THE BRAKING BEHAVIOUR OF HEAVY VEHICLE DRIVERS

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ABSTRACT

This paper deals with the in-service braking behaviour of heavy vehicle drivers which was examined to provide information for use in the development of design rules which would improve tractor/trailer braking compatibility under routine braking regimes. Results show that while braking is required every 500 m under heavy urban driving conditions, on roads with high levels of service this can reduce to once every 11 km on average. Under the right conditions, heavy vehicles can travel 90 km distances between brakings. Average braking duration is between 6 and 9 seconds with average deceleration rates of between 0.4 and 0.7 m/s^2. *These decelerations are considerably less than the 0.25g accepted as the limit of comfortable passenger car braking. The average speed change during braking was found to be small for all road types considered. Very few brakings were made from high to low speeds. The constant adjustment of speed to the conditions by drivers appears to pre-empt the need for severe braking.*

INTRODUCTION

Interest in the braking behaviour of heavy-vehicle drivers began at the Australian Road Research Board (ARRB) when the National Association of Australian State Road Authorities became interested in the implications of heavy vehicle braking performance associated with road design standards for heavy vehicles in the traffic stream.

Subsequent interest of the Australian Federal Office of Road Safety led to a widening of the ARRB project to include issues of the training, licencing and testing of drivers in heavy vehicle braking. There was also interest in a more detailed consideration of in-service brake use for design rule development, particularly associated with the compatibility between tractor and trailer braking.

This paper deals with the in-service braking behaviour of drivers which was examined to provide information for use in the development of design rules which would improve tractor/trailer braking compatibility under routine braking regimes.

A BRAKING REVIEW

A review of the information available on braking behaviour has been carried out (Jarvis 1988). Although the main interest was heavy vehicle braking, information on such brakings was found to be scarce. A background of the various levels of deceleration adopted by drivers of all types of vehicles was considered to allow a better understanding of heavy vehicle driver braking behaviour.

The braking capacity of passenger cars underwent considerable improvement between 1940 and 1950 but with little change in technology, performance remained much the same until the early 1970's. Since then, further improvements have been made to a point where, under optimal conditions, car decelerations of more than 1 g have become readily available (Tignor 1966, Samuels and Jarvis 1978).

Although car drivers have been given increased braking capacity, there does not appear to have been any significant change over the past 40 years regarding driver and passenger perceptions of braking severity. As long ago as 1940, car drivers considered 0.27 g as the limit of comfortable deceleration and 0.43 g as severe and uncomfortable and the onset of emergency stop conditions (Wilson 1940). Recent research has confirmed that 0.25 g is still considered a reasonable maximum for normal braking, while 0.5 g is tolerated by only a small percentage of drivers under conditions of limited choice (Wortman and Matthias 1983). During normal driving, Mortimer et al. (1970) showed that the majority of decelerations appeared to be in the range 0.05 g to 0.25 g and that if 0.5 g is indeed considered severe, on average car drivers are involved in 10 serious brakings per year.

Mackay (1978) pointed out the braking capacity differential which existed between vehicle types in the Australian traffic stream. Consideration of the relative braking requirements for Australian Design Rules 31 and 35 governing passenger cars and trucks of 3.5 T GVM showed that a heavy vehicle would require over 50 per cent greater distance to stops than a passenger car travelling at the same speed. However, Mackay also claimed that for typical car and truck speeds found in a commercial vehicle speed and operation study (Thompson 1978), low truck speeds would result in a much more theoretically balanced range of braking capability between vehicle types in the traffic stream. Such a balance relies upon suitable braking performance being both available and utilised. Even for new unladen trucks, tested under ideal conditions (and certainly not as semi-trailer combinations, for example), Horsham (1980) pointed to the considerable skill needed by test drivers to obtain braking levels required by ADR 35. For the braking test from 100 km/h drivers regularly used increasing pedal effort during successive of six attempts allowed to meet the standard of 3.78 m/sec^2 retardation required without losing control of the vehicle. Conversely, Samuels and Jarvis (1978) showed that under similar conditions modern passenger cars can consistently achieve decelerations in excess of 1 g.

In the most recent heavy vehicle brake testing carried out under the National Highway Traffic Safety Administration brake research program, Radlinski and Williams (1985) give a range of stopping distances that might be expected from 60 mph (100 km/h). Since total lock-up of wheels was considered an unstable condition, the tests gave the following average maximum decelerations for stable stops of the vehicle types given:

TABLE I

MAXIMUM STABLE DECELERATION RATES

buses	0.55 g to 0.60 g
loaded semi-trailers	0.43 g to 0.50 g
loaded rigid trailers	0.34 g to 0.46 g
empty semi-trailers and rigids	0.29 g to 0.39 g
tractor units	0.24 g to 0.38 g

With unlimited wheel locking the better friction characteristics of tyres on unloaded vehicles would have shown improved stopping performance compared with loaded trucks.

Regarding in-service braking of heavy-vehicles, little information was available. Many of the driver samples in reported work that was found were very small and results were more of anecdotal interest. Often the braking behaviour reported was only incidental to the main purpose of the testing being undertaken. Frood (1960) studied the braking behaviour of a heavy vehicle during a steep decent where the major contributor to vehicle retardation was use of low gears. The driver used only light brake applications between 0.025 g and 0.054 g (90 per cent at less than 0.05 g). In contrast the same decent in a passenger car showed only 3 per cent of brakings under 0.05 g and some adjusting decelerations were as high as 0.35 g.

Newcombe and Spurr (1967) brought together data from a number of braking proving trials which noted the reasons for braking. While bends and vehicles ahead were the predominant causes of passenger car braking, the public service vehicle (coach) tested used a markedly different braking pattern. A considerably smaller proportion of coach braking was caused by vehicles ahead and bends, with more braking taking place on hills and the approach to junctions and signalised intersections. Whilst these differences may partly have resulted from slower speeds associated with the coach, it is also likely to reflect a different driving strategy adopted by the driver to minimise the need for braking under normal driving conditions. Although always the subject of defensive driving courses for heavy vehicle drivers, the extent to which Australian truck drivers modify their behaviour to avoid emergency braking situations is unknown.

Information has been gathered at ARRB on the in-service braking of vehicles from high speed to a stop or give way sign, for a variety of purposes (Jarvis 1985). The study showed that the fastest approaching passengers cars experienced peak decelerations of 2.7 m/sec^2 some 25 metres from the intersection and their average deceleration over the final 200 m of approach was almost 0.2 g. Fig. 1 shows that both two-axled and larger multi axled trucks use decelerations which peak at 1.7 m/sec^2 in the vicinity of 15 to 25 m from the intersection. The average deceleration used by truck drivers over the whole stopping manoeuvre was found to be approximately 0.1 g, similar to cars with slower approach speeds. As with passenger cars, about half the stopping time (more than half the stopping distance), was spent by trucks decelerating at less than the average deceleration for the whole manoeuvre.

