effects that could explain the differences between behaviour (Aron, 1997).

## 5. Analysis of Following Headways

The first indicator to be examined was that of the time headway between successive vehicles. Although many models use a deterministic relationship between this variable and ground speed to give some idea of the 'desired following distance', more recent studies have shown that there is a great deal of variation about any 'best fit relationship' (eg. Leutzbach and Wiedemann, 1986, Brackstone, 2000). This variation may be caused by a degree of error or 'fuzziness' in distance choice, and/or through natural variations that are present as drivers attempt to 'home in' on their desired following distances. Such variations are the result of natural feedback delay, inherent in any time delay control system. Nonetheless, this indicator provides a basis for meaningful comparison of the overall flow regimes.

Data on following headways was extracted from each following sequence every 5 seconds to remove autocorrelation of consecutive headway readings. To enable differences between the site samples to be investigated using standard statistical tests, the distributions of headways was assessed for each site, with data divided into 10 kph speed bands (starting at 10 to 20 kph) according to the speed of the lead (test) vehicle. A typical distribution for these points is shown in Figure 3.

The time headway data for each speed band was tested against a normal distribution using the Kolmogorov-Smirnov test. A number of speed bands were found to be non-normal and a natural log transformation of the data was performed and the data retested. The transformed data in all but two of the speed bands was found to be normally distributed (see Table 2 and Figure 4). However, it is worth noting that there is a lack of data points between 80km/hr and 20km/hr. The data was collected at all sites under congested conditions. Significant amounts of time were spent in following sequences at speeds above that at which flow breakdown occurs. However, a

number of occasions were experienced where flow slowed to zero speed and periods of stop-start driving were encountered. The lack of data between 20 km/hr and 80km/hr indicates that this speed range occurs at the transition between flow and flow breakdown which cannot be experienced for long periods of time.

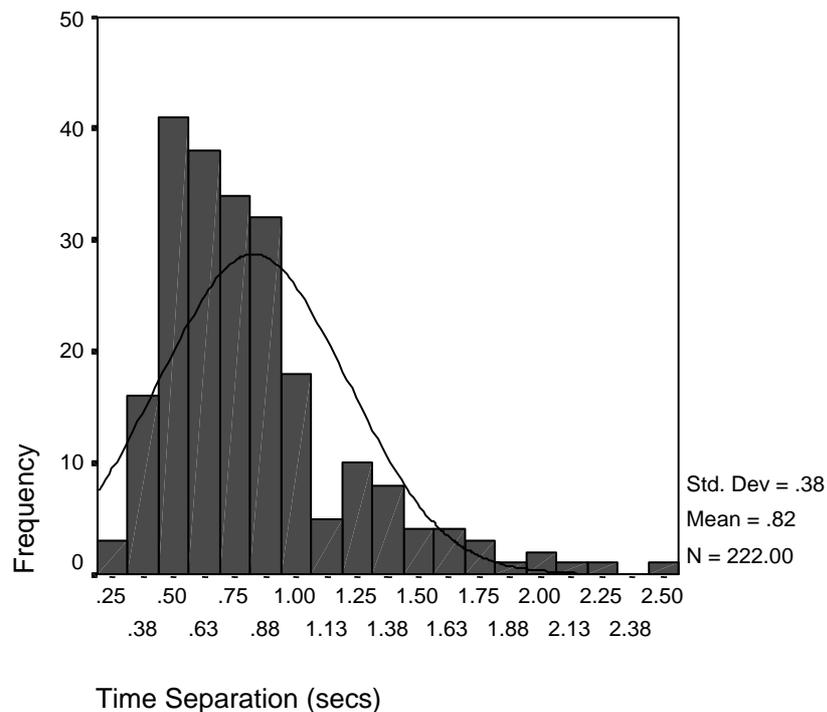


Figure 3. Distribution of following headways observed between 90 and 100 km/hr – Lille

