TOWARDS A CANADIAN STANDARD FOR THE GEOMETRIC DESIGN OF SPEED HUMPS

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A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of

Master of Engineering*

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Carleton University
Ottawa, Ontario, Canada
April, 1998

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* The Master of Engineering Program in Civil and Environmental Engineering is a joint program between Carleton University and the University of Ottawa, which is administered by the Ottawa-Carleton Institute for Civil Engineering.

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0-612-32410-9

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ABSTRACT

The purpose of this study was to help develop geometric design standards for speed humps in Canada. Off-road tests were carried out on several speed humps constructed out of wood using two automobiles and a transit bus. Accelerations were recorded on a test subject and compared to discomfort criteria determined by recording speeds over existing humps.

A multiple regression model was formulated to estimate the accelerations measured and predict additional accelerations. Optimal designs were found that produced acceleration levels equal to the discomfort criteria.

On streets expected to carry automobile traffic only, 5.2 m by 100 mm, 7.9 m by 100 mm and 9.1 m by 75 mm speed humps were recommended for desired speeds of 30, 40 and 50 km/h respectively. On bus routes, 6.1 m by 100 mm and 8.8 m by 100 mm speed humps were recommended for desired speeds of 30 and 40 km/h respectively.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my thesis supervisor, Professor John P. Braaksma, P.Eng., for his ideas, guidance, advice and Dutch translation.

I would also like to thank the Department of Civil and Environmental Engineering and the Faculty of Graduate Studies and Research at Carleton University for their generous monetary contributions, and the Civil Engineering Laboratories staff for their assistance in constructing the speed humps.

Also deserving of thanks are: Professor Claude Lupien, P.Eng., of the University of Sherbrooke, for his insight into speed humps in Québec; Dirk Klaasesz, for introducing me to the thousand or so speed humps in Montgomery County, Maryland; Professor Jo Yung Wong, P.Eng., for his mechanical engineering help; Lawrence King, P.Eng., for the accelerometer; Dave Case of Agriculture Canada for the use of the Experimental Farm; and Sean Rathwell, P.Eng., and Bill MacDonald of OC Transpo, for loaning me a transit bus.

Lest I forget my friends: Mark Langlois and Guislaine Moreau, for the French translation; Stephan Carriere for the wood; John Weber, Don Kells and Rob Ward for the hired muscle; and Michelle Ellis for her muscles and proof-reading skills. And mom and dad for the ground transportation.

Finally, I greatly appreciate the efforts of Professor Shirley Mills, for her assistance in the factorial design and multiple regression analysis. I certainly don't know what I would have done without her.

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SUMMARY

Speed humps are raised sections of roadway designed to reduce vehicle speeds. The most common type is the Watts Profile hump, which is a section of a cylinder 3.7 m long and 75 to 100 mm high that limits speeds to 25 or 30 km/h. Other designs have been developed for higher speeds, such as the Seminole Profile hump, which includes a 3 metre flat section to increase its length.

As with other traffic calming measures, speed humps can increase overall road safety and make streets more accessible and liveable for all users. Many countries use speed humps of various designs on their streets, even on bus and truck routes with posted speeds of up to 50 km/h. The designs have been developed through considerable research and testing. In North America traffic calming measures, particularly speed humps, are often looked upon by traffic engineers as obstacles to motor vehicles. Despite this, there is growing demand on many streets for measures to reduce automobile dominance.

The purpose of this study was to develop a set of geometric design standards for speed humps in Canada, where speed hump use is still quite limited and guidelines are rare. Tests were carried out on several speed humps constructed out of wood. Rather than subjective assessments from a variety of individuals, the humps were evaluated using an accelerometer to record accelerations on a test subject. These were compared to discomfort criteria.

Two of the lengths used in the tests were 3.7 and 6.7 m, which are the lengths of Watts and Seminole Profile humps. The other lengths were 4.9 and 9.1 m, and the heights were 75 and 100 mm. The humps were traversed by two automobiles and a regular transit bus at speeds corresponding to desired speeds of 30, 40 and 50 km/h. A factorial design was used to select the tests.

Baseline acceleration levels were ascertained for the test vehicles by recording speeds over several existing Watts and Seminole Profile humps. The humps were located at Algonquin College in Ottawa and in Montgomery County near Washington, DC. It was found that as hump lengths increased or heights decreased, motorists raised their speeds so as to maintain a fairly constant level of acceleration. When these hump dimensions and hump-crossing speeds were duplicated in the tests, the measure that best described this phenomenon was the root sum of squares (RSS) acceleration. This differs from other speed hump studies, which use peak vertical acceleration.

The tests were then carried out as prescribed in the factorial design. A multiple regression model was formulated to estimate the accelerations measured in the experiment. The model was used to predict additional RSS accelerations, which were plotted as regression curves of length for each height and speed tested. An optimal length was found at each speed that produced acceleration levels equal to the baseline levels, or discomfort criteria, for the automobiles and transit bus.

On streets expected to carry automobile traffic only, lengths were recommended solely for automobiles. On bus routes, speed humps were recommended that were a compromise between the optimal lengths for automobiles and transit buses. The recommended designs are summarized in the following tables.

Recommended Speed Humps for Non-Bus Routes

Desired Speed (km/h)	**Speed Hump Dimensions (m, mm) (ft, in.)**
30	5.2 x 100 (17 x 4)
40	7.9 x 100 (26 x 4)
50	9.1 x 75 (30 x 3)

Recommended Speed Humps for Bus Routes

Desired Speed (km/h)	**Speed Hump Dimensions (m, mm) (ft, in.)**
30	6.1 x 100 (20 x 4)
40	8.8 x 100 (29 x 4)
50	See Below

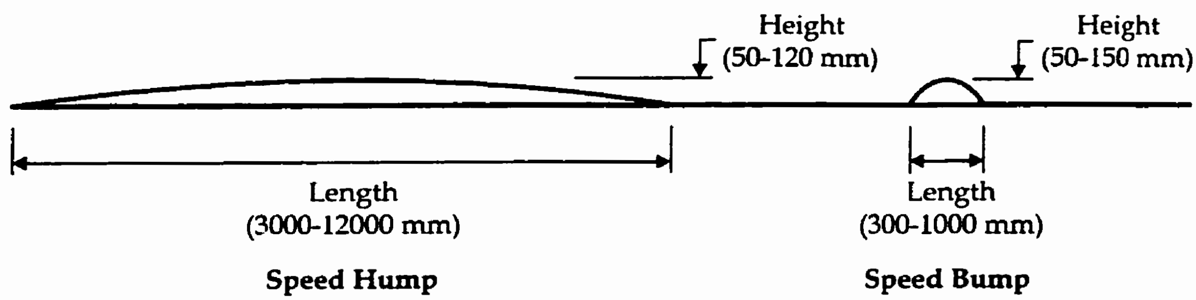
Speed humps could be used on bus routes having a posted speed of 50 km/h by employing the humps recommended for non-bus routes. Transit buses will be slowed even further. Humps could be placed near bus stops where bus speeds are already low.

CHAPTER 1 – INTRODUCTION

1.1 SPEED HUMPS AND TRAFFIC CALMING

Speed humps are raised sections of roadway designed to limit the speeds of motor vehicles. They are several metres long, about a tenth of a metre high, and can cover all or a portion of the width of a roadway. A speed hump is not the same as the much shorter speed *bump* (see Figure 1.1).

Figure 1.1
Profile of Speed Hump vs. Speed Bump



Speed humps are traffic calming measures. Traffic calming measures are physical design techniques that encourage or force motorists to drive at slow and constant speeds. They prevent speeding and can increase overall road safety. Traffic calming can also make streets more accessible and liveable for other users such as pedestrians, cyclists and nearby residents.

Many countries around the world employ traffic calming on their streets, and speed hump use is widespread. In North America, however, traffic calming is often regarded as an impediment to the efficient movement of motor vehicles. However, with increasing concern over the effects of continued high automobile use many municipalities are beginning to give traffic calming, and speed humps, serious consideration.

1.2 PURPOSE OF STUDY

Speed humps are a very effective means of calming traffic. The most common design is the Watts Profile or circular hump, which was developed in the 1970's.

It is a section of a cylinder 3.7 m long and 75 to 100 mm high extending over the width of the roadway. Most motor vehicles can traverse them safely at 25 or 30 km/h.

Research in Europe and elsewhere has led to other hump designs that feature different lengths, heights and profiles. This has allowed their use on local roads, collectors and even urban arterials, with speed limits of up to 50 km/h. Speed humps can also be found on bus and truck routes. They are designed so that most motor vehicles will cross them at 5 km/h lower than the posted speed, and are spaced so that over the length of a given street actual speeds will fluctuate around a predetermined desired speed.

Despite these developments speed hump use is limited in Canada. There are few guidelines for their application, and little research has been carried out to date concerning their geometric design. In fact, the only "official" design standard in North America is the publication *Guidelines for the Design and Application of Speed Humps* by the Institute of Transportation Engineers. The guidelines recognize the Watts Profile speed hump [ITE, 1993]. The Transportation Association of Canada also recognizes a Watts Profile type speed hump [TAC, 1995].

Speeds of 25 or 30 km/h are often considered unrealistically low for many streets in North America that could benefit from traffic calming. Also, Watts Profile and similar humps are too abrupt for many heavy vehicles. Other less severe designs are considered more suitable for these conditions. One such design developed in the United States is the Seminole Profile speed hump. The design features a flat 3 metre section inserted into a Watts Profile speed hump, making it 6.7 m long. Photographs of Watts and Seminole Profile humps are shown in Figures 1.2 and 1.3.

In Western Europe, Australia and elsewhere, optimal geometric design features are prescribed for speed humps using published standards. These often take the form of tables listing suitable humps for certain desired vehicle speeds. An example is shown in Table 1.1. The standards are the result of extensive research and vehicle testing.

The purpose of this study was to work towards the development of a similar set of standards for Canada, where vehicle characteristics, environmental conditions and motorist expectations may be different from those in other countries. The goal was to recommend speed hump lengths and heights for Canadian streets. The streets could be bus routes or non-bus routes, and have posted speeds between 30 and 50 km/h.

Figure 1.2
Watts Profile Speed Hump

Location: Mill Creek Road, Gaithersburg, Maryland (January 16, 1997).

Figure 1.3
Seminole Profile Speed Hump with Pedestrian Crossing

Location: Bel Pre Road, Rockville, Maryland (January 16, 1997).

Table 1.1
Recommended Circular Speed Humps in Denmark

Automobile Speed (km/h)	Bus Speed (km/h)	Speed Hump Dimensions (m, mm)
20	5	3.0 x 100
25	10	3.5 x 100
30	15	4.0 x 100
35	20	5.0 x 100
40	25	6.5 x 100
45	30	8.0 x 100
50	35	9.5 x 100

Source: Vejdirektoratet, *Road Standards Part 7 – Speed Reducers*, Denmark, Ministry of Transport, 1991.

1.3 APPROACH TO RESEARCH

In order to determine an approach for the study, an inventory of existing on-road speed humps was undertaken. Nearly all humps close to Ottawa, with isolated exceptions, are of the Watts Profile design. There are, however, a substantial number of Watts and Seminole Profile humps on roads near Washington, DC. It was therefore decided to focus research on humps of these types.

Speeds were recorded for vehicles travelling over several of the on-road Watts and Seminole Profile speed humps. An 85th percentile speed was calculated for each hump design. It was thought that motorists, being free to choose their own speeds, would keep discomfort at a relatively constant level by travelling at higher speeds over the less abrupt humps.

These hump dimensions and speeds were then duplicated in a series of off-road field tests. Accelerations were measured on a test subject travelling over the humps in two automobiles and a transit bus. These accelerations were termed the baseline acceleration levels, or discomfort criteria. The use of a baseline measure meant that subjective assessments of discomfort, which require many individuals and test vehicles, were unnecessary.

Additional tests were performed for two more speed hump lengths and design speeds of 25, 35 and 45 km/h, which corresponded to posted speeds of 30, 40 and 50 km/h. To reduce the number of test runs, a portion of all the possible tests was selected using a factorial design.

The accelerations measured in these tests were used to formulate a multiple linear regression model. The model was used to predict which speed hump lengths and heights would produce acceleration levels corresponding to the discomfort criteria for each vehicle at each design speed. The designs that did so were considered successful speed reducers that would be acceptable to most motorists.

From the optimal designs, speed humps were recommended for bus routes and non-bus routes. The methodology is presented in more detail in Chapter 4.

CHAPTER 2 – TRAFFIC CALMING

2.1 BACKGROUND

Speed humps, along with raised intersections and lateral shifts in the roadway such as chicanes, narrowings and mini-traffic circles, belong to a family of design techniques known as traffic calming measures. Traffic calming measures can quite literally calm the behaviour of motorists, eliminate opportunities to speed, and increase overall road safety.

2.1.1 Definition of Traffic Calming

In traditional traffic engineering, streets are primarily regarded as pathways for the efficient movement of motor vehicles, and the needs of other users are given secondary consideration. It is often appropriate that many streets instead "serve a broad range of transportation, social and environmental objectives" [Braaksma, 1994]. Traffic calming can help realize these objectives.

Traffic calming has recently been defined by the ITE as "... the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behavior, and improve conditions for non-motorized street users" [Lockwood, 1997].

Traffic calming has four main objectives [Pharaoh & Russell, 1991]:

- improve road safety
- reclaim road space from motor vehicles for pedestrians and other non-traffic activities
- improve mobility for other road users by reducing the barrier effects of traffic
- create environmental improvements.

Achievement of these objectives comes primarily through *speed reduction*. Traffic calming alters the role of streets through the use of specific design features which psychologically encourage or physically force motorists to drive at or below a predetermined speed.

Traffic reduction is not necessarily a goal of traffic calming. Traffic volumes can be reduced through the use of route modification techniques such as road closures and turn restrictions, but these can inconvenience local residents and are often opposed on those grounds. Traffic calming is concerned only with speed reduction and does not attempt to restrict vehicular access. It can, though, help to discourage through traffic on certain streets and encourage other means of travel.

2.1.2 Benefits of Traffic Calming

Traffic speeds are a critical factor in the real or perceived safety of a street. If speeds are excessive, a hostile and intimidating environment is created for more vulnerable street users. Traffic calming lessens the dominance of motor vehicles through measures that act to minimize braking and acceleration, reduce air pollution and lower speeds. Lower speeds mean less space is needed for safe vehicle movement. Portions of a street can often be reclaimed as space for wider sidewalks, bicycle paths, street furniture, outdoor cafés, green space and snow storage.

Studies in Europe have shown traffic calming reduces vehicle speeds up to 30 percent, and collisions to 60 percent on average [Kraay, 1987; Hass-Klau et al, 1992]. A report in the United Kingdom has claimed that many traffic calming projects pay for themselves within one to two years through savings in collisions and injuries from reduced speeds [Zein et al, 1997].

In Canada a British Columbia study found that streets in the Greater Vancouver area experienced a 40 percent reduction in collision frequency with the installation of traffic calming measures [Zein et al, 1997]. After Balliol Street in Toronto was traffic calmed the average vehicle speed dropped from 40 to 30 km/h, and the 85th percentile speed from 47 to 36 km/h [Bailey, 1995].

Public acceptance of traffic calming has been high, even in North America. A recent survey of several municipalities in the United States reported that almost no traffic calming measures have ever been removed because of local opposition. Even measures installed on a temporary basis have usually become permanent [Ewing & Kooshian, 1997].

2.2 HISTORY

Interestingly enough, the desire to slow vehicles on certain streets is not new, and the idea of calming motor vehicle traffic is nearly as old as the automobile itself. In 1928 an English lord, Cecil of Chelwood, published a "Road Vehicle

Regulation Bill" in which he suggested the use of "... speed humps or similar devices in the road surface in order to force drivers to slow down" [Hass-Klau, 1990].

2.2.1 Traffic Calming Overseas

Modern traffic calming got its start with the Buchanan Report "Traffic in Towns," published in 1963 in the United Kingdom. Colin Buchanan expanded on the ideas of Lord Cecil and another Englishman named Alker Tripp when he warned of the consequences of increasing automobile use. He recommended measures for managing traffic and developed the concept of an environmental capacity for streets [Hass-Klau, 1990].

The first example of a traffic calming project was created in the late 1960's. The Dutch community of Delft, in response to speeding traffic on one of its residential streets, installed a series of obstacles to physically alter its character and slow traffic. The street was called a *woonerf*, which translates into "residential yard" (see Figure 2.1). The scheme was a success, and several other communities quickly followed with *woonerven* of their own [Hass-Klau et al, 1992].