Consideration of individual peak decelerations used by trucks in the same work shows that 25 per cent of larger trucks use decelerations over 2.0 m/sec^2 and approximately four per cent use decelerations greater than 2.5 m/sec^2. Small two-axled trucks (van derivatives) use decelerations much more similar to those of cars, as shown in Table II.

TABLE II

PEAK TRUCK DECELERATIONS

Vehicle type	% of deceleration greater than	
	2.0 m/sec^2	2.5 m/sec^2
Small 2-axle truck (2-base < 3.75 m)	36.2	14.9
large 2-axle truck (w-base > 3.75 m)	25.2	4.1
Multi axled truck	25.0	4.5

The information found available on car and heavy vehicle braking shows that there is a difference in capacity of the two vehicle types to actually decelerate, and that drivers of heavy vehicles are likely to use lower levels of deceleration, although the braking profiles (non-uniform) would be of a similar nature. Heavy vehicle drivers also probably adopt a different driving strategy to reduce the need for braking, but the level of adherence to such 'defensive' strategies in a range of driving situations is not known.

While there was overseas information as to what might be acceptable and normally used levels of in-service deceleration associated with comfort and safety, this was only for light vehicles and similar information for Australian heavy vehicles would be of obvious value.

BRAKING COMPATIBILITY

One of the areas in which a knowledge of in-service braking behaviour would be of great value is in the development of balanced braking, particularly for tractor/semi-trailer combinations. Brake compatibility is the ability of tractor and trailer systems to function well together and provide a satisfactory overall braking performance for the vehicle combination. Radlinski and Flick (1986) discuss brake system compatibility in detail and point to the fact that the major result of poor compatibility expresses itself in terms of excessive brake lining and drum wear and even brake drum cracking on the 'overbraked' axles of a combination with poor brake balance. Although the trucking industry has obvious concerns regarding the safety aspects of poorly balanced units, the need for solutions is driven by excessive wear and subsequent maintenance costs. As Radlinski and Fink point out, high levels of wear have an effect on safety in that increased maintenance is required and if not carried out the braking systems will not be able to provide optimal braking should an emergency occur. Similarly, the performance of the braking system is degraded if it has to operate at the extremes of brake adjustment.

More directly, under heavy braking conditions, premature lockup of tractor axles can cause jack-knifing, trailer swing can result from lockup of the trailer axles and the vehicle cannot be steered with the steer axle locked.

Glynn (1988) considered brake compatibility in relation to Australian Design Rules 35, 35A and 38. He concluded that operator complaints of extreme lining wear and driver complaints of 'trailer push' and other unstable braking characteristics suggests that brake incompatibility is reasonably common at various levels of severity for various vehicle combinations in Australia.

The compatibility that has been achieved through current design rules and voluntary measures introduced by truck manufacturers relates mainly to high braking levels. Drivers and operators continue to complain of a lack of compatibility, however, even though almost all routine braking is not carried out at these high levels. If a test procedure was to be developed which would improve the ability of trucks and trailers to be interchanged without marked changes in brake performance or compatibility occurring (Glynn 1988), it would be essential that information on normal in-service braking behaviour be available in order that the tests be framed around those braking conditions.

The remainder of this paper describes testing which was carried out on a number of heavy vehicles to determine a variety of parameters associated with the normal braking behaviour of drivers in-service.

IN-SERVICE DATA COLLECTION

THE VEHICLES AND DRIVERS

Four vehicles were instrumented and various parameters logged during their normal in-service braking:

- Ford Louisville 6 x 4 tractor with Freighter Tautliner triaxle semi-trailer
- Scania H164 6 x 4 tractor with Maxi-cube tandem axle van semi-trailer
- Kenworth 6 x 4 rigid with dog trailer
- Mercedes 4 x 2 rigid van (air over hydraulic).

The Ford and Scania were each tested in two configurations:

- in standard forms which were considered to have less than satisfactory compatibility

- with various modifications to the braking systems to provide improved compatibility.

The two sem-trailers were logged over four nights on line haul operations. The dog trailer was logged for 4 days on urban/suburban bulk delivery and the Mercedes rigid for a similar period on metropolitan short haul.

Individual drivers were provided for the suburban bulk deliveries and metropolitan operations. The drivers were aged 38 and 62 respectively and had a combined experience of over 50 years driving. Six drivers were involved in the line haul operations, ranging in age and experience from a relief driver of 25 with 1 year's experience to a 56 year old with 32 years heavy vehicle driving experience.

INFORMATION OF INTEREST

The aim of the experiment was to examine both driver braking behaviour and the characteristics of the vehicles during braking. The parameters to be considered included:

Driver behaviour -

- braking duration
- braking levels
- time and distance between brakings
- rate of application/deceleration
- cause of braking
- road characteristics and conditions.

Vehicle characteristics -

- pedal valve pressure
- drive-axle chamber pressure
- rear-most trailer axle pressure
- lateral acceleration
- engine or exhaust brake operation.

DATA LOGGING

Data was logged using an ARRB AMBDAS data collection unit (see for example, Fraser 1981) configured as TRUCKDAS. Due to the complexity of the logging process, and the need for additional coding, it was necessary to have a researcher travel in the cab with the driver to operate the equipment. The system continuously monitored a buffer of data representing logged conditions over the previously travelled 50m. Logging began when the footbake was depressed including the contents of the buffer which gave information on conditions immediately prior to the braking. Logging was odometer pulse driven, generating timed readings of all inputs every two metres or so of travel, accurately calibrated for each vehicle.

This distance rather than time base for logging allowed approximately 6 to 8 readings per second at the onset of braking at normal open road speeds. As deceleration continued and the vehicle slowed, the sampling rate decreased allowing a more reasonable demand for data storage before data dumping was required.

The various elements of the instrumentation, data collection and logging are shown on the plan view schema of a typical vehicle given in Figure 2.

1) Collection box

This box contained the lateral accelerometer and acted as a collection point for all external inputs for transfer to the data logger. Filtering cicuits cleaned these input signals, such filtering being essential due to the considerable amount of electrical noise generated by the truck in the supply cabling.

2) Data logger

The data logger received clean signals from the collection box, direct signals from the brake pedal and coding box, and provided the time base, logging logic and on-board data storage.

3) Lap-top computer

This provided contol of the system and was used to dump to disk, at convenient opportunities, data stored in the logger during a logging run. The keyboard was initially used to input coded data on driver behaviour etc. but since this appeared to run the risk of distracting the driver, other arrangements were made.

4) Coder

In order not to distract the driver, a small coding box was connected to the logger which the experimenter rather surreptitiously used to to insert various codes directly into the data stream, generating a short log if logging was not already taking place.

5) Brake pedal

A signal denoting the depression of the brake pedal was used to commence logging. It was not possible to rely on the brake light circuits because, despite adjustment, they were subject to delays which seriously curtailed the logging process. Independent, often ingeniously contrived, switching was required under arduous operating conditions.

Switching was also included which coded whether the engine or exhaust brake was in operation during the braking.