Table 2. Ln(time separation headway) distribution tests

Distribution	N	Mean	Standard Deviation	Absolute max difference	Kolmogorov-Smirnov Z	2 tailed Significance
ln 0 to 10 th	113	-0.501	0.721	0.112	1.193	0.116
ln 10 to 20 th	198	-0.273	0.950	0.101	1.426	0.034
ln 20 to 30 th	5	0.316	0.239	0.269	0.601	0.863
ln 30 to 40 th	11	0.425	0.387	0.280	0.927	0.356
ln 40 to 50 th	15	0.420	0.455	0.191	0.741	0.643
ln 50 to 60 th	6	-0.010	0.459	0.203	0.496	0.966
ln 60 to 70 th	14	-0.109	0.394	0.192	0.719	0.680
ln 70 to 80 th	33	-0.390	0.397	0.116	0.667	0.764
ln 80 to 90 th	122	-0.412	0.345	0.065	0.719	0.679
ln 90 to 100 th	222	-0.285	0.421	0.052	0.780	0.577
ln 100 to 110 th	147	-0.257	0.443	0.069	0.838	0.483
ln 110 to 120 th	200	-0.148	0.525	0.064	0.909	0.381
ln 120 to 130 th	179	-0.081	0.516	0.046	0.616	0.842
ln 130 to 140 th	99	0.015	0.472	0.083	0.830	0.496

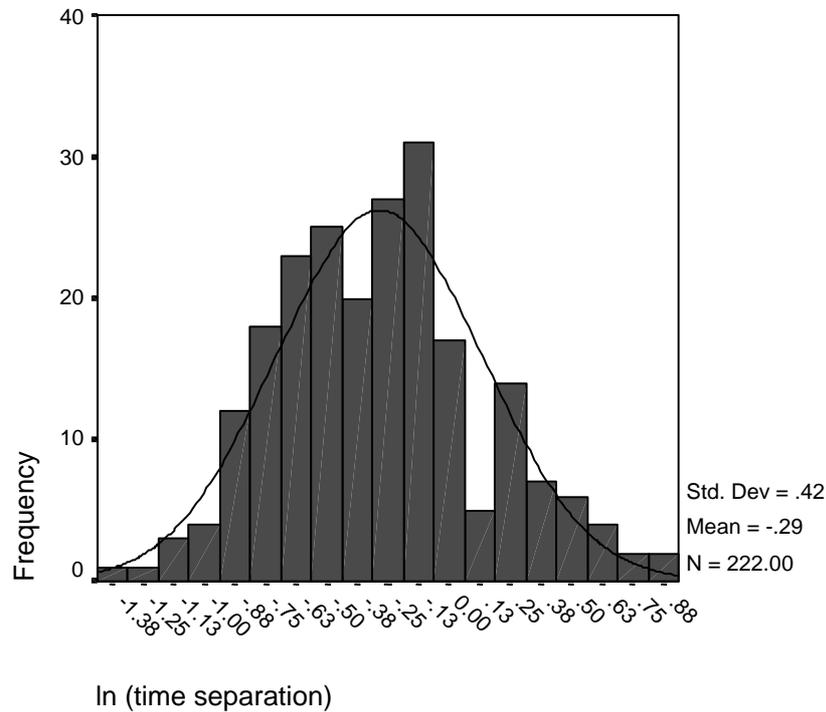


Figure 4. Log distribution of following headways observed between 90 and 100 km/hr - Lille