Soon afterwards woonerven were constructed in Germany, and by the 1970's and 1980's traffic calming was being applied in large-scale *verkehrsberuhigung* (literally, "traffic tranquilization") projects. In that time traffic calming practice gradually evolved toward the use of simpler and cheaper 30 km/h zones, which could be applied on higher-volume roads. The first example was the Berlin-Moabit project in 1983. The 30 km/h zones use fewer and less drastic speed reducing techniques, and rely more on measures such as road narrowings and speed humps [Keller, 1986].

The 1980's and 1990's have seen traffic calming proliferate throughout Europe and overseas to Australia, New Zealand, South Africa, Israel and Japan.[1] Traffic calming has also made its way into the Middle East and Southeast Asia [Kassem & Al-Nassar, 1981; Fwa & Tan, 1992]. The practice has expanded into shopping areas, school zones, village centres and even main roads, and speed humps have come into increasing use [Pharaoh & Russell, 1991].

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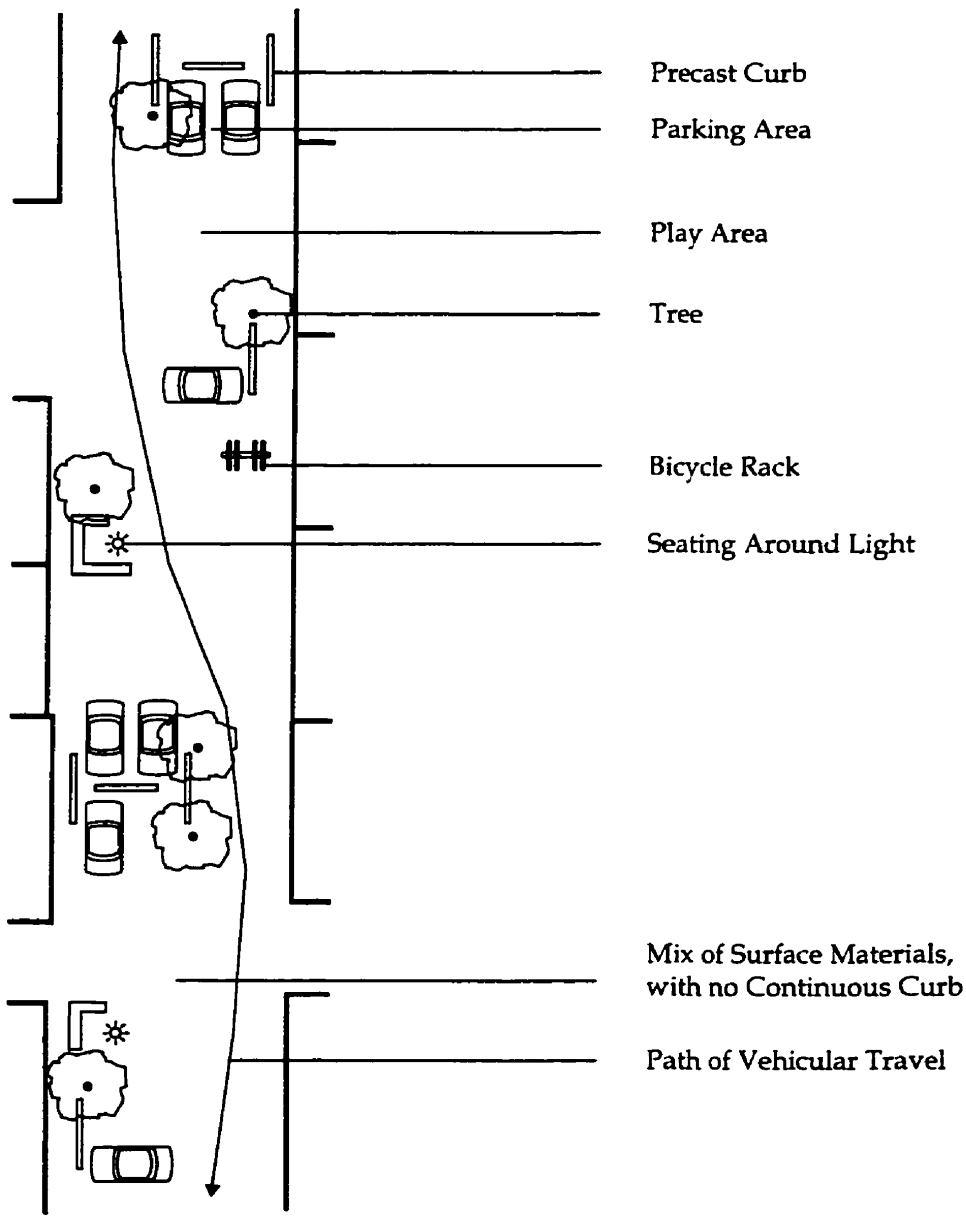
[1] Website at "http://old.city.toronto.on.ca/4service/spdhmp.htm".

Figure 2.1
Design Features of a Woonerf



Source: ANWB, *The Installation of a Woonerf*, The Netherlands, Traffic Department, undated.

2.2.2 Traffic Calming in North America

Traffic calming has not enjoyed nearly so long a history in North America. While Europeans were calming their streets, planners and traffic engineers in Canada and the United States have been adding lanes and widening intersections to accommodate rising automobile use.

There have been concerns in many residential areas about the social effects of high traffic levels. In the 1980's this led to traffic calming projects in several west coast cities, namely Vancouver and Victoria, BC, Seattle, Washington, and Portland, Oregon [Liivamagi, 1995]. Specific traffic calming measures have since been installed in other North American cities and, with interest in traffic calming on the rise, more projects are being proposed.

Two of the latest projects are for the Island Park and Centretown areas in Ottawa. They are the Island Park, Kirkwood and Churchill Area Transportation Assessment and Traffic Calming Plan, and the Centretown Traffic Calming Plan and Kent Street Traffic Calming Concept Plan [Braaksma, 1996 & 1997]. To date both plans have been approved in principle by the Regional Municipality of Ottawa-Carleton and City of Ottawa Councils.

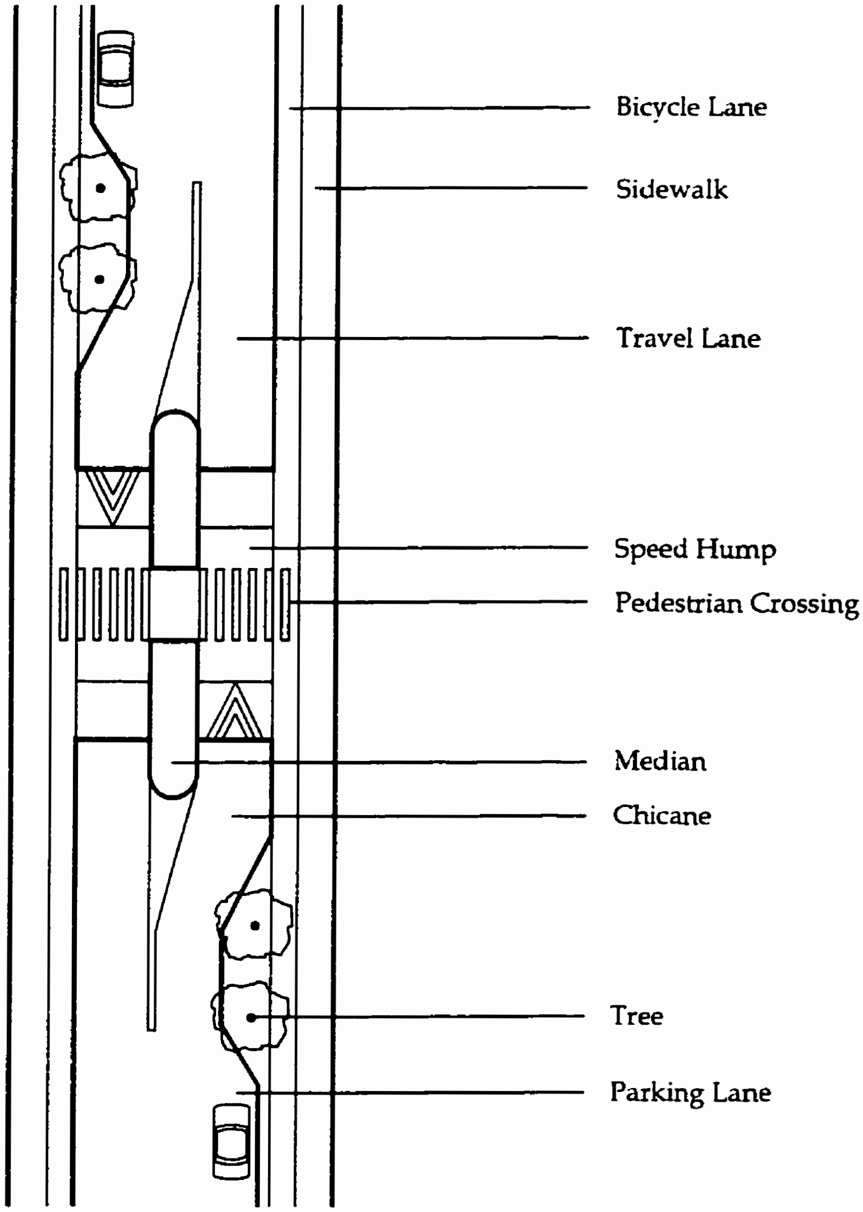
Among other traffic calming measures, each project calls for the installation of about one hundred speed humps. Several of the streets, such as Kirkwood Avenue, Churchill Avenue and Bank Street, are bus and truck routes while others, namely Island Park Drive, Kent Street and O'Connor Street, are also major commuter routes. Apart from ITE and TAC recognition of the Watts Profile speed hump, there are no standards for the geometric design of any of the traffic calming measures recommended in the plans.

2.3 TRAFFIC CALMING MEASURES

Traffic calming measures can be retrofitted to existing streets or integrated into new streets, and can be implemented mid-block or at intersections. Several are shown in Figure 2.2.

Lateral traffic calming measures involve a change in the width or horizontal alignment of a street. They rely on narrowing the optical width of the road or reducing sight distances so that drivers are psychologically inclined to exercise more caution. Examples include:

Figure 2.2
Chicane and Speed Hump at Pedestrian Crossing



<u>Source:</u> Vejdirektoratet, *Road Standards Part 7 – Speed Reducers*, Denmark, Ministry of Transport, 1991.

- shifts in the roadway such as chicanes and mini-traffic circles
- constrictions such as narrowings, bulbs and medians
- streetscaping features including gateways, landscaping and street furniture.

Vertical traffic calming measures slow motor vehicles by introducing a vertical shift in the roadway to physically create uncomfortable feelings for drivers, and the fear of possible damage to their vehicles and cargo at higher speeds. Examples include:

- platforms and raised intersections
- speed humps and speed cushions.

Vertical traffic calming measures are very effective, and can be designed to achieve specific speeds for most motor vehicles. It is difficult to obtain a similar relationship with lateral measures, as heavy vehicles are influenced by them to a much greater extent. Unless carefully designed, those intended for large trucks and buses often result in unacceptably high automobile speeds. The best traffic calming projects combine lateral and vertical measures [Vejdirektoratet, 1991].

Purely visual methods for slowing traffic such as special pavement markings and signs are sometimes considered traffic calming measures, as are acoustic means like rumble strips. They are usually successful in slowing motor vehicles only if supplemented with other measures.

CHAPTER 3 – SPEED HUMPS

3.1 SPEED HUMPS ON PUBLIC ROADS

Of all the traffic calming measures that have been developed, the best at reducing speeds has been the speed hump. However many concerns have been voiced about speed humps, particularly their effects on emergency response times and winter maintenance operations, their potential to create unwanted noise and vibration, and their legal implications.

According to Seminole County, Florida, and Burnaby, BC, the impact of speed humps on emergency vehicle effectiveness has been fairly small [Kaiser, 1991; Liivamagi, 1995]. Other traffic engineering practices such as one-way streets and road closures have the potential to affect police cars, fire trucks and ambulances to a much greater degree [Zaidel et al, 1992].

A concern often cited in Canada is the effectiveness of snow clearing equipment on streets with speed humps. Other countries that receive significant amounts of snowfall, like Sweden and Finland, employ speed humps on a regular basis without apparent ill effects. No problems were reported with removing snow over humps in Toronto or Sherbrooke, Québec [Moinat, 1991]. Nor were any problems experienced at Algonquin College in Ottawa.[2]

Studies in the Netherlands and Australia have shown that well-designed speed humps produce very low levels of unwanted noise, and little vibration except on passing vehicles. Impacts to adjacent buildings or individuals have been negligible [Zaidel et al, 1992].

The question of legal liability is always raised with speed humps. Attorneys in Florida have suggested that as long as speed humps are installed in a responsible and consistent manner, any lawsuits associated with their use will likely be unsuccessful [Nicodemus, 1991]. An international survey conducted in 1992 showed that "no successful legal action has ever been taken against a public road authority in connection with the use of humps" [Zaidel et al, 1992].

Traffic engineers have an obligation to make streets safer for everyone, not just motorists. The failure to install speed reducing measures on certain streets may

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[2] Conversation with Ron Moore of Ron Moore Equipment Ltd., Stittsville, Ontario, January 1997.

involve greater potential legal liability, and greater safety concerns, than the implementation of approved speed hump designs.

3.2 SPEED HUMP DESIGN

Unlike speed bumps, which are introduced on private roads and parking lots with little formal study, speed humps are used on public roads. A considerable amount of research has therefore been devoted to studying the effects of speed humps on vehicles and their occupants, and determining appropriate designs for various streets.

3.2.1 Theory

A speed hump works by transferring an upward force to a vehicle, and its occupants and cargo, as it traverses the hump. The force translates into a vertical acceleration and displacement, and induces a front-to-back pitching motion in vehicles having a wheelbase similar to the length of the hump [Jarvis, 1992]. At low speeds the acceleration is of small amplitude. As speeds increase the amplitude and pitching also increase, as does the displacement.

This differs from a speed bump. A speed bump induces high accelerations at low speeds because it is significantly shorter than the wheelbase of a motor vehicle. The accelerations can decrease with higher speeds due to absorption of the impact by the vehicle suspension [Watts, 1973]. At low speeds the longer speed hump gently lifts and pitches the vehicle. Only as speeds increase do the accelerations become more apparent as a jolt to the vehicle and its occupants and cargo.

Accelerations acting on seated individuals are primarily interpreted through the ischial tuberosities, or lower parts of the hip bone. If an acceleration is great enough it is interpreted as an uncomfortable sensation. The degree of discomfort perceived depends on the frequency of the acceleration, and increases with its duration and amplitude [Griffin, 1990]. Since accelerations produced by speed humps are of very short duration and low frequency, discomfort can be attributed to the amplitude, or magnitude, of the acceleration. This measure has been used in most speed hump evaluations.

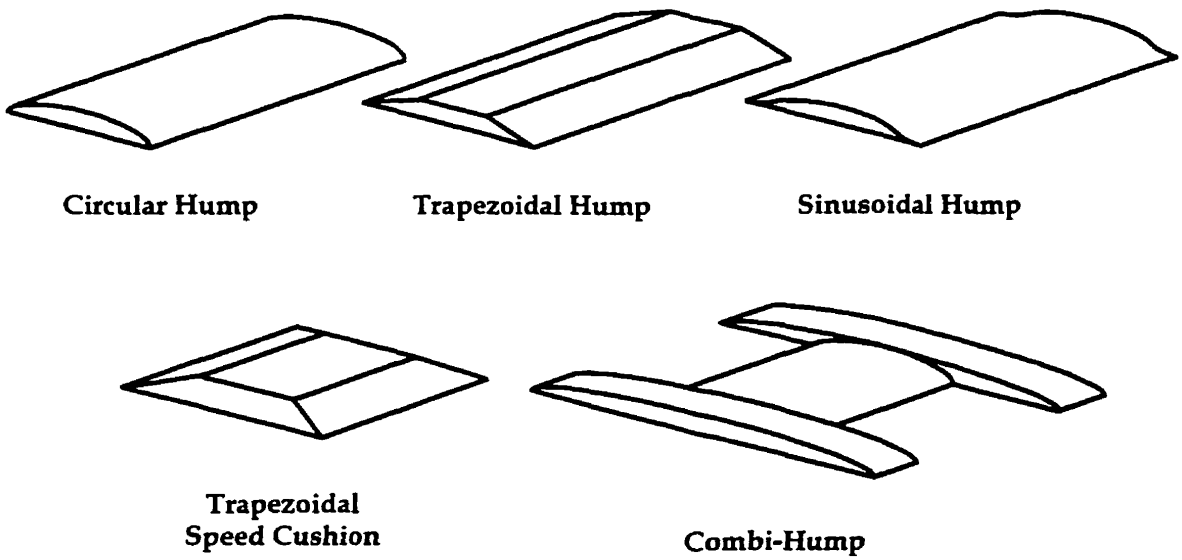
A design speed can be specified for speed humps through their geometry or spacing. It is difficult to design a speed hump that generates the same dynamic responses in all vehicle types. Heavy vehicles are affected to a greater degree than light vehicles because of their longer wheelbase, although drivers may compensate by tolerating higher levels of discomfort [Mak, 1986].