6) Pedal valve

With all air pressure monitoring, a transducer and signal conditioner/amplifier was inserted into the air lines of the vehicle as close as possible to the valve or chamber being monitored. These were then cabled to the collection box using a unique connector to ensure the same transducer was always used in the same ralative location on all vehicles. The transducers were calibrated before and after the experiment.

7) Odometer

An adjustable electrical pulse odometer was inserted between the gearbox and speedometer drive and adjustment made until a 2 kilometre calibration run indicated a pulse rate as close as possible to 2 metres.

8) and 9) Brake chambers

Brake chambers on the rearmost drive and trailer axles were instrumented in a similar way to the pedal valve after suitable changes to slack adjusters etc to ensure corredct operation.

The vehicle were obtained over one weekend and instrumented at the ARRB workshops. Any necessary changes to the braking configuration were made in the middle of the week after the first set of logging runs and the instrumentation removed the following weekend, usually at the vehicle depot.

DATA ANALYSIS

In order to capture data at the rate required for detailed analysis, of pressure gradients in the braking system for example, a great deal of data was logged during the experiment, some 6 million characters in total. Although collection could be largely automated, the behavioural nature of the data precluded totally automated analysis. The data had to be examined and spurious or unwanted information removed. For example, a braking was only considered for analysis if the depression of the footbrake ultimately resulted in a pressure rise in the system, which was often not the case. Similarly, when a vehicle was brought to rest the driver often kept the pedal depressed thereby artificially extending the braking time data of interest to the experiment. Considerable editing was required to remove data which might otherwise contaminate the good data collected.

Following editing, each braking was analised in detail and a summary of all likely required data prepared. These summaries were then extracted and amalgamated into descriptions of trips, each trip being part of an overall journey. Trips were used to keep the data to manageable proportions and to divide the trips into sections which were of predominantly of one road type.

While it was not possible to ensure complete uniformity over the total length of road, it was possible to divide trips into the following categories:

Urban - light and heavy traffic

These sections of major arterials were fully built-up and included the metropolitan area. Heavy traffic was generally the morning or evening peak, while light traffic was generally off-peak in the afternoons and evenings.

Suburban

Trips on major arterials in the built-up and semi built-up area of suburban Melbourne, avoiding the metropolitan area. Traffic was usually medium to heavy density.

Rural - high and medium levels of service.

These trips were predominantly on major highways in rural areas but did include travel through country towns etc. where necessary. High level of service generally included considerable lengths of divided highway or freeway. Medium level of service was all-purpose two-way two-lane highways of generally good standard.

Most analysis had been carried out using these categories where appropriate.

Almost 800 brakings have now been analysed within 22 different trips. Not all the factors have have as yet been included in the data set, current effort is being directed towards the incorporation of detailed road characteristics and codings associated with the reasons for braking.

RESULTS

BRAKING TIMES AND DISTANCES

Table III shows that while the average distance between brakings in urban and suburban areas is below 1 km, on rural roads with medium levels of service, this increases to almost 4.5 km and for high levels of service the distance extends to over 11 km. This is reflected in the speeds between brakings of around 40 km/h in urban areas and 100 km/h for rural trips. Similarly, these trips average 6.5 minutes at high speed between brakings compared to the urban average of under 1 minute at low speed.

Figure 3 shows the distances between brakings for an urban trip where none of the 34 brakings were more than 2 km apart. Fig. 4 shows a suburban trip with somewhat similar characteristics except for the evidence of use of an urban freeway of at least 23 km long.

The line haul, overnight type of operation on high level of service rural roads leads to the extraordinary braking pattern illustrated in Fig. 5. In the 300+ km from north of Melbourne to the outskirts of the City of Albury-Wodonga, there were 9 brake applications, three of these in the small city of Wangaratta. A further 19 brakings were necessary from entry to Albury through the contorted streets to the vehicle's depot.

TABLE III

DISTANCE AND TIMES BETWEEN BRAKINGS

Trip Type	Average Distance (m)	Between brakings Average Time (s)	Average Speed (km/h)
URBAN			
Heavy traffic	531	52.7	36.3
Light traffic	728	60.5	43.3
SUBURBAN	948	81.7	41.8
RURAL			
Medium level of service	4425	156.5	101.8
High level of service	11169	403.3	99.7

DURATION OF BRAKING

Table IV indicates that the great majority of brakings have a duration of between 2 and 15 seconds. A later Table shows that average braking duration is generally between 6 and 9 seconds for all types of road. Fig. 6 shows that there are more long brakings in urban ares but that 70% of these brakings are below 9 secs and that 70 % of rural brakings are less than 6 seconds long. These durations are measured from the onset of a rise in the pressure in the pedal valve until the return to a basic state. The rate at which the pressure rises in the pedal valve will be discussed later.

TABLE IV

BRAKING DURATION PERCENTILES

Trip Type	Average braking duration %iles (s) 15	85
URBAN		
Heavy traffic	2.4	10.5
Light traffic	2.7	14.1
SUBURBAN	3.1	14.7
RURAL		
Medium level of service	1.2	6.1
High level of service	2.7	9.1

SPEED BEHAVIOUR

The average initial speed at the onset of braking for rural high level of service roads is shown to be relatively low in Table V when compared to other road types. Fig. 7 suggests that initial speeds in rural areas are approximately 10 km/h higher than those for urban trips. Several of the trips used to generate the data for the rural high level of service results given in Table V have so few brakings during the high speed section of their trips that these are easily distorted by brakings in towns or at the end of the trip. In contrast, Fig. 7 contains data for medium level of service rural roads which have a higher proportion of brakings during the high speed sections of their runs.

Table V also shows that the average speed change during a braking is rather small. An examination of the data showed that very few brakings were made from high speed to very low speed even in urban areas. The constant adjustment to speed conditions by the driver appears to pre-empt the need for severe speed change.

TABLE V

SPEED BEHAVIOUR

	Initial speed (kmh)		Speed change km/h	
Trip Type	Average	Maximum	Average	Maximum
URBAN				
Heavy traffic	53.8	96.7	18.7	74.8
Light traffic	49.0	98.7	16.4	64.1
SUBURBAN	49.8	85.4	21.7	67.6
RURAL				
Medium level of service 84.7	126.2	5.2	27.8	
High level of service	66.8	109.1	15.5	96.6

DECELERATION RATES

As mentioned earlier, Table VI gives average braking durations generally ranging between 6 and 9 seconds. The Table also shows that the maximum deceleration used by vehicle is little more than 1.2 m/s^2 on average, while the mean deceleration used ranges from 0.4 to 0.7 m/s^2. This is considerably less than 2.5 m/s^2 or so already suggested as indicating a comfortable stop for passenger car drivers. Very few mean deceleration rates were in excess of 2 m/s^2 and few maximum deceleration rates exceeded 3.5 m/s^2. Table VII indicates that most decelerations were in the range 0.3 to 1.1 m/s^2.