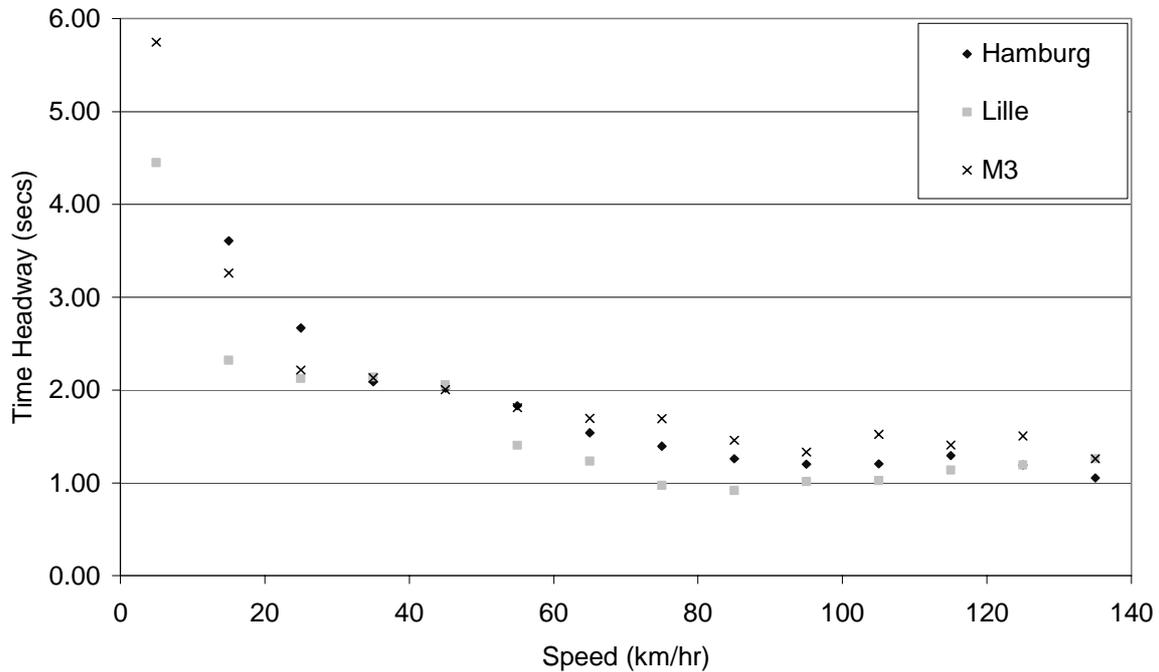
The mean headways observed for each of the speed bands at each of the sites is shown in Figure 4. The plot demonstrates some interesting trends, firstly, that the time headway may vary with speed, and secondly that differing headway characteristics would seem to be evident between countries.

Whilst the average following headways from Figure 4 imply a road capacity greater than that seen in reality, the figures do not paint a complete picture as, at any one time, only a small number of drivers are engaged in a following sequence. In addition, there is a considerable degree of variability in following headway for any one driver within a following event.

An analysis of variance was conducted to compare means of the log-normal transformed time headway data at each of the three sites. The data was analysed at three speed ranges (90 to 100, 100 to 110 and 110 to 120 km/hr), which were taken to be representative as relatively free-flow driving. Levene's test showed that the variances of each of the samples were statistically significantly different at the 95% confidence limit. The results of the ANOVA should therefore only be taken as indicative. The results are shown below in Table 3.

**Table 3. Results of ANOVA comparison of log-normal time headways**

Speed (km/hr)	M3 mean	Hamburg mean	Lille mean	F-Test
90 to 100	0.11	-0.10	-0.29	F(2,995) = 22.7, p<0.01
100 to 110	0.28	-0.07	-0.26	F(2, 836) = 37.3, p<0.01
110 to 120	0.19	0.04	-0.15	F(2, 986) = 24.5, p<0.01



*Figure 4. Time Headway against Speed*

Post-hoc tests of differences of means are sensitive to differences in group size and differing population variances (Field, 2000). A Games-Howell post-hoc test was therefore used to compare the differences between groups. The Games-Howell test showed that the mean log-normalised time headway at the M3 was always statistically significantly greater than that of Hamburg, which in turn was greater than that at Lille.

The analysis has therefore shown that the time headways observed in Lille were lower than those at Hamburg which were, in-turn, lower than those observed on the M3 in the UK at free flow speeds. This evidence points to differences in driver behaviour between the sites.