3.2.2 Development

The modern speed hump was created in 1973 by G. R. Watts of the Transport and Road Research Laboratory (TRRL) in the United Kingdom. The original Watts Profile hump was 3.7 m long and 100 mm high, although there are many versions 75 mm high. Today, circular or "round top" humps of various lengths and heights are the most common used as traffic calming measures.

Other profiles such as sinusoidal and trapezoidal or "flat top" humps have also been created. Sinusoidal and trapezoidal humps are used in the Netherlands, while a considerable amount of research has been done in Denmark with circular, trapezoidal and even combination humps (see Figure 3.1). Their experiences have indicated that because of the flat top trapezoidal humps are particularly useful when combined with pedestrian crossings, but that buses can comfortably traverse circular humps at higher speeds [Vejdirektoratet, 1991]. In Australia, trapezoidal humps or raised pavements are preferred, even on bus routes [Jarvis, 1992].

Figure 3.1
Types of Speed Humps



Speed *cushions* are raised sections of roadway limited in width to about 1.6 m, and were introduced in Germany in 1983 [Keller, 1986]. Automobiles must cross with at least one set of wheels on the cushions, but buses and wider vehicles can usually straddle them with only the inner wheels being affected. Cyclists can bypass the cushions, and bus speeds can be higher than with speed humps. As with humps, speed cushions vary in length, height and profile.

In Sweden the fear of bus undercarriages being struck while crossing speed cushions has led to an inverted version called the sink-cut or road depression [Hass-Klau et al, 1992]. There are visibility and drainage problems associated with sink-cuts, and they are more expensive than speed humps.

In Seminole County, Florida, concerns over the abruptness of Watts Profile humps at higher speeds resulted in the creation of the Seminole Profile speed hump [Nicodemus, 1991]. These humps are similar in profile to trapezoidal humps, with the difference being circular rather than straight ramps.

The *thump* is a circular hump just 0.9 m long and about 35 mm high [Webster, 1994]. Thumps and similar 50 mm high circular humps have been less successful in slowing faster vehicles than standard speed humps, but they use less material and are cheaper to construct [Watts, 1973; Hodge, 1993].

3.3 PREVIOUS RESEARCH

A review was made of previous theoretical research into speed humps, also known as road humps or pavement undulations. The research was limited to field tests and simulation studies. Evaluations of existing speed hump projects were not investigated due to their non-theoretical nature.

3.3.1 Field Tests

The first speed hump experiments coincided with the development of the Watts Profile hump. In off-road tests using several vehicle types operating over a range of speeds, Watts used analytical and subjective methods to measure vehicle and occupant responses to circular humps of various lengths and heights. He assumed that peak vertical accelerations from crossing the humps could be related to perceptions of discomfort, and formulated regression equations to predict hump-crossing speeds. Watts found that drivers attempted to limit vertical accelerations to 0.7g to 0.9g [Watts, 1973].

As a follow-up to Watts' tests, several of his recommended humps were installed around England and evaluated in a series of on-road trials. It was found that the humps followed closely the performance characteristics predicted by Watts, and that most motorists would not cross them faster than about 30 km/h [Baguley, 1981].

Comparable results with Watts Profile humps under similar conditions were obtained in Sweden and Australia, while somewhat lower occupant discomfort levels were reported in Finland [Stephens, 1986]. The latter finding suggests that perceptions of discomfort can vary among countries or cultures.

Experiments with trapezoidal humps were performed at the Australian Road Research Board (ARRB) using test procedures and conditions comparable to the original TRRL studies. Again, similar results were found. Tests were also carried out on lengthened trapezoidal humps to determine hump-crossing speeds and discomfort levels for buses. A peak vertical acceleration of 0.7g was used to represent a tolerable level of discomfort [Jarvis, 1992].

A study in Singapore related the geometric characteristics of speed humps to the hump-crossing speeds of passenger cars. From field measurements a statistical relationship was derived between crossing speeds and the area-to-length ratios of various humps [Fwa & Tan, 1992].

Other on-road studies of speed hump performance have been carried out in the United Kingdom and the Netherlands, as well as Denmark, France, Japan, Israel and the United States [Zaidel et al, 1992; Webster, 1993]. Many additional studies have examined traffic speeds and volumes on streets before and after speed hump installations, and conducted surveys of their perceived effectiveness [Clement, 1983; Mak, 1986].

3.3.2 Simulation Studies

The first simulation study of the effects of speed humps on vehicle behaviour was undertaken in Saudi Arabia. Rather than field tests a mathematical model of a vehicle and driver was developed. This allowed a detailed theoretical simulation of responses to various speed hump designs in terms of vehicle and occupant displacement, vertical and rotational acceleration, vertical and rotational motion of the vehicle chassis, and displacement of the front and rear wheels [Kassem & Al-Nassar, 1981].

In another study in Singapore, a mathematical model of an automobile was used to relate the geometric design of speed humps with an optimal hump-crossing speed and associated peak vertical acceleration. This model was calibrated using an actual vehicle driven in a series of on-road tests over Watts Profile humps. An average peak vertical acceleration of 0.74g was used, and the resulting hump designs were checked for speeds corresponding to accelerations between 0.6g and 0.9g [Fwa & Liaw, 1992].

A similar study was undertaken at Delft Technical University in the Netherlands, where again a computer model was developed to simulate the behaviour of vehicles and drivers. Hump-crossing speeds were predicted for a range of designs from 3.7 m sinusoidal humps to 12 metre trapezoidal humps, all of 120 mm height [De Wit, 1993].

3.3.3 Canadian Research

From 1989 to 1991 the City of Sherbrooke and the University of Sherbrooke, Québec, undertook the most comprehensive speed hump study to date in Canada [Moinat, 1991; Blais & Lupien, 1992]. Several circular and trapezoidal humps were constructed on roads at the university campus. Accelerometers were placed on two automobiles to measure horizontal and vertical accelerations at the front seats, and vertical accelerations at the front and rear bumpers. The humps were driven over at various speeds, and test subjects were asked to subjectively rate their feelings of discomfort.

A mathematical model was then developed that simulated a vehicle crossing a speed hump. The model was verified with actual tests, and while some agreement was found with Watts' experiments there were differences in predicted hump crossing speeds.

One of the main findings of the university study was that a good indicator of occupant discomfort is the pitching of vehicles as they traverse the humps. Only peak vertical accelerations were considered in many previous tests. In fact, at lower speeds the pitching was found to be the main component of discomfort. Vertical acceleration magnitudes only become significant at speeds over about 37 km/h, depending on the hump length and vehicle type [Moinat, 1991]. This finding is discussed in Chapter 5.

In the fall of 1996 the City of Ottawa performed several off-road tests to evaluate the dynamic responses of a transit bus and a fire truck to the 100 mm high Watts

Profile speed hump. The operators were asked to traverse the humps at increasing speeds until they felt they had exceeded the limits of the vehicles' suspensions. "Through the tests we were able to establish speeds at which these vehicles could be expected to cross the speed humps" [Marchand & Tweedie, 1997]. On-road tests are currently being used to confirm these findings for some city streets.

Speed humps currently exist in British Columbia, Alberta, Manitoba, Ontario and Québec. As in other countries, before and after studies have been carried out to determine their effects on traffic speeds and volumes, and some resident opinion surveys have been conducted [Bailey, 1995; Liivamagi, 1995]. The Transportation Association of Canada and the Canadian Institute of Transportation Engineers (CITE) are currently developing a set of traffic calming standards, which may include guidelines for the geometric design of speed humps.

3.4 SPEED HUMP PARAMETERS

Speed humps can be fully described using several geometric and layout design parameters. The geometric design parameters are length, height, profile and width. The layout design parameters are speed hump spacing and type of materials, marking and signage.

3.4.1 Length

Length is the most important speed hump geometric design parameter. Effective humps and cushions should be at least as long as an automobile wheelbase to isolate the effects of entering and exiting the humps for these vehicles [Jarvis, 1992]. Longer speed humps should be used if heavier vehicles are expected. Experiments have shown that as lengths are increased peak accelerations tend to occur at higher speeds, and more linear dynamic effects are created. In general, longer humps exhibit better characteristics for speed reduction [Watts, 1973; Moinat, 1991].

Watts Profile humps are usually used to reduce speeds to under 30 km/h in their vicinity. If desired speeds in the order of 40 to 50 km/h are specified, other studies have found these humps to be unsuitable and have recommended increased lengths [Clement, 1983; De Wit, 1993]. In Denmark, circular humps up to 9.5 m long are used to reduce speeds to 50 km/h for automobiles and 35 km/h for buses [Vejdirektoratet, 1991]. Trapezoidal humps as much as 12 metres long are used in the Netherlands and Australia [Hass-Klau et al, 1992]. Longer humps may be even better suited for heavy vehicles, although upper limits have not been firmly established.

In British Columbia the Watts Profile speed hump is considered adequate for design speeds of 30 km/h, but too severe for the 40 or 50 km/h speed limits posted on most residential streets [Liivamagi, 1995]. The Seminole Profile hump has provided better results at these speeds [Nicodemus, 1991].

3.4.2 Height

Speed hump heights can influence the magnitudes of vertical accelerations and the maximum levels of perceived discomfort [Kassem & Al-Nassar, 1981]. High humps, and high speed cushions, may cause damage to vehicle undercarriages as they exit the measures. Low humps can be ineffective. Heights usually range from 50 to 120 mm, with the most common being 75 or 100 mm.

3.4.3 Profile

The effects of speed hump profile, particularly the effects of varying the slopes of the entry and exit ramps, have not been examined as thoroughly as length or height. Research is ongoing to determine the optimal ramp slopes for various speed hump designs, particularly trapezoidal humps [Jarvis, 1992].

Circular, trapezoidal and sinusoidal speed humps and speed cushions of equivalent dimensions have been found to perform about equally well, although the Dutch regard sinusoidal humps as having the best dynamic characteristics at higher speeds [Kassem & Al-Nassar, 1981; De Wit, 1993].

3.4.4 Width

Speed humps can either span the entire width of a road or taper short of the curb or road edge. The advantage of the latter approach in an urban setting is that drainage at the curb and gutter is not affected, and installations are therefore less expensive. Drivers can attempt to exploit reduced widths and manoeuvre around humps unless preventative measures are taken [Webster, 1993].

3.4.5 Spacing

High hump-crossing speeds can lead to high speeds between humps, as can large distances between them. Since an objective of traffic calming is to reduce vehicle speeds over entire streets, the layout design or spacing of speed humps and speed cushions is critical.

Research from several countries suggests that to achieve overall speeds of 25 to 30 km/h, speed humps should be placed between 40 and 60 metres apart. Greater spacings, up to 100 metres, can be used for speeds of 50 km/h. Tables have been generated in the Netherlands and Denmark relating design speed to hump spacing, and equations are used in the United Kingdom and Australia [Hass-Klau et al, 1992; Webster, 1993]. Hump spacings can be increased with the presence of additional traffic calming measures.

3.4.6 Materials, Marking and Signage

Speed humps and cushions, as with all speed reducing measures, should be highly visible to warn drivers to lower speeds and avoid vehicle damage or loss of control. This essentially eliminates the potential for any legal liability on the part of the public road authority [Jarvis, 1980]. Most countries have developed special signs and markings for their speed hump installations, and pre-warnings, design speed signs, contrasting materials and protective bollards are usually employed [Lockwood, 1995].

CHAPTER 4 – EXPERIMENTAL DESIGN

4.1 OBJECTIVES OF STUDY

For this study the successful speed hump designs had to meet the following six objectives:

- reduce automobile and heavy vehicle speeds
- produce acceptable levels of discomfort for vehicle occupants
- result in no vehicle damage
- maximize overall road safety
- minimize vehicle noise and displacement
- minimize installation and maintenance costs.

The purpose of the first, second and third objectives was to ensure the designs reduced vehicle speeds to the hump-crossing speeds of 25, 35 and 45 km/h without producing intolerable feelings of discomfort for drivers, and damage to their vehicles and cargo.

The purpose of the fourth and fifth objectives was to recognize that potential stakeholders in the design of speed humps should include not only motorists, but also individuals adjacent to them. The sixth objective was to ensure that the designs were of reasonable cost.

It was realized that any speed hump lengths and heights ideal for automobiles will probably be too severe for heavy vehicles such as transit buses. Humps suitable for these vehicles will likely allow excessive automobile speeds. The speed humps recommended for bus routes were therefore a compromise between automobile effectiveness and bus safety.

4.2 CONSTRAINTS

There were constraints due to the academic nature of the study, and from the type of speed humps chosen for investigation.

4.2.1 Study Limitations

Only the effects of varying speed hump length and height were examined. The effects of varying speed hump profile were not considered, nor were aspects of layout design such as spacing, materials, marking and signage. While the effects of width were not considered, the conclusions of this study should be relevant for speed cushions.

There were limitations on the number of speed humps that could be evaluated and the number of tests performed. Four speed hump lengths and two heights were used in the field tests. Acceleration measurements were taken as the eight hump designs were traversed by just three test vehicles travelling at three speeds. It was thought that any additional measurements would result in an unduly large experimental design.

Additional constraints arose from the availability of test locations, as well as the cost and constructibility of the test humps. Also, only one portable accelerometer was available.

This study evaluated the hump designs as if they existed in isolation. It has been shown that drivers will reduce speeds even further if speed humps are combined with other traffic calming measures [Vejdirektoratet, 1991].

4.2.2 Speed Hump Design Constraints

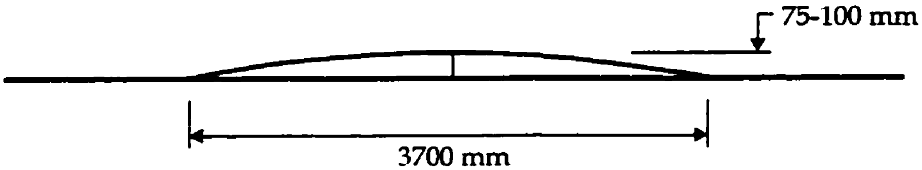
Most speed humps in North America, and nearly all in Canada, are of the Watts Profile type. Seminole Profile humps are used in some areas of the United States. The closest of these to Ottawa are in Montgomery and Howard County, both in the State of Maryland near Washington, DC [Walter, 1995].

The discomfort criteria were established using existing on-road speed humps. Since all possible types could not be investigated, it was decided to concentrate on designs based on the Watts and Seminole Profile humps. Montgomery County has 75 mm high Watts Profile humps, and 75 and 100 mm high Seminole Profile humps. Algonquin College in Ottawa has 100 mm high Watts Profile humps. The college humps were also used in a pilot study.

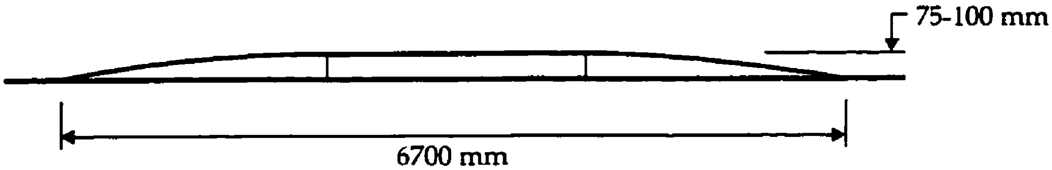
It was necessary to assume that motorist behaviour towards speed humps is the same in the United States as in Canada. For the most part vehicle types, road standards and driving habits and expectations are very similar compared to other countries.

The Watts Profile speed hump is circular in profile and 3.7 m in length, while the Seminole Profile hump features the addition of a 3 metre flat section for an overall length of 6.7 m. Watts and Seminole Profile humps of the same height have the same ramp slopes. This study examined these two hump designs, as well as two more created by adding flat sections of other lengths, for heights of 75 and 100 mm (see Figure 4.1). Trapezoidal and sinusoidal humps were not investigated, as they are rare in North America.