TABLE VI

DECELERATION BEHAVIOUR

Trip Type	Average Braking Duration(s)	Maximum dec. (m/s^2)		Mean dec. (m/s^2)	
		All Vehs	Absolute Maximum	All Vehs	Highest Mean
URBAN					
Heavy traffic	7.5	-1.1	-2.9	-0.66	-1.8
Light traffic	5.9	-1.2	-3.5	-0.73	-2.3
SUBURBAN	8.6	-1.2	-3.8	-0.68	-2.2
RURAL					
Medium level of service	3.6	-1.8	-5.9	-0.41	-1.38
High level of service	6.3	-1.2	-2.9	-0.58	-1.85

TABLE VII

AVERAGE DECELERATION PERCENTILES

Trip Type	Average deceleration percentiles (m/s^2)	
	15	85
URBAN		
Heavy traffic	-0.30	-1.01
Light traffic	-0.31	-1.14
SUBURBAN	-0.28	-1.09
RURAL		
Medium level of service	-0.05	-0.80
High level of service	-0.27	-0.94

PRESSURE RISE AND MODULATION

As an indication of some of the data developed to directly contribute to improved Australian Design Rules, Table VIII gives information on pressure rises found for a selection of vehicles used for trips on the given road types. Detailed analysis was required of each pedal valve pressure trace (Figure 8) and the rise in pressure was noted over the initial build-up until a plateau was reached. Table VIII is prepared from indicative trips and not the entire data base.

There is a delay of some 0.4 - 0.75 seconds between the pedal being depressed and a pressure rise through the valve. The duration of the initial rise is relatively short, but since most pressures reached are not very high, the rate of pressure rise remains fairly modest. Very few pressure rises were found to have a rate in excess of 400 Kpa/sec.

A larger number of pressure traces were examined to determine the extent to which drivers modulated their braking as shown in Figure 9. Less than 1% of the brakings examined demonstrated any form of modulation.

TABLE VIII

PRESSURE RISE CHARACTERISTICS

Trip Type	Ave. delay in lift (s)	Average duration (s)	Ave. pressure rise rate (kpa/sec)	maximum pressure rise (kpa)
URBAN				
Heavy traffic	0.53	0.76	111.2	368.4
Light traffic	0.39	0.94	67.3	202.2
SUBURBAN	0.75	0.54	80.9	228.2
RURAL				
Medium level of service	0.75	0.21	215.9	971.4
High level of service	0.67	0.76	82.1	204.2

DISCUSSION

This paper deals with the in-service braking behaviour of heavy vehicle drivers which was examined to provide information for use in the development of design rules which would improve tractor/trailer braking compatibility under routine braking regimes.

Results show that while braking is required every 500 m under heavy urban driving conditions, on roads with high levels of service this can reduce to once every 11 km on average. Under the right conditions, heavy vehicles can travel 90 km distances between brakings.

Average braking duration is between 6 and 9 seconds with average deceleration rates of between 0.4 and 0.7 m/s^2. Very few decelerations had maximum values in excess of 3.5 m/s^2. These decelerations are considerably less than the 0.25g accepted as the limit of comfortable passenger car braking. The average speed change during braking was found to be small for all road types considered. Very few brakings were made from high to low speeds. The constant adjustment of speed to the conditions by drivers appears to pre-empt the need for severe braking.

The rise of pressure in the system once the footbrake was depressed was examined. The duration of the initial rise was found to be short, but since most of the pressures reached were not very high the rate of pressure rise was found to be generally quite modest. A large number of pressure traces were examined but there was no evidence to suggest that drivers modulate their braking, quite the opposite, there was an almost complete absence of brake modulation.

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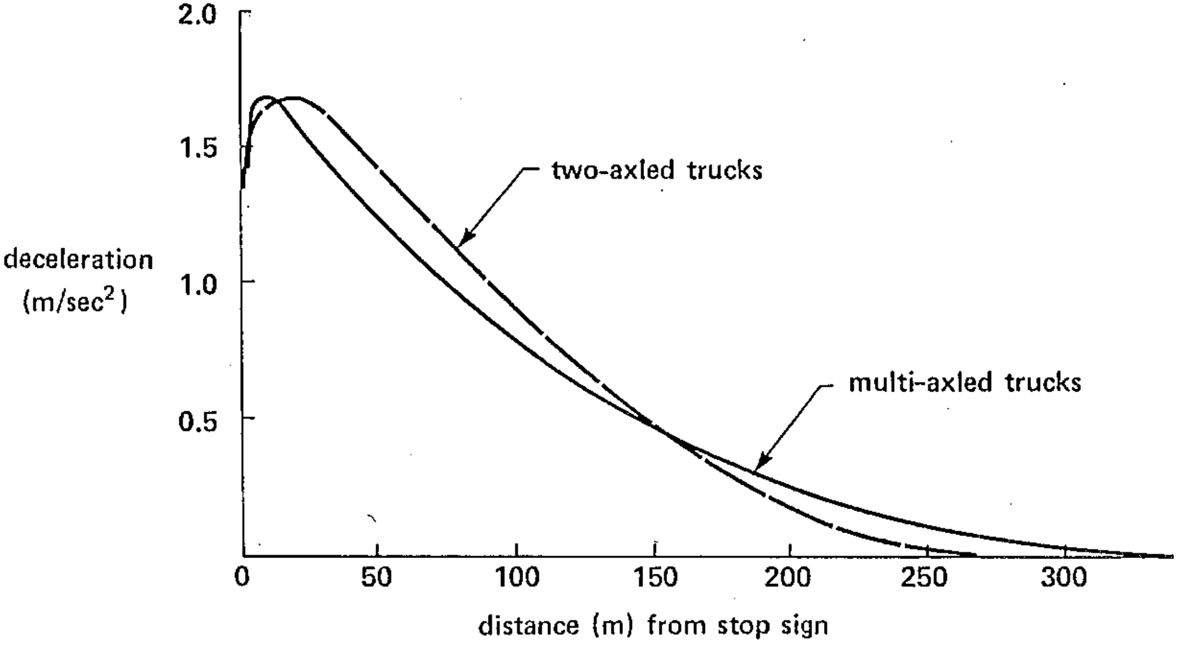