## **6. Analysis of Relative Speed Tolerances**

Whilst the identification of different time headway selection by drivers at different sites is interesting, the consequences of such behaviour to safety and traffic flow stability are perhaps of greater interest. This section sets out a comparison of Times to Collision (TTC) exhibited by the observed drivers at each site. TTC, given by the relative distance (DX) divided by the relative speed (DV), represents the time available to a driver within which he must adjust his relative speed to zero in order to avoid a collision. TTC has been linked over the last twenty years increasingly with driver decision making as a measure of the 'risk' associated with any situation where the following vehicle is gaining on the vehicle in-front (eg. Janssen and Nilsson, 1990, Van Winsum and Heino, 1996).

One of the stimuli which drivers respond to during car following is the rate of change of the apparent size of the vehicle in front. In the case where the rear vehicle approaches the lead

vehicle, the rate of change of vehicle size alerts the driver that they are closing and a compensatory action is taken. Data from Van Winsum and Heino (1996) allows us to estimate that this corresponds to a level of TTC in the region of 5 to 6 seconds during normal following. Figure 5 shows the comparison of the cumulative frequency distributions of TTC measurements between 0 and 20 seconds from all of the drivers at each of the three test sites.

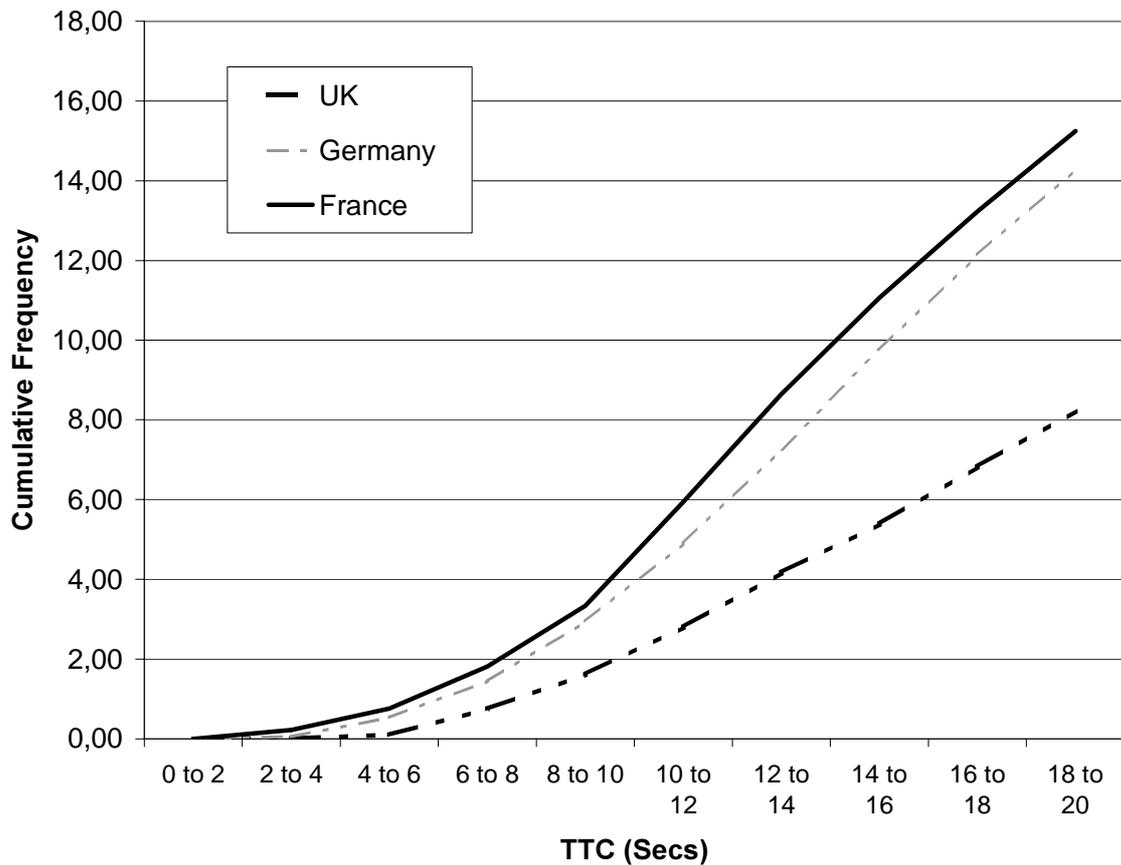


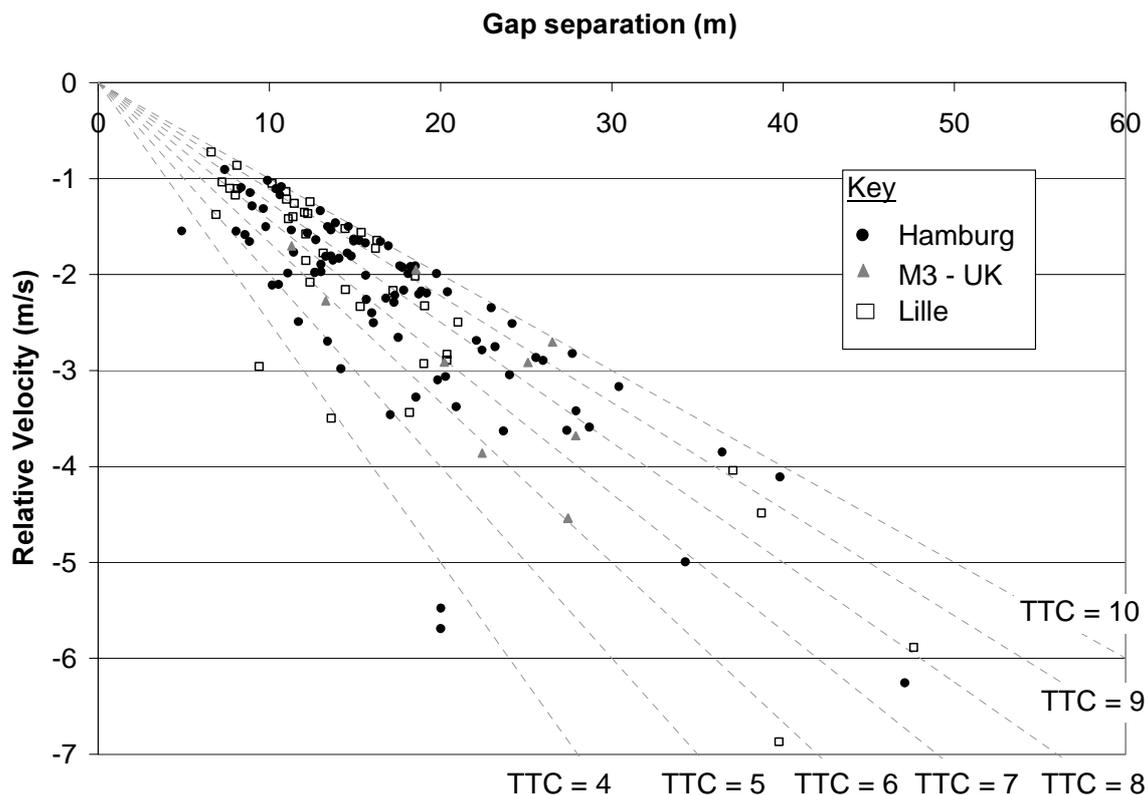
Figure 5. Cumulative Frequency Distributions of TTC values below 20 seconds

Statistical comparisons of the full distributions using the Kolmogorov-Smirnov test showed that the data from the UK test site is statistically significantly different from that at the German and French test sites ( $p < 0.05$ ). The TTC distributions for the French and German test sites are also statistically significantly different at the 95% level ( $p < 0.05$ ). Whilst the data in Figure 5 shows that TTC events under 10 seconds form a very small proportion of a typical following event, there is still a marked difference between the proportion of time spent under such thresholds between the sites. Lille, which showed the shortest time headways, also had the greatest amount of time with TTC less than 10 seconds. For any given speed, the shorter the time headway, the shorter the following distance (DX). DX is the numerator in the equation for the calculation of TTC and changes in lead or rear vehicle speed to create a negative DV will quickly lead to a short TTC.