Figure 4.1
Watts and Seminole Profile Speed Humps



Watts Profile Hump



Seminole Profile Hump

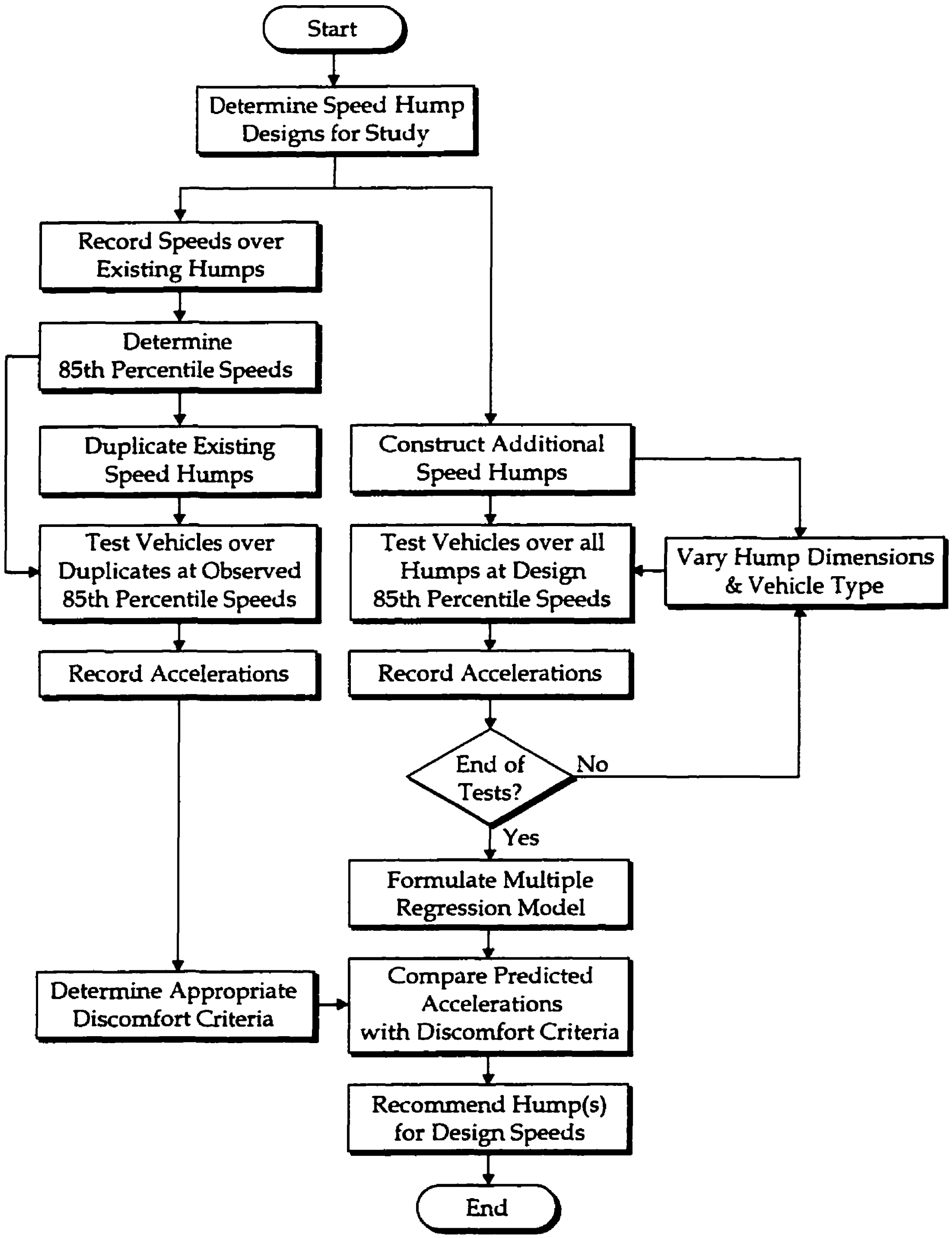
Both the Watts and Seminole Profile speed humps are proven designs. They can be easily constructed in the field, and present few maintenance problems.[3] The question was whether these specific humps are the best for Canadian conditions, or whether some variations on their design, featuring different lengths or heights, would prove more effective.

4.3 METHODOLOGY

This study investigated the suitability of the various speed hump designs for Canada through a series of off-road tests. A two-phase approach was used, as shown in Figure 4.2.

[3] Meeting with Dirk Klaasesz, Neighborhood Traffic Planning, Montgomery County, Maryland, January 1997.

Figure 4.2
The Experimental Procedure



In the first phase of the experiment, speeds were recorded as motorists travelled over the existing 75 and 100 mm Watts and Seminole Profile speed humps. The 85th percentile hump-crossing speed for automobiles, and the mean speed for transit buses, were determined for each of the hump designs.

Off-road tests were then carried out using two automobiles and a transit bus. Humps of the same dimensions as the existing on-road humps were constructed out of wood. Horizontal and vertical accelerations were measured on a test subject as the duplicate humps were traversed at the observed 85th percentile or mean speeds.

In the second phase of the experiment additional tests were performed using the same test vehicles with two more speed hump lengths and three design speeds. Again, horizontal and vertical accelerations were measured. The peak, root-mean-square (rms) and root-mean-quad (rmq) accelerations were calculated for each test run.

The measure resulting in the most consistent acceleration values for automobiles at the 85th percentile speeds for each hump design was selected as the baseline level, or discomfort criterion, for automobiles. The same measure was used to find discomfort criteria for the transit bus.

The accelerations measured in the second phase of the experiment were entered into multiple linear regression model to estimate the test data and predict additional accelerations. The model was used to predict hump lengths for each height, speed and vehicle tested that resulted in the same accelerations as the discomfort criteria. Designs producing accelerations above the discomfort criteria were considered too severe on acceptability, vehicle damage and safety grounds. Those producing accelerations below the criteria were considered not severe enough to reduce speeds.

The designs were also evaluated in terms of the remaining noise and displacement and cost objectives. The optimal designs for automobiles were recommended for non-bus routes. Compromises between the optimal designs for automobiles and transit buses were found for bus routes.

4.4 VARIABLES

Four variables were used in the experimental design: four speed hump lengths, two heights, three hump-crossing speeds and three test vehicles.

4.4.1 Speed Hump Dimensions

Two of the four speed hump lengths used in the experiment had to match the lengths of Watts and Seminole Profile humps, namely 3.7 and 6.7 m (12 and 22 feet) respectively. Mainly for ease of construction, lengths of 4.9 and 9.1 m (16 and 30 feet) were also used. It was thought important that at least one of the humps be longer than the wheelbase of a bus to isolate the effects of entering and exiting the humps for all of the test vehicles.

Most speed humps in North America are either 75 or 100 mm (3 or 4 inches) in height. Humps above or below these heights are uncommon. It was decided that these two heights should be represented in the field tests but that additional heights, such as another between 75 and 100 mm, would be unlikely to generate significantly different accelerations.

4.4.2 Test Speeds

Hump-crossing speeds of 35 and 45 km/h were chosen because they are 5 km/h lower than commonly posted speeds on Canadian streets. A speed of 25 km/h could be considered appropriate for streets where Watts Profile humps are now used, or if any are converted to 30 km/h zones similar to those in Europe.

4.4.3 Test Vehicles

Two automobiles and a regular transit bus were employed as test vehicles. The automobiles, a 1989 Suzuki Swift GTi and a 1997 Chevrolet Monte Carlo LS, were taken to be representative of the range of automobiles currently in common use in North America. A regular transit bus was selected because speed humps may become commonplace on bus routes. The bus was used to represent other heavy vehicles, such as fire trucks and commercial vehicles.

The Suzuki is a small lightweight automobile with a stiff suspension, 2.3 m wheelbase, 185/60/14 tires, and short front and rear overhangs. The Chevrolet is larger, with a more compliant suspension, 2.7 m wheelbase, 225/60/16 tires, and longer overhangs. Acceleration measurements were taken from the driver seat for both vehicles.

The transit bus was a 1991 GM Classic by MCI in service with OC Transpo, the Ottawa regional transit company. The bus had an air suspension and a 7.1 m wheelbase. Acceleration measurements were taken at the driver seat, which also had an air suspension and where the bus operator would choose appropriate hump-crossing speeds, and at the rear seat. The rear seat position was chosen because it has been shown to produce the highest vertical accelerations in most transit buses [Jarvis, 1992].

4.5 FACTORIAL DESIGN

In this study the field tests were carried out with the aid of a technique known as factorial design. Rather than conduct separate tests for each variable, factorial designs include all of the variables simultaneously, resulting in fewer tests needed for a given experiment.

4.5.1 Factorial Experiments

Four speed hump lengths, two heights, three speeds and four vehicles were tested (although there were three vehicles, accelerations were measured at two positions in the bus for a total of four vehicle readings). Length, height, speed and vehicle type were referred to as factors in the experiment, and the possible values for each factor were called levels [Cochran & Cox, 1957]. The factors and levels were assembled into a $4^2 \times 3 \times 2$ factorial design (see Table 4.1).

Table 4.1
The Factorial Design

Factor	Level	Description
Length	0	3.7 m (12 foot) Long Hump
	1	4.9 m (16 feet)
	2	6.7 m (22 feet)
	3	9.1 m (30 feet)
Height	0	75 mm (3 inch) High Hump
	1	100 mm (4 inches)
Speed	0	25 km/h Hump-Crossing Speed
	1	35 km/h
	2	45 km/h
Vehicle	0	Suzuki Swift
	1	Chevrolet Monte Carlo
	2	GM Classic – Driver Seat
	3	GM Classic – Rear Seat

A factorial design permits the simultaneous evaluation of main and interaction effects for the factors. In this study main effects were attributable to differences in the dependent variables, the measured horizontal and vertical accelerations, due to varying length, height, speed or vehicle type. Interaction effects arose from combinations of two or more of the factors such as length and vehicle type, or length, height and speed.

All the factors and levels were expressed in factorial notation of the form (*ijkl*), where *i* indicates the level of factor Length (0, 1, 2 or 3), *j* the level of factor Height (0 or 1), *k* the level of factor Speed (0, 1 or 2) and *l* the level of factor Vehicle (0, 1, 2 or 3). As an example, 0 0 0 1 stood for a test run using a 3.7 m long by 75 mm high speed hump traversed at 25 km/h by the Chevrolet Monte Carlo.

4.5.2 Confounding and Modular Notation

Even though the factorial design was limited in size, there were still 96 possible treatment combinations in the experiment. As it would have been a demanding task to perform 96 separate test runs, plus those required for the discomfort determination, the factorial design was confounded.

Confounding reduces a factorial design to a fraction of its original size. With judicious use experimental error can be better controlled, and treatment combinations can be assigned to blocks in ways that permit the most important sources of variation to be estimated from a single block. The drawback is that information on some higher-order interactions is lost, or confounded, between blocks. The manner in which a factorial design is confounded determines which effects are lost. It was decided the most important information to be gained likely concerned differences in accelerations due to the main effects and the second- and third-order two-factor interactions.

The main effects came from the factors Length, Height, Speed and Vehicle. Since Length has four levels, it contains three degrees of freedom and can vary as a linear function (L), a quadratic (L^2), or a cubic (L^3). Similarly, Height can vary as a linear function (H), and Speed as a linear function (S) or a quadratic (S^2). Vehicle is a qualitative factor, and so was defined through the use of dummy variables rather than functions.

The two-factor interactions of interest were the second-order functions LH, LS, LV, HS, HV and SV, and the third-order functions L^2H, L^2S, LS^2 and HS^2. It was thought that any higher-order functions, and three- and four-factor interactions, would be difficult to explain and not have any practical meaning in traffic engineering.

The use of terms such as L^3 or S^2 were referred to in this context as modular notation. "Modular" means modular arithmetic, where a term is divided (or its exponent subtracted) by a modulus and its remainder retained [Winer, 1962]. A factor with four levels such as Length would have a modulus of four, while Height would have a modulus of two. As examples of modular arithmetic, 13 (mod 4) equals 1, while L^6 (mod 4) equals L^2.

If each effect is multiplied by a defining factor, it produces an *alias*, which will be confounded with the original effect. $L^3HS^2V^3$ was chosen as the defining factor because it produced complex, and therefore impractical, aliases for the thirteen effects of experimental interest. $L^3HS^2V^3$ also produced a block distribution favourable for testing the transit bus, as discussed in the next section.

As an example of aliasing, multiplying the defining factor by L gives

$$\begin{aligned} [L^3HS^2V^3](L) &= L^4HS^2V^3 \\ &= HS^2V^3 \end{aligned} \tag{4.1}$$

where L is speed hump length, H is height, S is the hump-crossing speed and V is the vehicle type.

The L^4 term drops out of the equation because it is equivalent in this case to L^0 or 1. L is thus aliased with HS^2V^3. Since HS^2V^3 is much more complicated than L it can be reasonably stated that any observed variations in the measured accelerations occur solely due to L, a linear function of Length.

If the term LHV was of interest, then multiplying by the defining factor gives

$$\begin{aligned} [L^3HS^2V^3](LHV) &= L^4HS^2V^3 \\ &= S^2. \end{aligned} \tag{4.2}$$

In this case L^4, H^2 and V^4 become L^0, H^0 and V^0, leaving only S^2. Any variations in measured accelerations can no longer be reasonably attributed to LHV, as its alias S^2 could also be a likely candidate. All the possible effects and their aliases are described in Appendix A.

The defining factor was used to divide the factorial design into four equal blocks of 24 treatments. Using the factorial notation for $L^3HS^2V^3$, the equation $3i+j+2k+3l$ (mod 4) was applied to the treatment combinations and the remainder, either 0, 1, 2 or 3, was assigned to a block. A modulus of four was used because the highest number of levels among any of the factors is four.

4.5.3 Test Treatments

Refer to Table 4.2 for the hump dimensions, speeds and vehicles corresponding to the test treatments in block 0, the block used. Note that when $3i+j+2k+3l$ (mod 4) is applied to the treatments using modular arithmetic, the remainder is always zero.

Table 4.2
Test Treatments from the Factorial Design

Factor and Level (L, H, S, V)	Hump Dimensions (m, mm)	Speed (km/h)	Vehicle
0 0 0 0	3.7 x 75	25	Suzuki
0 0 1 2	3.7 x 75	35	Bus – Driver Seat
0 0 2 0	3.7 x 75	45	Suzuki
1 0 0 3	4.9 x 75	25	Bus – Rear Seat
1 0 1 1	4.9 x 75	35	Chevrolet
1 0 2 3	4.9 x 75	45	Bus – Rear Seat
2 0 0 2	6.7 x 75	25	Bus – Driver Seat
2 0 1 0	6.7 x 75	35	Suzuki
2 0 2 2	6.7 x 75	45	Bus – Driver Seat
3 0 0 1	9.1 x 75	25	Chevrolet
3 0 1 3	9.1 x 75	35	Bus – Rear Seat
3 0 2 1	9.1 x 75	45	Chevrolet
0 1 0 1	3.7 x 100	25	Chevrolet
0 1 1 3	3.7 x 100	35	Bus – Rear Seat
0 1 2 1	3.7 x 100	45	Chevrolet
1 1 0 0	4.9 x 100	25	Suzuki
1 1 1 2	4.9 x 100	35	Bus – Driver Seat
1 1 2 0	4.9 x 100	45	Suzuki
2 1 0 3	6.7 x 100	25	Bus – Rear Seat
2 1 1 1	6.7 x 100	35	Chevrolet
2 1 2 3	6.7 x 100	45	Bus – Rear Seat
3 1 0 2	9.1 x 100	25	Bus – Driver Seat
3 1 1 0	9.1 x 100	35	Suzuki
3 1 2 2	9.1 x 100	45	Bus – Driver Seat

Two of the blocks yielded treatments whereby the largest test vehicle, the transit bus, would cross the three most severe humps (the 75 and 100 mm Watts Profile humps and the 4.9 m by 100 mm hump) at the highest speed of 45 km/h. It was thought that these test runs would prove difficult for the bus to safely perform. Block 0 was chosen because it represented the best combination of hump dimensions and speeds for the bus.

The block was run twice, for a total of 48 test runs. Repeating test treatments improve variance estimates, and permit the identification of any suspicious test results. The field tests were performed, then, using a quarter $4^2 \times 3 \times 2$ factorial design with two replications. The design was completely confounded because the same defining factor was used for both replications. The confounding and blocking processes are also described in Appendix A.

CHAPTER 5 – EXPERIMENTAL PROCEDURE

5.1 ACCELERATIONS

During the field tests different speed humps were traversed at various speeds, and horizontal and vertical accelerations produced on vehicle occupants were recorded with an accelerometer. The approach allowed relative comparisons to be made between length, height, speed and vehicle type.