Fig.1 - Average truck decelerations

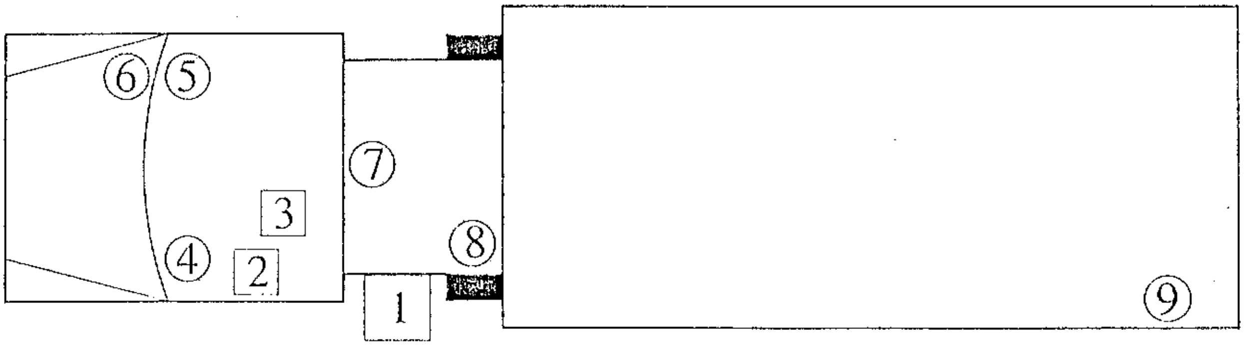

Fig.2 - Vehicle instrumentation, data collection and logging elements

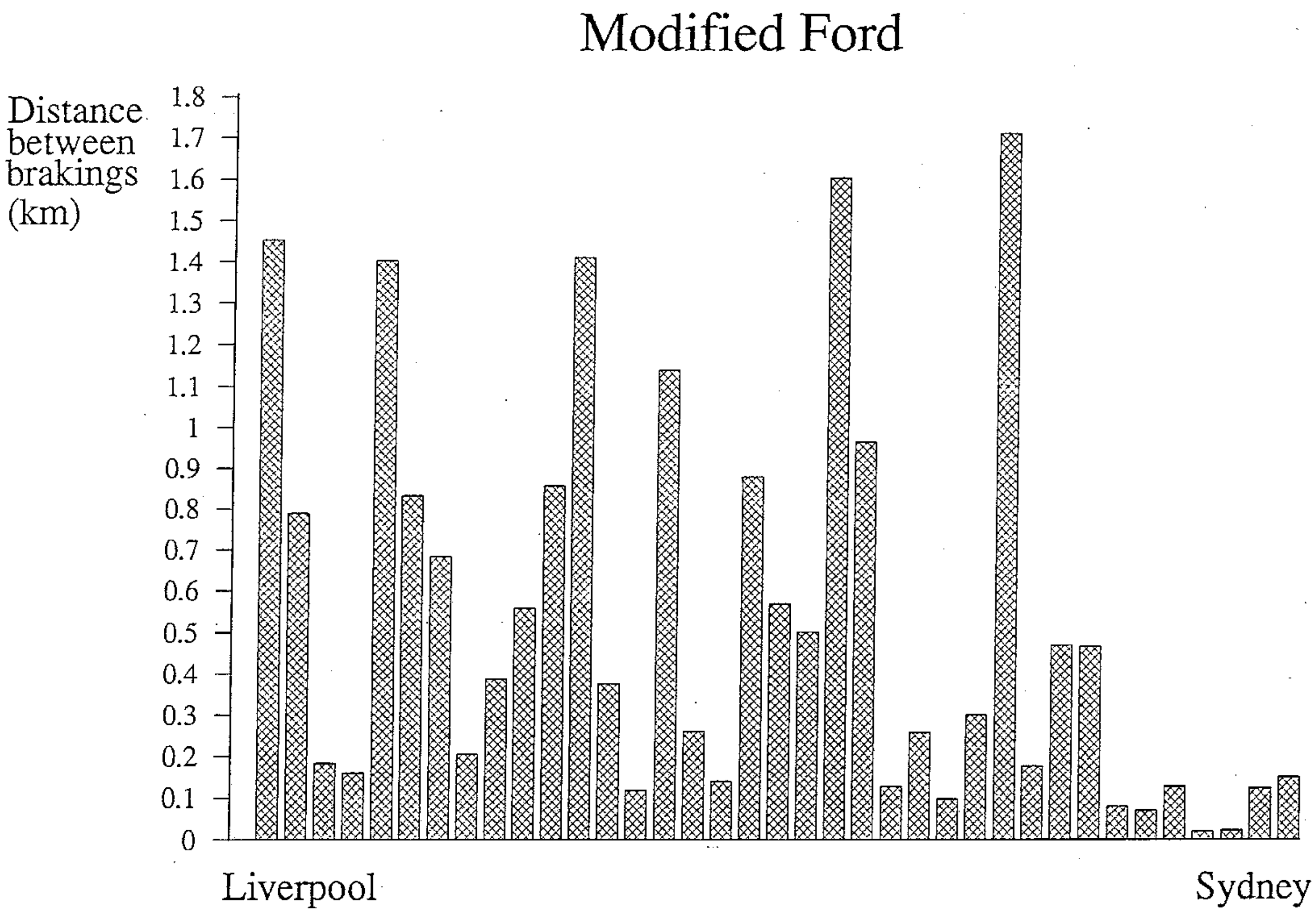

Fig.3 - Distances between brakings, urban, heavy traffic.