A further analysis was performed to confirm that the shorter following headways were indeed linked with the occurrence of significant proportions of low TTC events. Each individual

following trace was analysed to extract the minimum TTC event for any sequence of driver behaviour that led to a TTC under 10 seconds. To ensure that none of the events with TTC below 10 seconds belonged to the initial approach process of a vehicle to the Instrumented Vehicle, the first 20 seconds of data was discarded. In addition to this, only data that belonged to a series of data which was above 80 km/hr for longer than 10 seconds was considered. During a following sequence with a low TTC it is possible for more than one “minimum” TTC to occur, i.e. the TTC rises again slightly before falling to the true minimum. To avoid selecting two “minimum TTC” which belonged to the same low TTC event, the minimum TTC was only selected if it was a minimum of all data within the following 10 seconds. This does not preclude one following sequence from having more than one short time to collision registered in the new database.

The plot of relative velocity against gap separation of the vehicles (the negative ratio of which gives time to collision) for the points of minimum TTC calculated using the conditions stipulated above is shown in Figure 6. In addition, the isolines of TTC from 4 to 10 seconds are plotted. The number of points from each of the test sites is affected by the amount of measurement time at each site.



*Figure 6. Relative Velocity against gap separation for minimum TTC events*

The majority of data points are clustered below a gap separation of 20 metres and a relative velocity of  $-2$  m/s, confirming that short following is more likely to lead to low TTC events than following at longer distances. This finding has significance in that each low TTC event

will require a braking response to prevent vehicles from closing to dangerous distances. Such behaviour can have a knock on effect further back up the carriageway, initiating mini shock waves (see for example Marsden et al, 2001). Figure 6 also shows that very few observations fall below a TTC of 4 seconds. Janssen and Nilsson (1990) suggested this value as a threshold for a Collision Warning system and the data for following behaviour above 80 km/hr supports this.

## **7. Conclusions**

The macroscopic assessment of time headway showed that the values adopted during typical motorway driving conditions (above 80 km/hr) are considerably lower than those recommended by the National Authorities (2 seconds in England and France and around 1.6 in Germany). Whilst this would perhaps indicate the potential for higher capacity on the motorways the benefits of closer following headways are offset by an increase in low time to collision events and the resultant likely instability that this will generate in the traffic stream. Statistically significant differences were found in the time headway distributions observed at each site during free-flow speed conditions. In addition, the data showed differences in variances between the sites which indicates that the samples are not from the same population. The data also showed statistically significant differences between the number of low time to collision events found at each site. The lower the following headway observed, the greater the proportion of observations that were found to be low time to collisions. Whilst we conclude that the driver behaviour observed at each site was different, this is not in itself evidence of systematic differences between behaviour at the sites because of the nature of the experiment.

The study has highlighted several areas requiring further research. Of particular importance is further work into the potential differences in driving style between different sites both within and between countries. With the advent of new advanced telematics systems that make subtle changes to the behaviour of drivers (both fixed infrastructure and in-car systems) it is essential to have microscopic traffic models that represent the wide variety of individual driver behaviours accurately. The acceptability and benefits of in-car AVCSS could vary dramatically between driver types and perhaps roads, an issue of importance to road operators as well as vehicle manufacturers.

It is also clear that following headways observed during typical motorway driving are significantly below the national standards. It may be time to re-assess such guidelines in the light of a more in-depth country wide research program. Automated driving systems offer the prospect of computer controlled driving at very short headways. One of the stumbling blocks to implementation is concern about operator liability, caused partially by the differences between system characteristics and objectives and national limit guidelines which, it has been shown, may not reflect the current base case.

This study has highlighted significant differences between driver behaviour at three sites. Further research will be necessary to understand how widespread and stable this phenomenon is and to understand the principle factors behind it.

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