5.1.1 Acceleration Characteristics

During a speed hump crossing, the frequency of the accelerations experienced by vehicle occupants depends on the length of the hump and the speed of the vehicle. After a hump crossing, a vehicle will undergo free vibration as a front-to-back pitching motion about its pitching frequency. The pitching frequency for most automobiles varies from 1.0 to 1.5 Hz [Wong, 1993]. The pitching frequency for most transit buses varies from 1.5 to 3.0 Hz.[4]

The acceleration frequencies experienced can be approximately determined by considering a speed hump as one half of a sine wave. From the hump length and hump-crossing speed (in metres per second), the frequency of the accelerations can be calculated from the equation

$$f = S / 2L \tag{5.1}$$

where f is the acceleration frequency, S is the hump-crossing speed and L is speed hump length.

For both heights in this study the highest acceleration frequency occurred when the 3.7 m hump was crossed at 45 km/h (1.7 Hz), and the lowest frequency was when the 9.1 m hump was crossed at 25 km/h (0.4 Hz). If a hump were traversed at a speed such that the acceleration frequency was less than the pitching frequency of the vehicle, then the hump crossing would occur as two separate events as the vehicle vibrated about its pitching frequency.

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[4] Conversation with Gordon Mutch, Program Director of Ortech Industries, Mississauga, Ontario, February 1997.

Although most vehicles are designed to filter out high-frequency vibrations such as irregularities in the road surface, they still allow low-frequency vibrations to reach their occupants unimpeded [Wong, 1993]. This means that differences between automobile suspensions and tires have relatively little effect on perceptions of low-frequency accelerations. Individual variability and posture also have little effect [Griffin, 1990]. Because of these properties, the dynamic responses of the Suzuki and the Chevrolet were averaged and assumed to be representative of all light vehicles.

For the regular transit bus, the dynamic responses at the driver and rear seats were averaged and assumed to be representative of all buses and heavy vehicles. It was hoped this would adequately characterize discomfort levels for most bus passengers, with the least discomfort experienced by the operator and the greatest discomfort experienced by the rear seat passengers.

5.1.2 Method of Measurement

The human body tends to act as a unit mass at vertical acceleration frequencies under 2 Hz. For lateral and horizontal accelerations, seated individuals experience an upper body resonance in the vicinity of 1.5 Hz [Harris, 1988]. This suggests that horizontal accelerations at such a frequency may dominate perceptions of discomfort. It may also explain why the speed hump study in Sherbrooke, Québec, found the pitching of a vehicle to be a principal source of discomfort [Moinat, 1991].

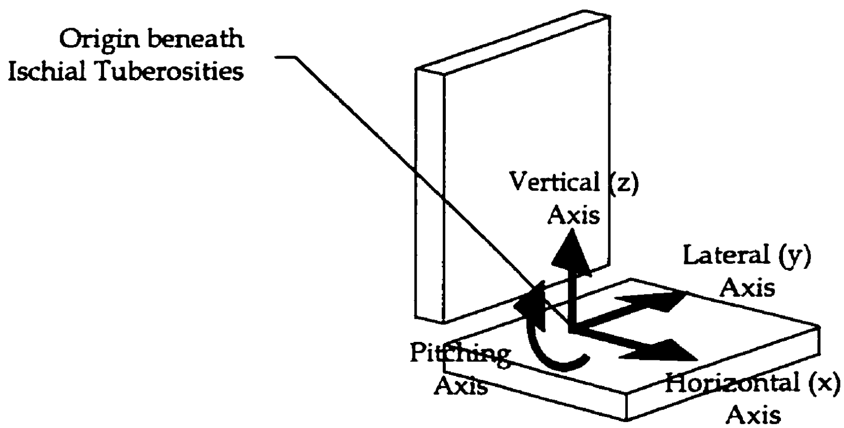
Pitching accelerations can be approximated at low frequencies by measuring horizontal accelerations with an accelerometer. As long as the pitching axes are below the seat and centred at the axles, individual responses can usually be predicted with reasonable accuracy by measuring accelerations at the vehicle seat [Griffin, 1990]. Pitching accelerations are difficult to calculate, and require two accelerometers positioned at the vehicle axles.

Since accelerations are primarily interpreted by seated vehicle occupants through the ischial tuberosities, they should be measured at the interface between the seat and individual. A Society of Automotive Engineers (SAE) pad will produce repeatable results for most seats. An SAE pad is a semi-rigid circular pad housing an accelerometer that sits between the individual and the seat. It bends to the contours of the seat but does not compress under the individual [Griffin, 1990].

For this study the SAE pad was constructed from a 200 mm diameter plastic sheet. The accelerometer was mounted on a metal plate in the centre of the sheet so that it would be held rigid while the rest of the pad remained flexible. Details of the SAE pad are included in Appendix B.

Horizontal (x-axis) and vertical (z-axis) accelerations were measured with the origin beneath the ischial tuberosities, as shown in Figure 5.1. This procedure differed from Watts' experiments, where an accelerometer was attached to a box on the lap of a seated passenger, or from other studies where the accelerometer was positioned on the chest of the driver or under the seat [Watts, 1973; Fwa & Liaw, 1992].

Figure 5.1
Measurement Origin and the Basicentric Coordinate System



Source: M. J. Griffin, *Handbook of Human Vibration*, London, Academic Press, 1990.

The acceleration readings were adjusted by calibrating the accelerometer. Each of the six sides of the cube-shaped accelerometer was placed on a level surface and readings were taken. The difference in readings when opposite sides faced down had to correspond to 2g, or twice the force of gravity. The acceleration readings were subsequently adjusted by interpolation or extrapolation. The procedure is described in Appendix B.

The peak, root-mean-square (rms) and root-mean-quad (rmq) horizontal and vertical accelerations were determined for each test run. Rms values lie between the average and peak values for a waveform, and are often used to relate vibration and discomfort [Griffin, 1990]. Rmq values are similar, but give more relative weight to the waveform peaks. Unlike peak values, rms and rmq values can convey information about duration.

The peak accelerations were determined by comparing the absolute values of the greatest positive and negative accelerations. Rms accelerations were calculated from the equation

$$rms(a_n) = \left(\frac{1}{T} \sum_{i=0}^{T} a_i^2 \right)^{1/2} \tag{5.2}$$

and rmq accelerations were calculated from the equation

$$rmq(a_n) = \left(\frac{1}{T} \sum_{i=0}^{T} a_i^4 \right)^{1/4} \tag{5.3}$$

where a_n is the acceleration along axis n, a_i represents an individual acceleration value for each unit of time, and T is the waveform duration in seconds [Thomson, 1988].

The duration of each test run was taken as the time from when the hump was entered to when the vertical acceleration waveform crossed the origin after decaying to half its peak value. This measure was assumed to be reasonably representative of motorist perceptions when crossing speed humps. Again, refer to Appendix B.

5.2 DISCOMFORT DETERMINATION

An analytical approach was used to establish appropriate levels of discomfort for speed humps. Mean and 85th percentile speeds were recorded as motorists travelled over several existing humps. The dimensions and speeds were later duplicated in the field tests, and the corresponding accelerations were assumed to represent tolerable levels of discomfort for most motorists.

5.2.1 Discomfort Levels

Since the perception of discomfort can be highly subjective, it was thought an investigation was needed to determine the discomfort experienced with existing speed humps. Other studies have used peak vertical acceleration values in the order of 0.7g as representative of the amount of discomfort tolerable to motorists crossing speed humps [Fwa & Liaw, 1992; Jarvis, 1992]. However, these studies have been carried out in other countries. A similar assessment was needed for North America. Since vehicle and road conditions are different, perceptions of discomfort may be different as well.

The International Standards Organization (ISO) has published guidelines for acceptable levels of fatigue or decreased proficiency whole-body vibration, as experienced when driving a vehicle. According to ISO 2631, recommended limits are about 0.6g for vertical accelerations and about 0.2g for lateral or horizontal accelerations [Wong, 1993]. Both are for a one minute duration and a vibration frequency of 1 Hz, the latter of which is appropriate for speed humps. There are no values for accelerations below 1 Hz, which when experienced for long durations usually cause motion sickness.

The ISO guidelines suggest that lateral and horizontal accelerations are tolerated to a lesser extent than vertical accelerations. They also indicate that sensitivity to vertical vibrations is greatest from 4 to 8 Hz, and sensitivity to lateral and horizontal vibrations is greatest from 1 to 2 Hz. Individuals typically experience horizontal accelerations in this range when crossing speed humps.

For this study it was decided that the on-road 85th percentile hump-crossing speeds for each hump design should be used to establish the discomfort criteria. Such speeds are commonly employed in traffic engineering to determine appropriate posted speed limits. Also, studies in the Netherlands have shown that residents and vulnerable street users tend to be more attuned to maximum vehicle speeds, and that the use of an 85th percentile speed is appropriate when designing traffic calming measures [CROW, 1988].

5.2.2 Pilot Study

Before the off-road field testing, a pilot study was undertaken at Algonquin College in Ottawa to gain experience with the use of a radar gun and an accelerometer. The college has installed five 3.7 m long Watts Profile speed humps at its Woodroffe Campus. Two are 100 mm high, while the other three are about 90 mm high. The pilot study also served to determine the 85th percentile hump-crossing speed for a 100 mm high Watts Profile speed hump, and act as a check for the corresponding accelerations in the field tests.

The two 100 mm high speed humps off Woodroffe Avenue were chosen in the first stage of the pilot study. A Tribar X-band radar gun was used to obtain thirty speed readings for all motor vehicles crossing the two humps in each direction of travel. The vehicles had to cross the humps under free-flow conditions so that drivers could choose their own hump-crossing speeds. Vehicle types and any undue noise or displacement were also noted. A video camera was set up at the west hump to look for any unusual vehicle behaviour.

These readings were supplemented with additional speed measurements at the east hump, so that thirty readings in each direction of travel were obtained for automobiles. The 85th percentile hump-crossing speed for the automobiles was found to be 25 km/h, which is the posted speed.

This speed was duplicated by a test vehicle driven over the east 100 mm high hump in the second stage of the pilot study. The vehicle was the same Suzuki Swift later used in the field testing. Horizontal and vertical accelerations were recorded with an Analog Devices accelerometer powered from the 12 volt DC cigarette lighter and connected to an AST laptop computer. The accelerometer was housed in an SAE pad placed under the driver, and fed instantaneous acceleration readings to the computer at a rate of 1024 readings per second.

Two test runs were made at 25 km/h, the 85th percentile hump-crossing speed. Because of the insensitivity of automobile speedometers at low speeds it was difficult to ascertain whether the number was exact.

After adjusting the readings using the accelerometer calibration the peak accelerations between the two runs differed by a maximum of 0.06g, as shown in Table 5.1. The peak, rms and rmq data and plots of the acceleration waveforms are included in Appendix C.

Table 5.1
Pilot Study Peak Accelerations

Test Run	**Horizontal Acceleration (g)**	**Vertical Acceleration (g)**
Speed Hump at 25 km/h (1st Run)	0.45	0.60
Speed Hump at 25 km/h (2nd Run)	0.44	0.54
Level Crossing at 60 km/h	0.44	0.60
Speed Bump at 15 km/h	0.70	0.56

To place these numbers in context, the peak horizontal and vertical accelerations for the same vehicle driven over a speed bump and a railway level crossing are also shown in Table 5.1. While of shorter duration, the level crossing produced similar peak accelerations at 60 km/h, while higher peak horizontal accelerations were recorded over the speed bump at only 15 km/h.

Additional test runs were made at the mean and 15th percentile hump-crossing speeds (see Appendix C). Tests were also carried out to compare accelerations measured from the driver or passenger seat, with and without seatbelts, and to examine altering the position of the SAE pad. Of these, only moving the SAE pad forward or backward in the seat seemed to affect the accelerations.

5.2.3 Speeds Over Existing Humps

Additional speed humps, differing in length and height from the 100 mm high Watts Profile hump at Algonquin College, were needed to establish the discomfort criteria. Five speed humps in Montgomery County were ultimately chosen for the speed study:

- three 75 mm high Watts Profile speed humps in Rockville, Silver Spring and Gaithersburg
- one 100 mm high Seminole Profile hump in Bethesda
- one 75 mm high Seminole Profile hump in Rockville.

The Montgomery County humps were all located in residential neighbourhoods. A level was used to confirm that the heights were within acceptable tolerances. Several of the humps were not within 5 mm of 75 or 100 mm, and were eliminated from further consideration. Humps on steep grades were also eliminated. In many cases the speed humps were on slight grades, so height measurements were taken on both sides and averaged.

In all instances the speed humps had been in place for at least one year. This ensured that the motorists driving over them were familiar with their effects, and were not being overly cautious with their choice of crossing speeds. A necessary assumption was made that motorists were not aware their speeds were being recorded. Radar detectors are legal in the State of Maryland, but it was hoped they are not commonly used in residential areas.

Speed readings were taken of automobiles, and in the case of the Seminole Profile hump in Rockville, transit buses as well. The vehicles had to cross the speed humps under free-flow conditions and not be slowing for turns or stops.

Speeds were not recorded for vans, minivans, pickup trucks, sport utility vehicles or delivery trucks, as these vehicles were not used in the field tests. A video camera was used to record some of the crossings.

The 85th percentile hump-crossing speeds for automobiles, and the mean hump-crossing speed for transit buses, are shown in Table 5.2. Thirty readings were obtained in each direction for automobiles. A mean speed was used for transit buses to reflect their greater impact on the perceptions of residents and vulnerable street users, and because only ten bus speeds were recorded.

The 85th percentile hump-crossing speeds for automobiles traversing the three 75 mm high Watts Profile humps were 27, 28 and 31 km/h, which averaged to 29 km/h.

Table 5.2
Existing Hump-Crossing Speeds

Hump Design	Automobile 85%-tile Speed (km/h)	Transit Bus Mean Speed (km/h)
100 mm Watts Profile	25	-
75 mm Watts Profile	29	-
100 mm Seminole Profile	40	-
75 mm Seminole Profile	44	30

The location of the speed hump tested in Ottawa, and the five speed humps tested in Montgomery County, are shown in Appendix C. The individual recorded automobile and transit bus speeds for all six humps are also listed in Appendix C.

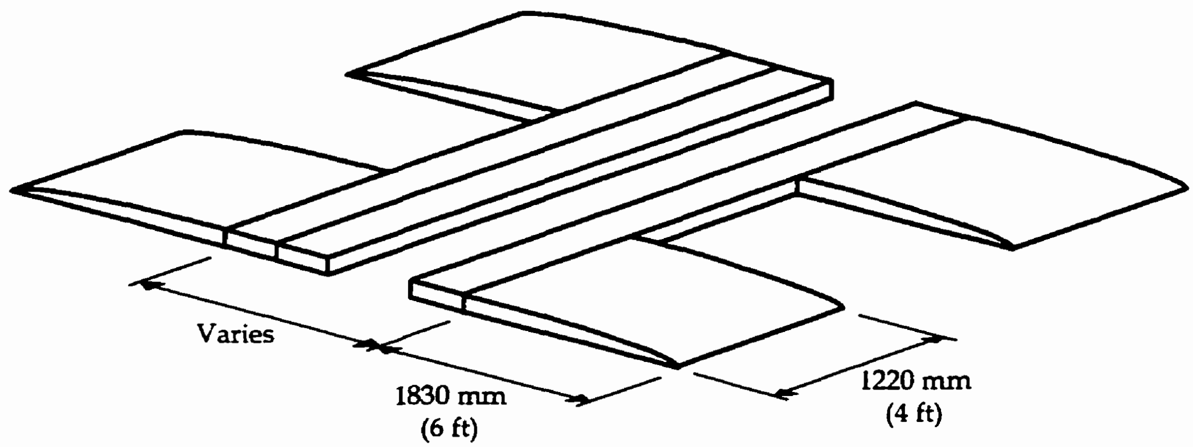
5.3 FIELD TESTS

The off-road field tests were performed using the test runs required for the discomfort determination along with those prescribed in the factorial design. For heights of 75 and 100 mm, test runs were made at the 85th percentile speeds for the Watts and Seminole Profile speed humps to establish the discomfort criteria. For these same heights, test runs were made at 25, 35 and 45 km/h for all four speed hump lengths as per the factorial design.

5.3.1 Test Speed Humps

The test humps were constructed out of wood and arranged as shown in Figure 5.3. The ramp sections were built from unfinished 2 x 4's cut to the circular profile required, and covered by planed 1 x 4's. The flat inserts were built in a similar manner in lengths of 1.2, 3.0 and 5.4 m (4, 10 and 18 feet). The inserts were added between the ramp sections for both heights to create the overall lengths needed. The specifications used for building the ramp sections, and the assembly of the test humps, are described in Appendix D.