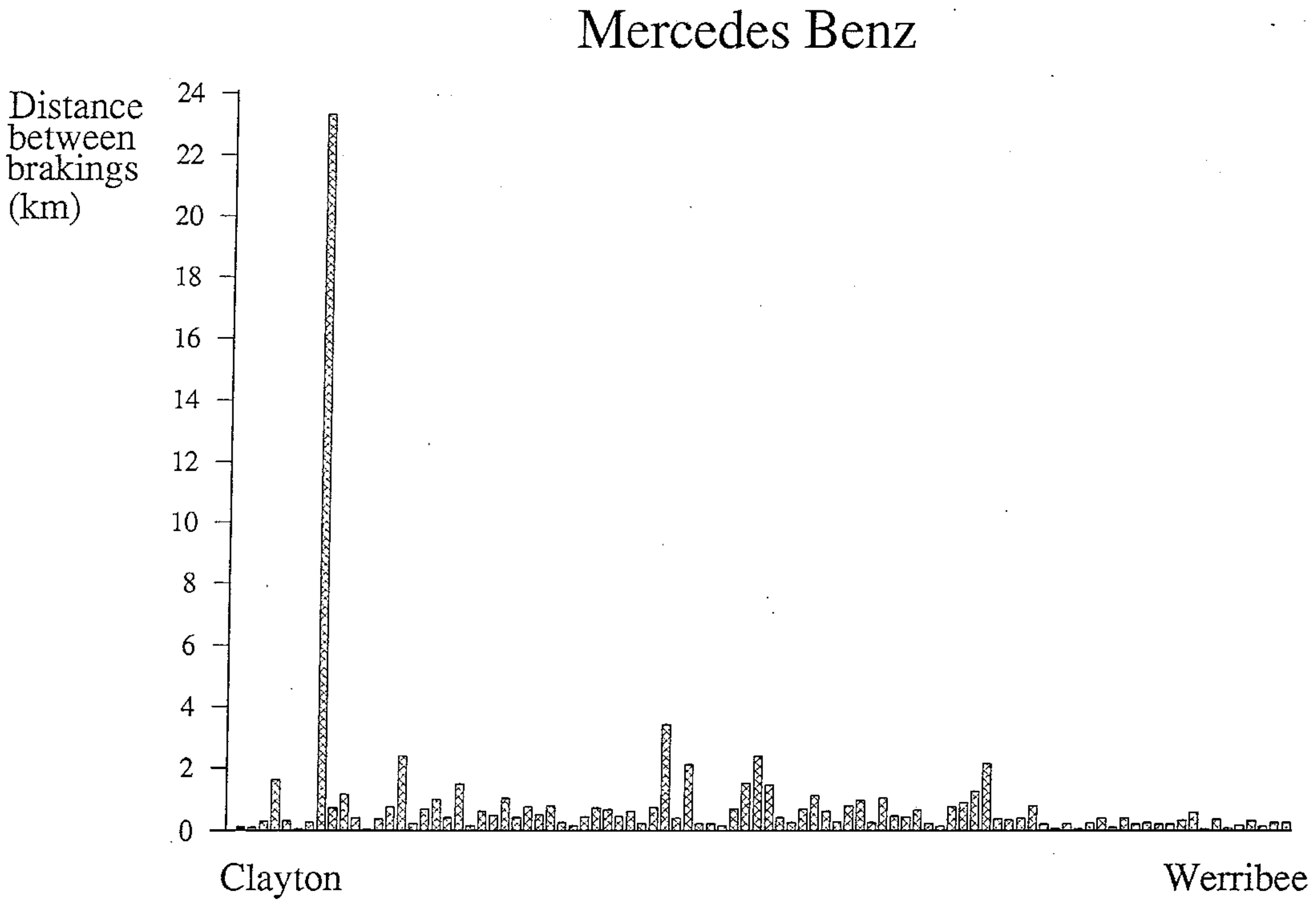

Fig.4 - Distances between brakings - suburban.