Figure 5.2
Representation of a Test Hump



The full-scale field testing was carried out along Morningside Lane at the Central Experimental Farm in Ottawa. Morningside Lane has an asphalt surface and mountable concrete curb, and is 5.2 metres wide with about three percent crossfall. Due to the narrow width the test humps were centred over the crown of the road. The leading and trailing edges of the ramp sections were fastened to the pavement with concrete nails.

5.3.2 Automobile Test Runs

As in the pilot study, horizontal and vertical acceleration measurements for the two test automobiles were taken with an accelerometer connected to a laptop computer. The accelerometer was housed in an SAE pad placed under the driver (the same driver was used for both automobiles).

A radar gun was used to measure the hump-crossing speeds. It was thought a 1 km/h tolerance would be reasonable and attainable. The device, the same radar gun used in the pilot study, was operated from the test vehicles and aimed at a stationary object at the side of the road. The radar gun was powered from the cigarette lighter, and a 12 volt battery was used for the accelerometer.

The field test designs and hump-crossing speeds for the two test automobiles are described in Tables 5.3 and 5.4. All of the runs associated with 75 mm high speed humps were done first, followed by all the runs associated with 100 mm high humps. Each test run was performed twice.

The peak, rms and rmq acceleration data, and plots of the horizontal and vertical acceleration waveforms for the 38 automobile test runs, are included in Appendix D. Since the 85th percentile speed for the 100 mm high Watts Profile hump, 25 km/h, happened to be identical to a test run prescribed in the factorial design, two fewer test runs were required for the Chevrolet.

Table 5.3
Suzuki Swift Test Runs

Test Runs for Discomfort Determination	Test Runs from Factorial Design
3.7 m x 75 mm at 29 km/h	3.7 m x 75 mm at 25 km/h
6.7 m x 75 mm at 44 km/h	3.7 m x 75 mm at 45 km/h
	6.7 m x 75 mm at 35 km/h
3.7 m x 100 mm at 25 km/h	4.9 m x 100 mm at 25 km/h
6.7 m x 100 mm at 40 km/h	4.9 m x 100 mm at 45 km/h
	9.1 m x 100 mm at 35 km/h

Table 5.4
Chevrolet Monte Carlo Test Runs

Test Runs for Discomfort Determination	Test Runs from Factorial Design
3.7 m x 75 mm at 29 km/h	4.9 m x 75 mm at 35 km/h
6.7 m x 75 mm at 44 km/h	9.1 m x 75 mm at 25 km/h
	9.1 m x 75 mm at 45 km/h
6.7 m x 100 mm at 40 km/h	3.7 m x 100 mm at 25 km/h
	3.7 m x 100 mm at 45 km/h
	6.7 m x 100 mm at 35 km/h

5.3.3 Transit Bus Test Runs

As with the automobiles, horizontal and vertical accelerations for the transit bus were measured with an accelerometer housed in an SAE pad. The accelerometer and radar gun were powered by 12 volt batteries. The SAE pad was placed under the bus operator for the driver seat measurements and under a passenger for the rear seat measurements. A video camera was used to record the tests.

The field test designs and hump-crossing speeds for the two positions on the transit bus are described in Tables 5.5 and 5.6. Again, all of the runs associated with 75 mm high humps were done twice, and then all the runs associated with 100 mm high humps were done twice.

Table 5.5
GM Classic Test Runs – Driver Seat

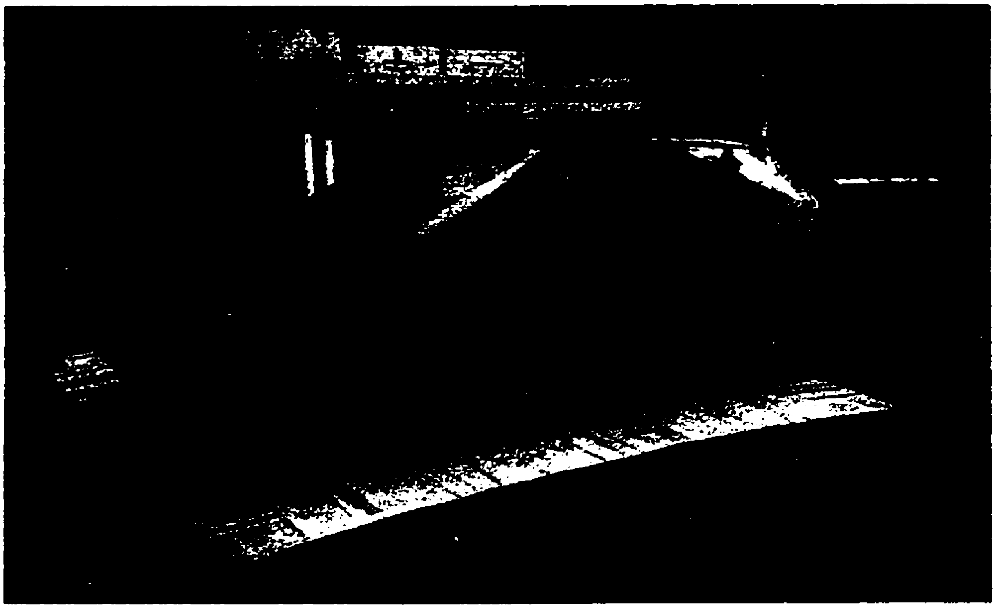
Test Runs for Discomfort Determination	Test Runs from Factorial Design
6.7 m x 75 mm at 30 km/h	3.7 m x 75 mm at 35 km/h
	6.7 m x 75 mm at 25 km/h
	6.7 m x 75 mm at 45 km/h
	4.9 m x 100 mm at 35 km/h
	9.1 m x 100 mm at 25 km/h
	9.1 m x 100 mm at 45 km/h

Table 5.6
GM Classic Test Runs – Rear Seat

Test Runs for Discomfort Determination	Test Runs from Factorial Design
6.7 m x 75 mm at 30 km/h	4.9 m x 75 mm at 25 km/h
	4.9 m x 75 mm at 45 km/h
	9.1 m x 75 mm at 35 km/h
	3.7 m x 100 mm at 35 km/h
	6.7 m x 100 mm at 25 km/h
	6.7 m x 100 mm at 45 km/h

Photographs of the Suzuki Swift and the GM Classic with two of the test humps are shown in Figures 5.3 and 5.4.

Figure 5.3
Suzuki Swift and 3.7 m by 75 mm Test Hump



Location: Carleton Univeristy, Ottawa, Ontario (October 15, 1997).

Figure 5.4
GM Classic and 4.9 m by 75 mm Test Hump

Location: Central Experimental Farm, Ottawa, Ontario (October 14, 1997).

The peak, rms and rmq acceleration data, and plots of the horizontal and vertical acceleration waveforms for the 28 transit bus test runs, are included in Appendix D.

It was originally thought that in addition to the 85th percentile speeds, discomfort would be related to mean and 15th percentile automobile hump-crossing speeds as well. It was later decided that only 85th percentile speeds were important in the speed study. This resulted in 32 additional test runs (again, see Appendix D) that were carried out but not analyzed.

CHAPTER 6 – DATA ANALYSIS

6.1 DISCOMFORT CRITERIA

The hump-crossing speeds determined in Montgomery County, Maryland, and at Algonquin College were duplicated in the off-road tests to establish the discomfort criteria. The accelerations measured at the 85th percentile speeds were related to perceptions of discomfort for automobile occupants. The mean speed was related to an average perception of discomfort for those on transit buses.

6.1.1 Discomfort Criterion for Automobiles

Accelerations were measured as the two test automobiles traversed the 75 and 100 mm high Watts and Seminole Profile speed humps in the off-road field tests at the observed 85th percentile speed of each. It was assumed that these speeds could correspond to a single discomfort level chosen not to be exceeded by most automobile drivers.

The means and standard deviations were calculated for the peak, rms and rmq horizontal and vertical accelerations. They were also calculated for the root sum of squares (RSS) and root sum quad (RSQ) values. For the horizontal and vertical (x and z) axes

$$RSS(a_{xz}) = \left(\frac{1}{2}\text{rms}(a_x)^2 + \frac{1}{2}\text{rms}(a_z)^2\right)^{1/2} \tag{6.1}$$

and

$$RSQ(a_{xz}) = \left(\frac{1}{4}\text{rmq}(a_x)^4 + \frac{1}{4}\text{rmq}(a_z)^4\right)^{1/4} \tag{6.2}$$

where $RSS(a_{xz})$ and $RSQ(a_{xz})$ are the root sum of square and root sum quad accelerations, and a_x and a_z are the accelerations along the x- and z-axes, respectively.

One of the lowest standard deviations came from examining the RSS accelerations. Also providing low standard deviations were the rms and rmq horizontal accelerations. It was decided to use RSS accelerations in the regression analysis since they combine both horizontal and vertical accelerations in one measure, and they had slightly lower standard deviations than the RSQ accelerations. Many other studies of multi-axis vibrations on individuals also employ RSS values [Griffin, 1990].

The peak vertical and RSS accelerations (averaged between identical test runs) for the 75 and 100 mm Watts and Seminole Profile speed humps and the two test automobiles are shown in Table 6.1. Other accelerations at the 85th percentile speeds are listed in Appendix E.

Table 6.1
Automobile Accelerations at the 85th Percentile Speeds

Speed Hump Test Run	Vehicle	Peak Vertical Acceleration (g)	RSS Acceleration (g)
3.7 m x 100 mm at 25 km/h	Suzuki	0.67	0.17
3.7 m x 100 mm at 25 km/h	Chevrolet	0.57	0.18
3.7 m x 75 mm at 29 km/h	Suzuki	0.56	0.15
3.7 m x 75 mm at 29 km/h	Chevrolet	0.33	0.12
6.7 m x 100 mm at 40 km/h	Suzuki	0.70	0.20
6.7 m x 100 mm at 40 km/h	Chevrolet	0.62	0.18
6.7 m x 75 mm at 44 km/h	Suzuki	0.61	0.18
6.7 m x 75 mm at 44 km/h	Chevrolet	0.52	0.14
Mean		**0.57**	**0.17**
Standard Deviation		**0.11**	**0.03**

The baseline acceleration level, or discomfort criterion for the automobiles, was taken to be an RSS acceleration of 0.17g. The peak vertical accelerations, used to represent discomfort in most other speed hump studies, had a much higher standard deviation over the range of hump designs and speeds tested.

Interestingly enough, the mean peak vertical acceleration of 0.57g found in this study is lower than the average of 0.7g usually used to model discomfort in other studies [Watts, 1973; Fwa & Liaw, 1992; Jarvis, 1992]. This suggests that compared to other countries lower discomfort levels are tolerated by motorists travelling over speed humps in North America.

6.1.2 Discomfort Criteria for Transit Buses

A much less rigorous treatment of discomfort was possible with buses since only ten speeds were recorded over one existing hump. Accelerations were measured at the driver and rear seats as a regular transit bus traversed the 75 mm high Seminole Profile test hump at the mean speed of 30 km/h. It was assumed that this speed could correspond to tolerable discomfort levels for most seated bus passengers.

The discomfort criterion at the driver seat of the transit bus was an RSS acceleration of 0.20g, and the discomfort criterion at the rear seat was an RSS acceleration of 0.23g. Other accelerations for the transit bus at the mean hump-crossing speed are included in Appendix E.

Accelerations were higher for the bus at the mean speed than for the automobiles at the 85th percentile speed. This implies that bus passengers tolerate and experience higher levels of discomfort.

Additional accelerations were measured as another transit bus travelled along a typical route of well-maintained local roads and collectors in Ottawa. Peak lateral and horizontal accelerations in the order of 0.5g, and peak vertical accelerations of about 0.4g, were recorded at the rear seat. The highest values came when the bus was decelerating or turning. RSS accelerations were as much as 0.16g (see Appendix E).

6.2 FACTORIAL DESIGN DATA

After establishing the discomfort criteria the remaining test results, all from the factorial design, were examined prior to the regression analysis.

6.2.1 Summary of Experimental Results

The RSS accelerations for the 48 test runs prescribed in the factorial design are shown for the test vehicles in Tables 6.2 to 6.5.

Differences between identical test runs were usually in the order of 0.01g to 0.03g. The one exception (0.06g) was at the rear seat of the transit bus when the 100 mm high Watts Profile hump was traversed at 35 km/h.

Table 6.2
Suzuki Swift RSS Accelerations

Speed Hump Test Run	RSS Acceleration 1st Run (g)	2nd Run (g)
3.7 m x 75 mm at 25 km/h	0.12	0.13
3.7 m x 75 mm at 45 km/h	0.27	0.25
6.7 m x 75 mm at 35 km/h	0.11	0.13
4.9 m x 100 mm at 25 km/h	0.14	0.16
4.9 m x 100 mm at 45 km/h	0.38	0.41
9.1 m x 100 mm at 35 km/h	0.18	0.18

Table 6.3
Chevrolet Monte Carlo RSS Accelerations

Speed Hump Test Run	RSS Acceleration 1st Run (g)	2nd Run (g)
4.9 m x 75 mm at 35 km/h	0.13	0.12
9.1 m x 75 mm at 25 km/h	0.08	0.07
9.1 m x 75 mm at 45 km/h	0.14	0.12
3.7 m x 100 mm at 25 km/h	0.18	0.18
3.7 m x 100 mm at 45 km/h	0.26	0.26
6.7 m x 100 mm at 35 km/h	0.16	0.18

Table 6.4
GM Classic RSS Accelerations – Driver Seat

Speed Hump Test Run	RSS Acceleration 1st Run (g)	2nd Run (g)
3.7 m x 75 mm at 35 km/h	0.20	0.20
6.7 m x 75 mm at 25 km/h	0.15	0.15
6.7 m x 75 mm at 45 km/h	0.20	0.20
4.9 m x 100 mm at 35 km/h	0.28	0.27
9.1 m x 100 mm at 25 km/h	0.18	0.19
9.1 m x 100 mm at 45 km/h	0.25	0.24

Table 6.5
GM Classic RSS Accelerations – Rear Seat

Speed Hump Test Run	RSS Acceleration 1st Run (g)	RSS Acceleration 2nd Run (g)
4.9 m x 75 mm at 25 km/h	0.19	0.22
4.9 m x 75 mm at 45 km/h	0.41	0.40
9.1 m x 75 mm at 35 km/h	0.18	0.20
3.7 m x 100 mm at 35 km/h	0.40	0.34
6.7 m x 100 mm at 25 km/h	0.23	0.24
6.7 m x 100 mm at 45 km/h	0.51	0.54

6.2.2 Observations

As expected, the RSS accelerations were highest at the rear seat of the transit bus. Also as expected:

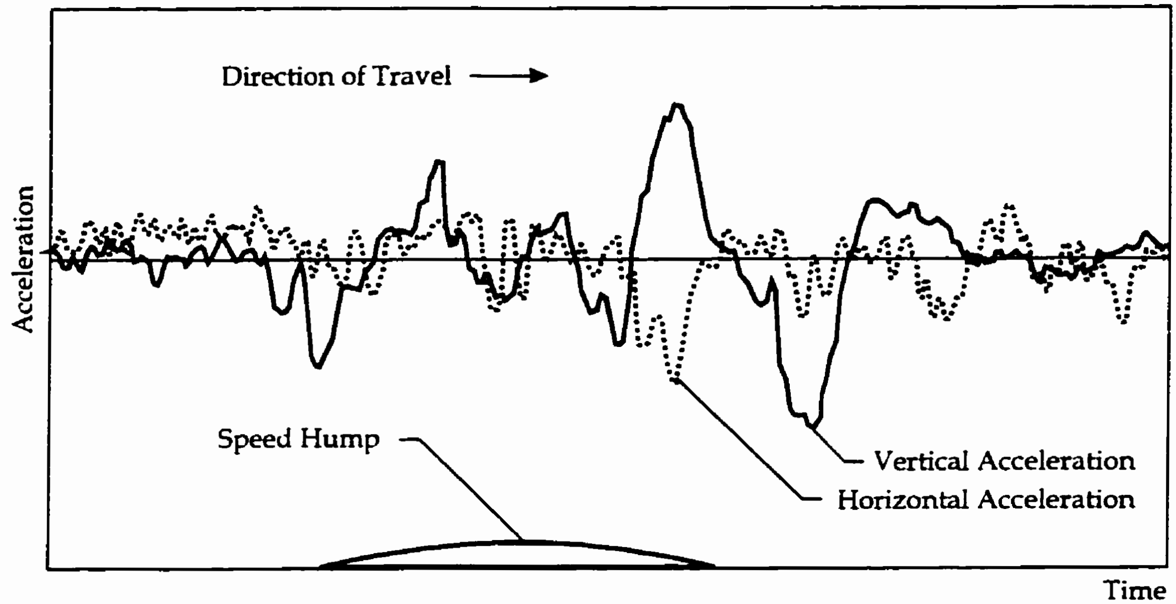
- accelerations seemed to decrease with increasing hump length
- accelerations seemed to increase with increasing hump height
- accelerations seemed to increase with increasing hump-crossing speed.

Each test run produced acceleration waveforms similar to those shown in Figure 6.1. Entering the hump created an initial negative peak in vertical accelerations as the motorist was lifted. Exiting the test humps resulted in the greatest overall accelerations because of the additional downward force of gravity. This effect has been observed in other studies [Moinat, 1991; Jarvis, 1992].

The horizontal and vertical acceleration waveforms were of greater duration with longer humps or lower speeds, resulting in lower RSS accelerations. Vibrations were highly undamped at the driver seat of the bus, likely due to its air suspension, while vibrations were more impulsive at the rigid rear seat.

In the field tests the 100 mm high Watts Profile hump induced a pronounced front-to-back pitching motion in the Chevrolet at 25 km/h, and scraping under the front bumper. Similar incidents were observed in the speed study for some automobiles travelling over Watts Profile humps between about 25 and 35 km/h. This suggests that these humps may be unsuitable at such speeds, since for higher or lower speeds the pitching was less severe. No excessive horizontal or vertical accelerations were associated with the pitching.

Figure 6.1
Typical Acceleration Waveforms



High amounts of vehicle noise and displacement were observed at 45 km/h with the Suzuki traversing the 4.9 m by 100 mm hump, and the transit bus traversing the 100 mm high Seminole Profile hump. There was no vehicle damage in either case, and the hump crossings appeared safe.

6.3 SOURCES OF EXPERIMENTAL ERROR

An approximation of the total error associated with the experimental design was determined, bearing in mind that humps in the field are subject to construction tolerances. It was thought simplest to express the error in terms of the discomfort criteria, which could be equated to speed hump designs in the regression analysis.

One component of the total error was the between-run error, or differences between identical test runs. For example, RSS accelerations of 0.12g and 0.13g were measured when the Suzuki traversed the 75 mm Watts Profile hump at 25 km/h. This between-run error could be explained in part by the 1 km/h tolerance allowed with the hump-crossing speeds. Also, the radar gun has a parallax error, and a built-in error of 0.5 km/h.[5] Parallax error comes with the use of a radar gun at large angles. The angles were kept small in the field tests, and were taken into account when speeds were recorded over the existing humps.

The other component of the total error was the experimental error, which existed because:

- only two automobiles were used to represent all light vehicles, and only one regular transit bus was used to represent all heavy vehicles
- of inaccuracies involved in averaging automobile dynamic responses, which arose from differences in suspensions, tires and seats (although differences are small for low-frequency vibrations)
- the SAE pad was placed under one individual for the automobiles and the rear seat of the transit bus, and another for the driver seat (although the pad is designed to minimize such differences)
- of instrumentation errors for the radar gun and accelerometer
- there were slight differences in the position of the accelerometer on the vehicle seats (the pilot study showed this to be a large *potential* source of error, although it would not affect the between-run error)
- speeds were recorded over only one 100 mm and three 75 mm Watts Profile humps, and one 75 mm and one 100 mm Seminole Profile hump
- only one of the existing speed humps was on a bus route
- thirty speed measurements were taken in each direction for automobiles, and only five in each direction for buses
- the on-road and off-road speed humps were not of exact dimensions and profiles (although they were measured or built to close tolerances).

An additional source of error involved the use of horizontal rather than pitching accelerations. As one of the test runs indicated, high amounts of pitching were not always reflected in the RSS accelerations. The error was mitigated in part through the objective of limiting undue noise and displacement.

For the Algonquin College pilot study the RSS acceleration at 25 km/h for the Suzuki was 0.14g. The equivalent values for the 100 mm high Watts Profile hump in the field tests were 0. 18g and 0.17g. The difference could have arisen from speed inaccuracies in the pilot study, since a radar gun was not used. Although the test humps were constructed out of wood rather than asphalt, they did not flex or move as any of the vehicles were driven over them. As the field

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[5] Manufacturer's specifications.

test analyses were based only on relative comparisons, these errors were not an influence in the experiment.

Since extra test runs were performed at the mean and 15th percentile hump-crossing speeds, it was possible to approximate the effect of a 1 km/h change in speed. The maximum difference in RSS accelerations was 0.01g (refer to Appendix D). Instrumentation and SAE pad positioning could possibly add another 0.01g to the figure.

An additional error of 0.02g was used for the automobiles because of the limited sampling of hump-crossing speeds over the existing humps. This corresponded to the 2 km/h difference between the highest or lowest and average 85th percentile speeds for the three existing Watts Profile humps (27, 28 and 31 km/h). It was decided an additional error of 0.04g would be suitable for the transit bus.

The discomfort criterion for the automobiles was thus modified to 0.17g ± 0.04g. The discomfort criteria for the transit bus were 0.20g ± 0.06g at the driver seat and 0.23g ± 0.06g at the rear seat.

CHAPTER 7 – REGRESSION ANALYSIS

7.1 REGRESSION MODELS

Multiple linear regression was used to model the experimental data. Variables representing the main effects and interactions of the four factors were input into the computer program SPSS, and their partial regression coefficients calculated using two different methods.

7.1.1 Input Variables

The variables used in the analysis were those of experimental interest, the main effects and two-factor interactions. The main effects of the factors Length, Height, Speed and Vehicle were represented by the variables L, L^2, H, S, S^2 and V. The second-order two-factor interactions were the functions LH, LS, LV, HS, HV and SV, and the third-order two-factor interactions were the functions L^2H, L^2S, LS^2 and HS^2. It was thought from the tests that Length would be unlikely to vary as a cubic function, and so the variable L^3 was not included.

Since Vehicle was a qualitative factor its four levels were defined by three dummy variables as follows:

$$D1 = \begin{cases} 1 \text{ if Suzuki Swift} \\ 0 \text{ otherwise} \end{cases}$$

$$D2 = \begin{cases} 1 \text{ if GM Classic - Driver Seat} \\ 0 \text{ otherwise} \end{cases}$$

$$D3 = \begin{cases} 1 \text{ if GM Classic - Rear Seat} \\ 0 \text{ otherwise} \end{cases}$$

The case for when D1 = 0, D2 = 0 and D3 = 0 corresponded to the Chevrolet Monte Carlo.

7.1.2 The Enter Uncentred Model

A multiple linear regression model where the values of a dependent variable Y are determined as a function of *k* independent variables has the form [Sheaffer & McClave, 1986]

$$Y = B_0 + B_1 x_1 + B_2 x_2 + \ldots + B_k x_k + \varepsilon \tag{7.1}$$

where B represents the variable coefficients and ε is used for random error. For this study the dependent variable was the RSS acceleration, and the independent variables were the main effects and two-factor interactions. The model was linear in the partial regression coefficients even though some of the variables, such as L^2 or LS^2, had quadratic terms.

Regression procedures assume the random errors are independent, normally distributed, have a mean of zero and constant variance. For this experiment the RSS values were close between identical test runs, and their differences were of the same order of magnitude. It was therefore concluded the assumptions were reasonable.

The first regression model developed was the enter uncentred model. All the variables of interest were entered or "forced" into a regression equation, and their optimal coefficients estimated using the method of least-squares. The result was the equation

$$\begin{aligned} RSS(a)_{EU} = {} & 0.467089 - 0.087429\,L + 2.71165 \times 10^{-4}\,H - 0.006713\,S \\ & - 0.225714\,D1 + 0.131367\,D2 - 0.118648\,D3 - 0.001380\,LD1 \\ & - 0.012866\,LD2 - 0.001726\,LD3 + 8.46374 \times 10^{-4}\,HD1 \\ & + 9.91224 \times 10^{-4}\,HD2 + 6.33220 \times 10^{-4}\,HD3 + 0.005759\,SD1 \\ & - 0.002479\,SD2 + 0.006655\,SD3 + 0.010981\,L^2 - 2.16008 \times 10^{-4}\,S^2 \\ & + 1.27830 \times 10^{-4}\,L^2H - 3.91772 \times 10^{-4}\,L^2S + 7.58665 \times 10^{-5}\,LS^2 \\ & + 1.65285 \times 10^{-6}\,HS^2 \end{aligned} \tag{7.2}$$

where L is speed hump length, H is height, S is the hump-crossing speed and D1, D2 and D3 are dummy variables representing the vehicle type.

A good indicator of how well a model fits the experimental data is the multiple coefficient of determination (R^2). It measures the variability in the dependent variable accounted for by the independent variables.

For the enter uncentred model the adjusted R^2 was very high at 98%, meaning that 98 percent of the variations in RSS accelerations were due to the presence of the input variables. An adjusted value was used to recognize the large number of variables in the model. Because the remainder was the amount of variability attributable to random error, the model seemed to be a very good fit of the data. The adjusted R^2 and other summary statistics are shown in Table 7.1.

Table 7.1
Summary Statistics and ANOVA for Enter Uncentred Model

Summary Statistics			
Multiple R = 0.995			
Adjusted R^2 = 0.982		Std. Dev. = 0.014	
Analysis of Variance			
Source	DF	Sum of Squares	Mean Square
Regression	21	0.5256	0.0250
Residual	26	0.0053	0.0002
F-statistic = 123.498		Sig. *F* = 0.000	

Also shown in Table 7.1 are the results of an analysis of variance (ANOVA), which tested the null hypothesis that there was no linear relationship between the dependent and independent variables. This was done using the global *F*-statistic, which is the ratio of what is accounted for by the linear regression (the regression mean square) to what is not accounted for (the random error or residual mean square).

For the enter uncentred model the *F*-statistic was 123.498, with a significance level of 0.000. Since this was less than a chosen significance level of $\alpha = 0.05$, the null hypothesis was rejected. There was no evidence to suggest a lack of fit for the regression model.

Similarly, *t*-statistics tested the null hypothesis that each of the partial regression coefficients was zero. Most significance levels were low, so the probability the coefficients for these variables were zero was also low. Some were not, however. The null hypothesis could not be rejected for these coefficients even at a significance level of $\alpha = 0.10$. Some of the statistics for the independent variables are shown in Table 7.2.

The interpretation that certain partial regression coefficients could be zero implied that these independent variables did not contribute significantly to the regression model. The reason was likely because they were linearly related to other variables. One measure of this redundancy, or multicollinearity, is the variance inflation factor (VIF).

The variance inflation factors for some of the variables were quite high (see Table 7.2), signifying that most of the information they were conveying were already being supplied by other variables. When independent variables are highly correlated, precision in estimating their partial regression coefficients can be reduced, and some of the true coefficients can lose their importance [Neter & Wasserman, 1974]. It was therefore decided to develop a second regression model that would generate lower levels of multicollinearity.

Table 7.2
Independent Variable Statistics for Enter Uncentred Model

Variable	Coefficient, *B*	Sig. *t*	VIF
L	-0.087429	0.004	755.8
H	2.71165×10^{-4}	0.678	15.5
S	-0.006713	0.286	600.3
D1	-0.225714	0.002	191.3
D2	0.131367	0.068	211.9
D3	-0.118648	0.125	249.1
LD1	-0.001380	0.742	26.6
LD2	-0.012866	0.003	33.1
LD3	-0.001726	0.634	22.8
HD1	8.46374×10^{-4}	0.161	120.3
HD2	9.91224×10^{-4}	0.128	138.9
HD3	6.33220×10^{-4}	0.295	122.4
SD1	0.005759	0.000	39.3
SD2	-0.002479	0.008	43.0
SD3	0.006655	0.000	54.7
L^2	0.010981	0.009	2527.0
S^2	-2.16008×10^{-4}	0.119	1400.6
L^2H	1.27830×10^{-5}	0.135	93.0
L^2S	-3.91772×10^{-4}	0.001	2800.8
LS^2	7.58886×10^{-5}	0.001	1964.5
HS^2	1.65285×10^{-6}	0.000	55.3

7.1.3 Correlation Between Variables

Variables in this study were assessed for correlation by determining their Pearson correlation coefficients. If two variables are perfectly correlated, their correlation coefficient is 1. If they are perfectly negatively correlated the Pearson coefficient is -1, and if they are not correlated at all the coefficient is 0. The Pearson correlation coefficients between L and L^2, and S and S^2, were very close to 1, as were the coefficients between L and S and L^2H, L^2S, LS^2 and HS^2.

All the factors of experimental interest, including the third-order variables, were retained for the second regression model. In order to lessen their association with the main effects, the higher-order variables were *centred*. Quadratic functions can be centred by squaring their differences from the mean value of the factor. For example, L^2 was centred by setting

$$L_c^2 = (L - \bar{L})^2 \tag{7.3}$$

where L is speed hump length and L_c is the centred length. For this experiment the mean value of L was 6.1 m, and the mean value of S was 35 km/h. The centred equivalents of L^2, S^2, L^2H, L^2S, LS^2 and HS^2 were expressed as L_c^2, S_c^2, L_c^2H, L_c^2S, LS_c^2 and HS_c^2.[a]

Centred data are new variables that do not contribute to multicollinearity to the same degree as uncentred data. Descriptive statistics, and a matrix of Pearson correlation coefficients for all the variables, are included in Appendix F.

7.1.4 The Stepwise Centred Model

The second regression model developed was the stepwise centred model. All the variables of interest were entered into a regression equation using stepwise selection, and centred data were used for the quadratic functions. The result was the equation

$$\begin{aligned} RSS(a)_{SC} = {} & 0.104030 - 0.013574\ L - 0.005484\ S - 0.175290\ D1 + 0.123595\ D2 \\ & - 0.151776\ D3 - 0.010807\ LD2 + 1.00889 \times 10^{-4}\ HS + 0.006324\ SD1 \\ & + 0.008948\ SD3 - 4.66573 \times 10^{-5}\ L_c^2 S + 6.62871 \times 10^{-5}\ LS_c^2 \end{aligned} \tag{7.4}$$

where L is speed hump length, L_c is the centred length, H is height, S is the hump-crossing speed, S_c is the centred speed and D1, D2 and D3 are dummy variables representing the vehicle type.

Stepwise selection means that variables are entered one at a time, rather than all at once, starting with the variable having the lowest significance level for the *t*-statistic. After each one is entered, *t*-statistics for the variables in the model are recalculated, and any no longer contributing significantly are removed. [Norušis, 1995]. The criteria for entering and removing variables were significance levels of $\alpha = 0.05$ and $\alpha = 0.10$ respectively.

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[a] For the computer program SPSS, L^2 was entered as LSQ, LS_c^2 was entered as LSSQC, etc.

The stepwise method ultimately required fewer variables than the enter method. Yet the adjusted R^2 was 97%, suggesting that it too seemed to be a very good model for the test data. In the ANOVA the global *F*-statistic was 165.846, and its significance level was also 0.000, indicating there was no evidence to suggest a lack of fit. Summary statistics are shown in Table 7.3.

Table 7.3
Summary Statistics and ANOVA for Stepwise Centred Model

Summary Statistics			
Multiple R = 0.990			
Adjusted R^2 = 0.975		Std. Dev. = 0.017	
Analysis of Variance			
Source	DF	Sum of Squares	Mean Square
Regression	11	0.5206	0.0473
Residual	36	0.0103	0.0003
F-statistic = 165.846		Sig. *F* = 0.000	

All the variables retained in the equation had *t*-statistics with significance levels of α = 0.10 or better, due to the nature of stepwise selection. Unlike the enter uncentred model, every independent variable contributed significantly in the stepwise centred model. As a result the variance inflation factors were much lower, signifying a lesser degree of multicollinearity (see Table 7.4).

Table 7.4
Independent Variable Statistics for Stepwise Centred Model

Variable	Coefficient, *B*	Sig. *t*	VIF
L	-0.013574	0.000	1.6
S	-0.005484	0.000	5.1
D1	-0.175290	0.000	22.3
D2	0.123595	0.000	17.2
D3	-0.151776	0.000	22.4
LD2	-0.010807	0.003	18.6
HS	1.00889×10^{-4}	0.000	3.9
SD1	0.006324	0.000	22.3
SD3	0.008948	0.000	22.7
L_c^2S	-4.66573×10^{-5}	0.045	1.4
LS_c^2	6.62871×10^{-5}	0.000	1.7

It was therefore decided to proceed with the remaining analysis using the stepwise centred model. The full development of the stepwise centred model, and the enter uncentred model, are detailed in Appendix F.