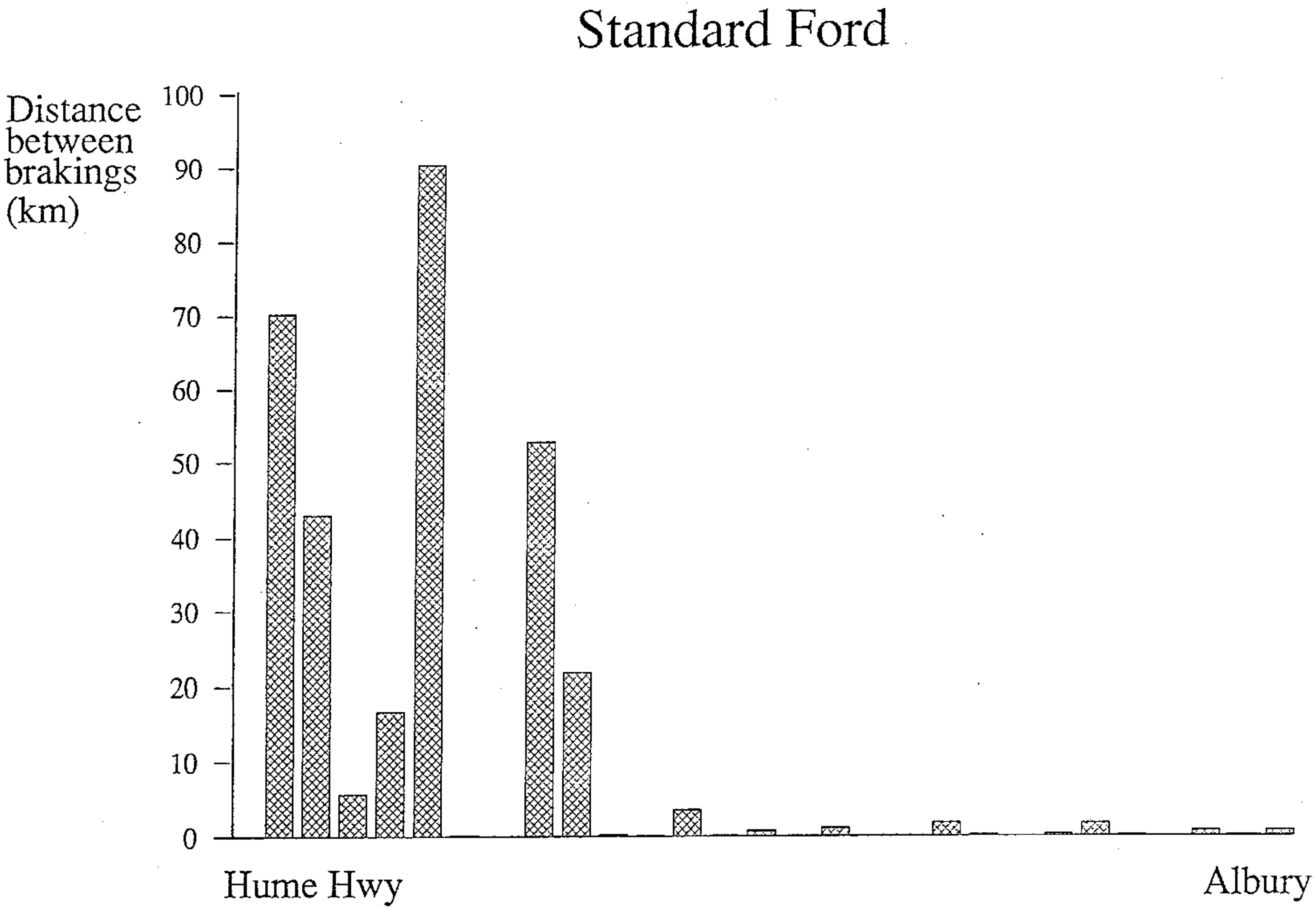

Fig.5 - Distances between brakings, rural, high level of service

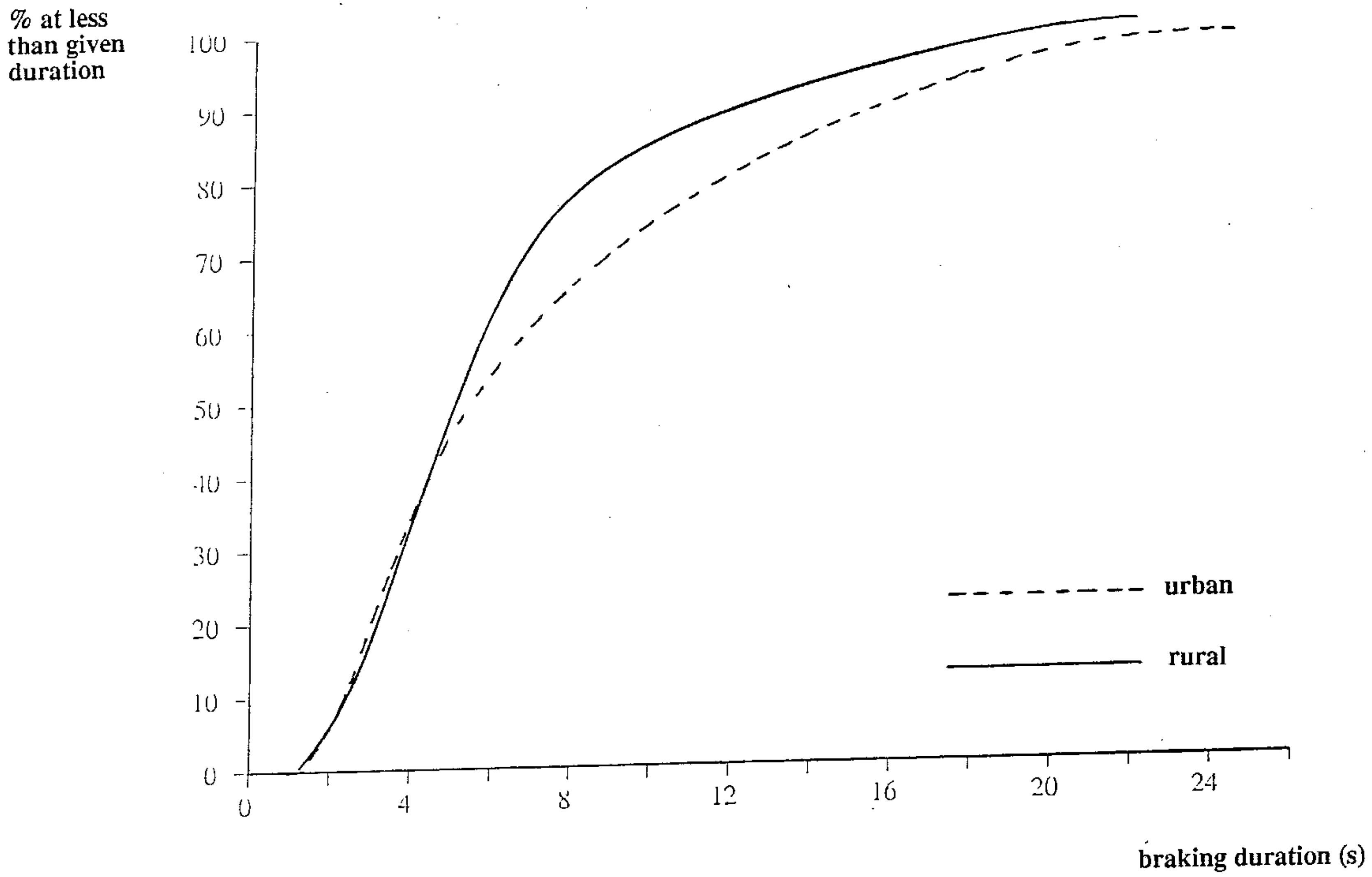

Fig.6 - Braking durations

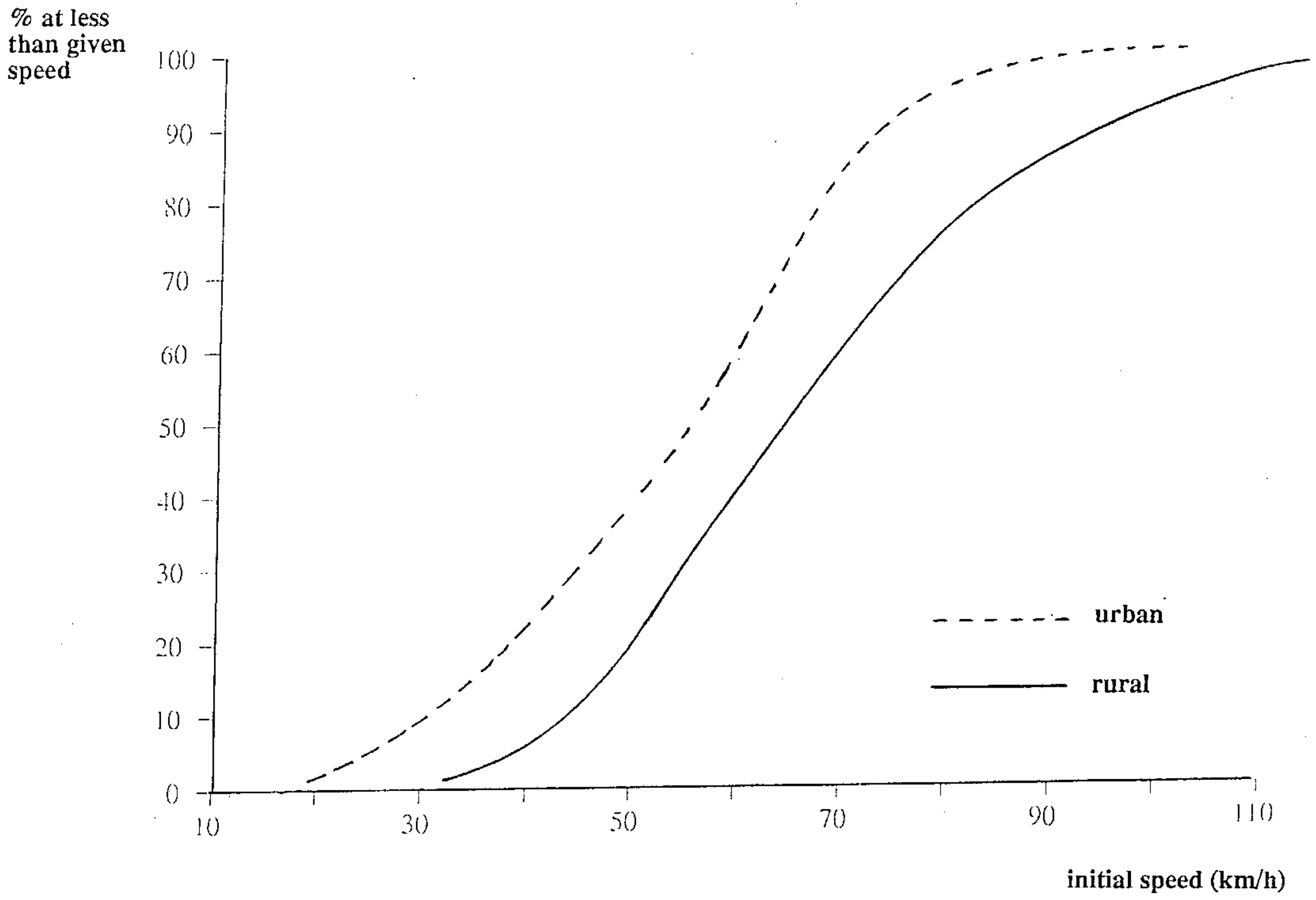

Fig.7 - Differences in initial speed

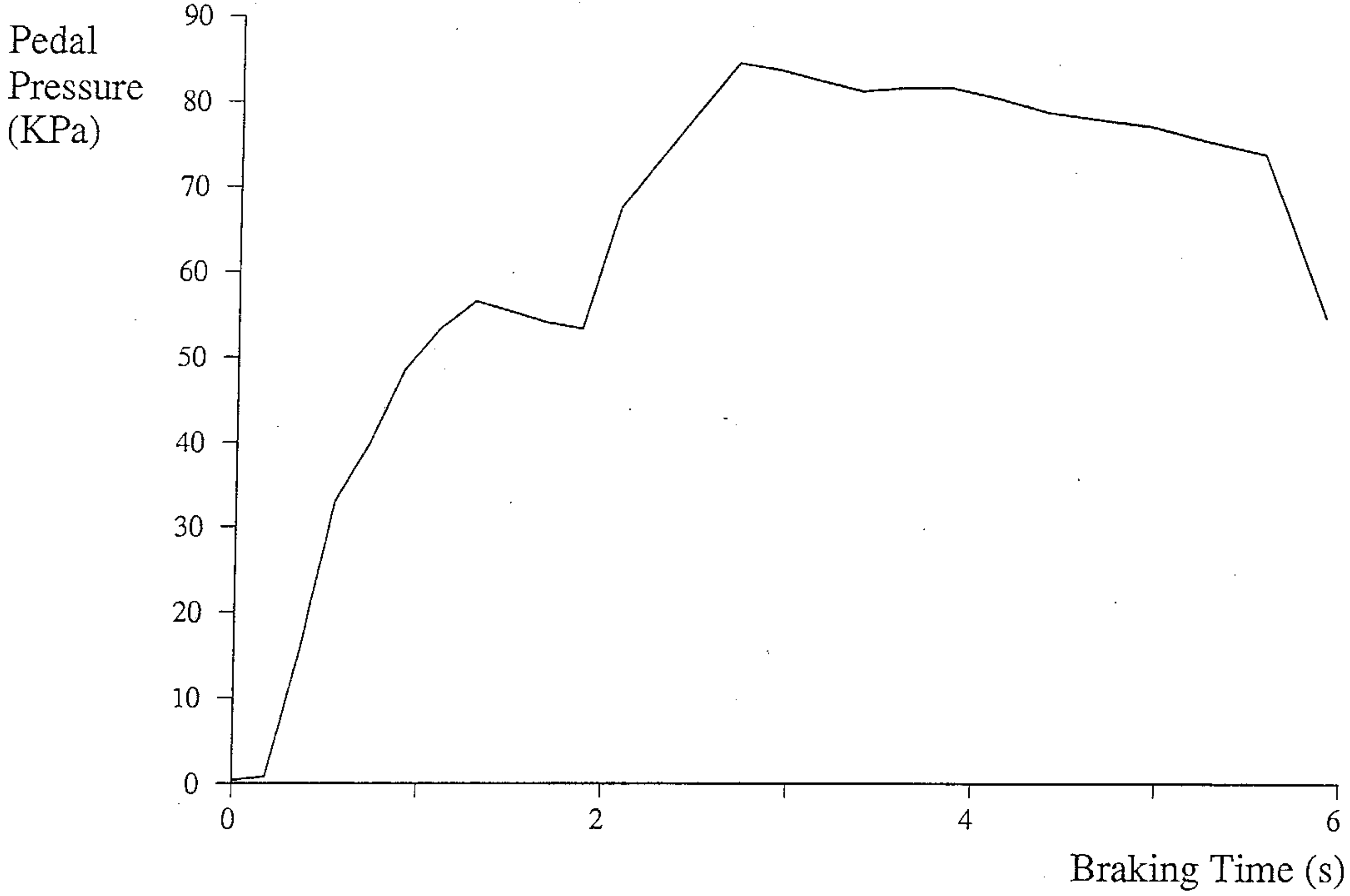

Fig.8 - Pedal pressure trace

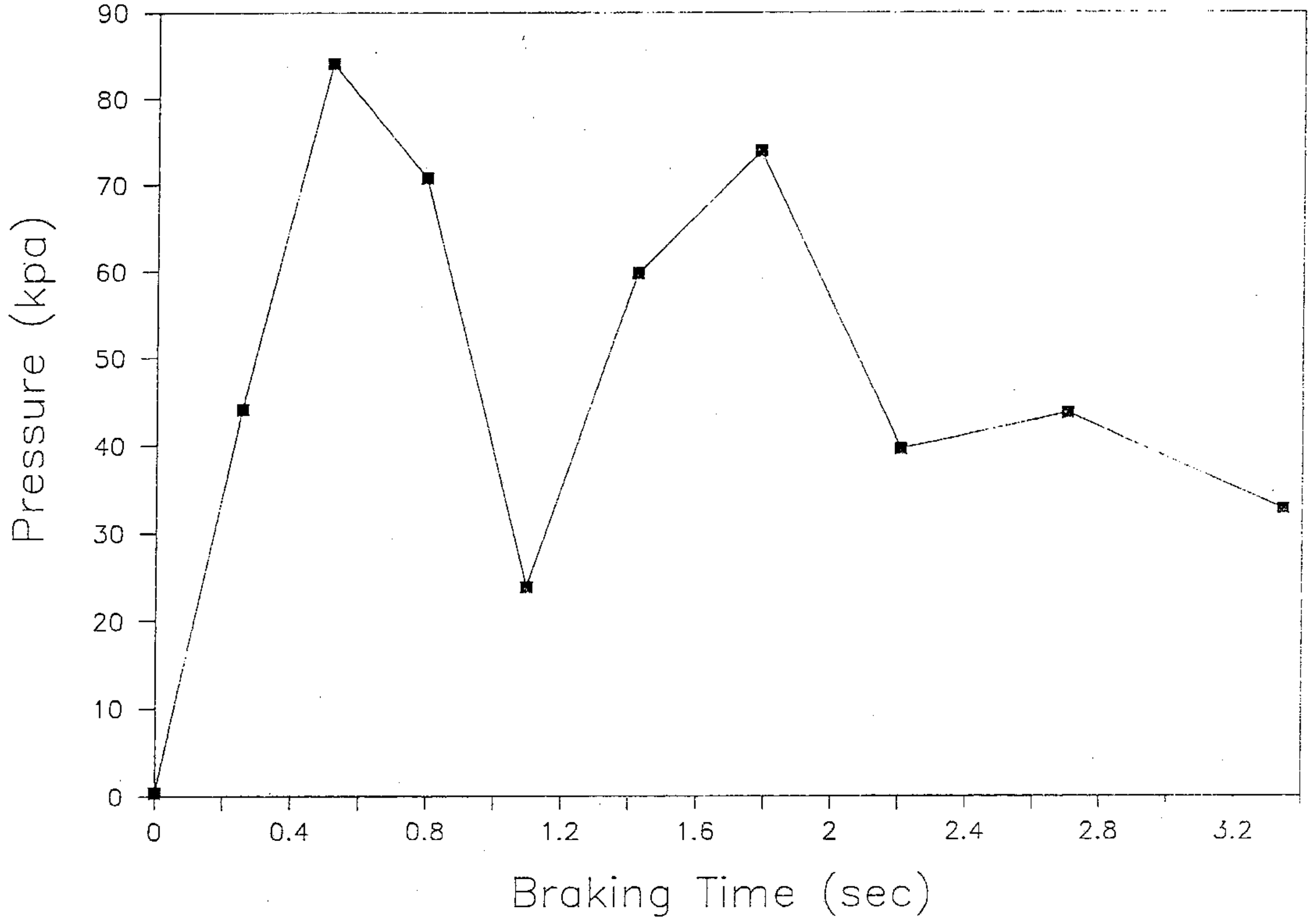

Fig.9 - Brake modulation