7.2 REGRESSION RESULTS

A multiple regression equation for each vehicle type was developed from the stepwise centred model. The equations were used to estimate the accelerations measured in the field tests and predict new values. These were plotted to produce a series of curves, to which the discomfort criteria were applied to find the optimal speed hump designs.

7.2.1 Testing the Model

The stepwise centred model was split into separate equations for each vehicle type by substituting for the dummy variables. For the Chevrolet Monte Carlo (D1 = 0, D2 = 0 and D3 = 0) the regression model reduced to

$$\begin{aligned} RSS(a)_{SC} &= 0.104030 - 0.013574\ L - 0.005484\ S + 1.00889 \times 10^{-4}\ HS \\ &\quad - 4.66573 \times 10^{-5}\ L_c^2 S + 6.62871 \times 10^{-5}\ LS_c^2 . \end{aligned} \tag{7.5}$$

For the Suzuki Swift (D1 = 1, D2 = 0 and D3 = 0) the regression model reduced to

$$\begin{aligned} RSS(a)_{SC} &= -0.071260 - 0.013574\ L + 0.000840\ S + 1.00889 \times 10^{-4}\ HS \\ &\quad - 4.66573 \times 10^{-5}\ L_c^2 S + 6.62871 \times 10^{-5}\ LS_c^2 . \end{aligned} \tag{7.6}$$

For the GM Classic – Driver Seat (D1 = 0, D2 = 1 and D3 = 0) the regression model reduced to

$$\begin{aligned} RSS(a)_{SC} &= 0.227625 - 0.024381\ L - 0.005484\ S + 1.00889 \times 10^{-4}\ HS \\ &\quad - 4.66573 \times 10^{-5}\ L_c^2 S + 6.62871 \times 10^{-5}\ LS_c^2 . \end{aligned} \tag{7.7}$$

For the GM Classic – Rear Seat (D1 = 0, D2 = 0 and D3 = 1) the regression model reduced to

$$\begin{aligned} RSS(a)_{SC} &= -0.047746 - 0.013574\ L + 0.003464\ S + 1.00889 \times 10^{-4}\ HS \\ &\quad - 4.66573 \times 10^{-5}\ L_c^2 S + 6.62871 \times 10^{-5}\ LS_c^2 \end{aligned} \tag{7.8}$$

where L is speed hump length, L_c is the centred length, H is height, S is the hump-crossing speed, S_c is the centred speed and D1, D2 and D3 are dummy variables representing the vehicle type.

These four equations were used to estimate the actual RSS accelerations measured in the experiment. As an example, for the test treatment 0 1 0 1 (L = 3.7 m, H = 100 mm, S = 25 km/h and V = Chevrolet), the RSS acceleration estimated by the model was

$$\begin{aligned} RSS(a)_{SC} &= 0.104030 - 0.013574(3.7) - 0.005484(25) + 1.00889 \times 10^{-4}(100)(25) \\ &\quad - 4.66573 \times 10^{-5}(3.7 - 6.1)^2(25) + 6.62871 \times 10^{-5}(3.7)(25 - 35)^2 \\ &= 0.187g \end{aligned} \tag{7.9}$$

This compared with actual values of 0.181g and 0.182g from the two test runs. The 95% confidence interval for the estimated acceleration was 0.187g ± 0.016g, or 0.171g to 0.202g. All the values from the regression model were within 0.02g of the measured RSS accelerations.

7.2.2 Optimal Speed Hump Designs

The four equations were then used to predict additional accelerations. Within the range of speed hump lengths tested, regression curves were plotted of length against RSS acceleration for each of the two heights and three hump-crossing speeds. Refer to Figures 7.1 to 7.6. It was decided to set length as the factor for design. Unlike length, speed hump heights are usually standardized in North America at 75 or 100 mm.

As expected, the curves on each graph demonstrated the quadratic relationship between length and RSS acceleration, with the dependent variable decreasing with increasing length. The curves between graphs indicated that RSS accelerations increased with increasing height as a linear function and with increasing speed as a higher-order function. What was not expected was that accelerations decreased more rapidly with length for the driver seat of the bus than for the other vehicles. Perhaps the difference was due to the air suspension of the driver seat.

In Figure 7.1, speed hump length was plotted for a height of 75 mm and a speed of 25 km/h. The discomfort criteria of 0.17g for the automobiles, 0.20g for the driver seat of the transit bus and 0.23g for the rear seat were added to the graph to determine which speed hump lengths would result in acceptable acceleration levels. The only criterion that intercepted its regression curve was the one for the driver seat of the bus. The other two criteria passed above their respective curves. Therefore there were no suitable speed hump lengths between 3.7 and 9.1 m that would produce high enough levels of discomfort for these vehicles.

In Figure 7.2, the height was 100 mm and the speed was 25 km/h. The automobile discomfort criterion of 0.17g intercepted both the Suzuki and Chevrolet regression curves, the former at 3.7 m and the latter at 6.7 m. These two lengths were averaged, and it was concluded that the optimal speed hump length for all automobiles under these conditions was 5.2 m (17 feet). Similarly, the 0.20g criterion intercepted the driver seat regression curve at 7.8 m, and the 0.23g criterion intercepted the rear seat curve at 8.0 m. It was likewise concluded that the optimal speed hump length for transit buses and heavy vehicles was 7.9 m (26 feet).

In Figure 7.3 (H = 75 mm and S = 35 km/h), the transit bus discomfort criteria intercepted their respective regression curves at 3.7 and 7.7 m. It was concluded that the optimal speed hump length for buses in this case was 5.7 m (19 feet). The automobile criterion passed above the Suzuki and Chevrolet regression curves, meaning that there was no length under these conditions that would produce high enough levels of discomfort.

In Figure 7.4 (H = 100 mm and S = 35 km/h), the automobile criterion intercepted the Chevrolet and Suzuki regression curves at 6.9 and 9.1 m. It was concluded that the optimal speed hump length for automobiles under these conditions was 8.0 m (26 feet). Only the driver seat criterion intercepted its regression curve, meaning there was no suitable speed hump length that would produce low enough levels of discomfort for most passengers in a transit bus.

In Figure 7.5 (H = 75 mm and S = 45 km/h), the automobile criterion did not intercept either regression curve. However, it did land midway between the Chevrolet and Suzuki curves at a length of 9.1 m (30 feet). Again, for the transit bus only the driver seat criterion intercepted its regression curve, meaning there was no suitable length that would produce low enough levels of discomfort for most passengers.

In Figure 7.6 (H = 100 mm and S = 45 km/h), the discomfort criteria passed under all four regression curves. In other words, there were no suitable speed hump lengths within the range of 3.7 to 9.1 m that would produce low enough levels of discomfort for these vehicles.

Figure 7.1
Length Regression Curves for H = 75 mm and S = 25 km/h

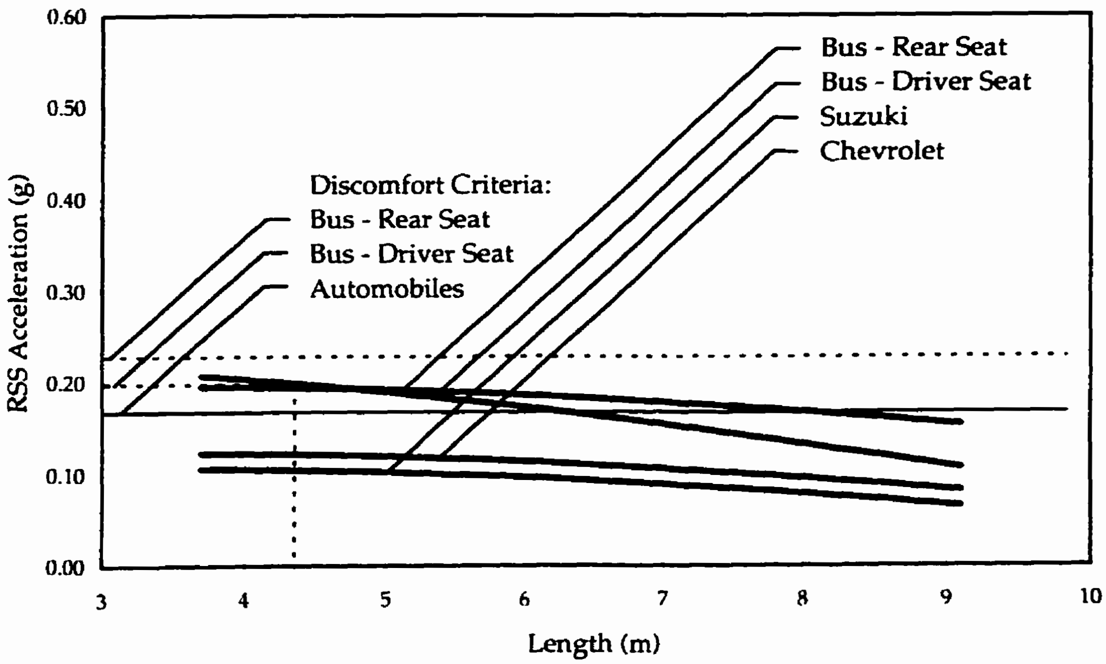


Figure 7.2
Length Regression Curves for H = 100 mm and S = 25 km/h

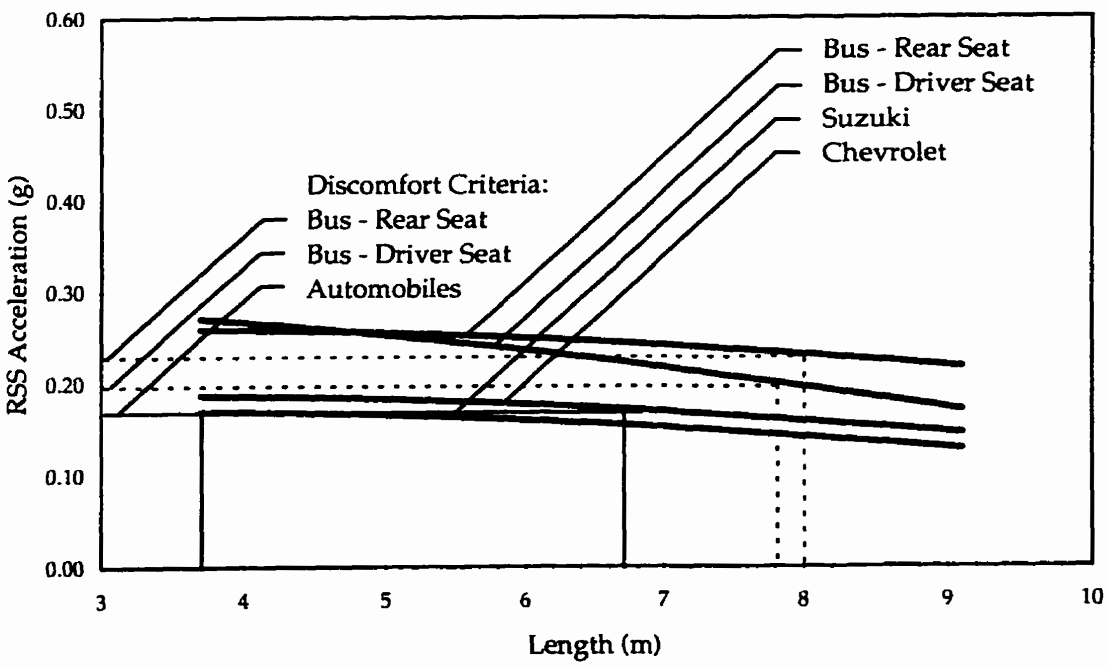


Figure 7.3
Length Regression Curves for H = 75 mm and S = 35 km/h

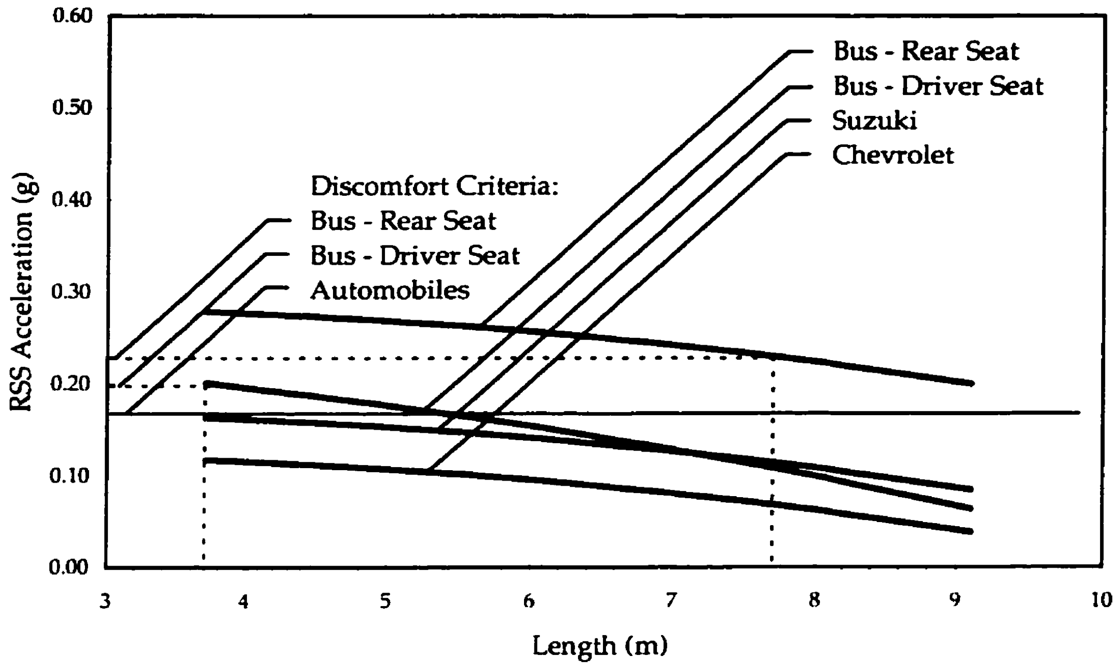


Figure 7.4
Length Regression Curves for H = 100 mm and S = 35 km/h

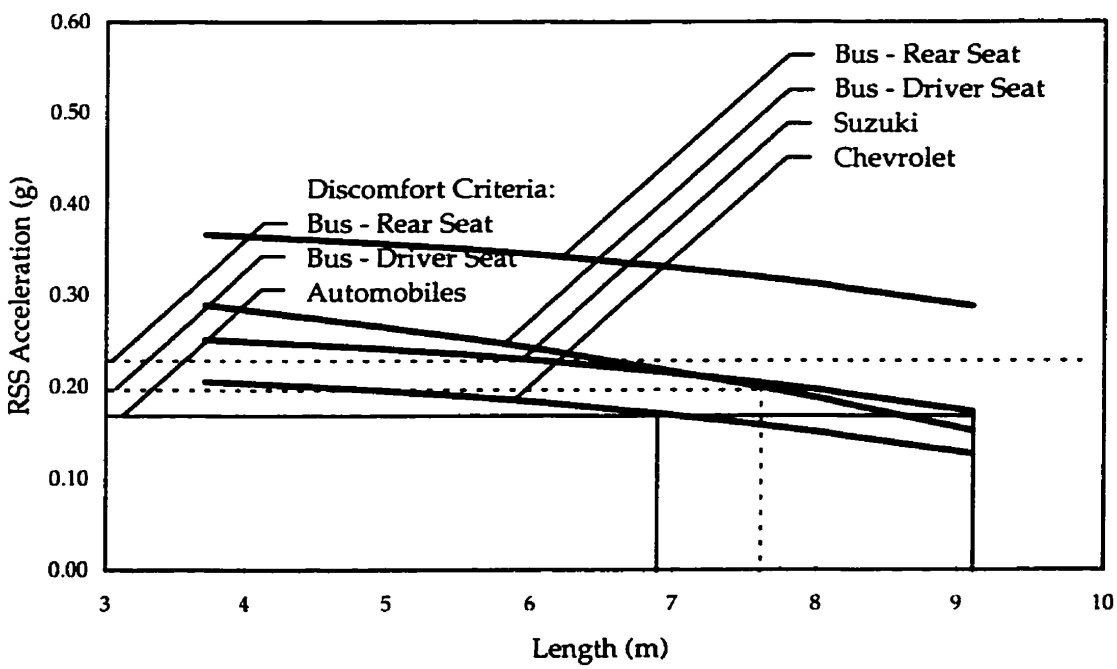


Figure 7.5
Length Regression Curves for H = 75 mm and S = 45 km/h

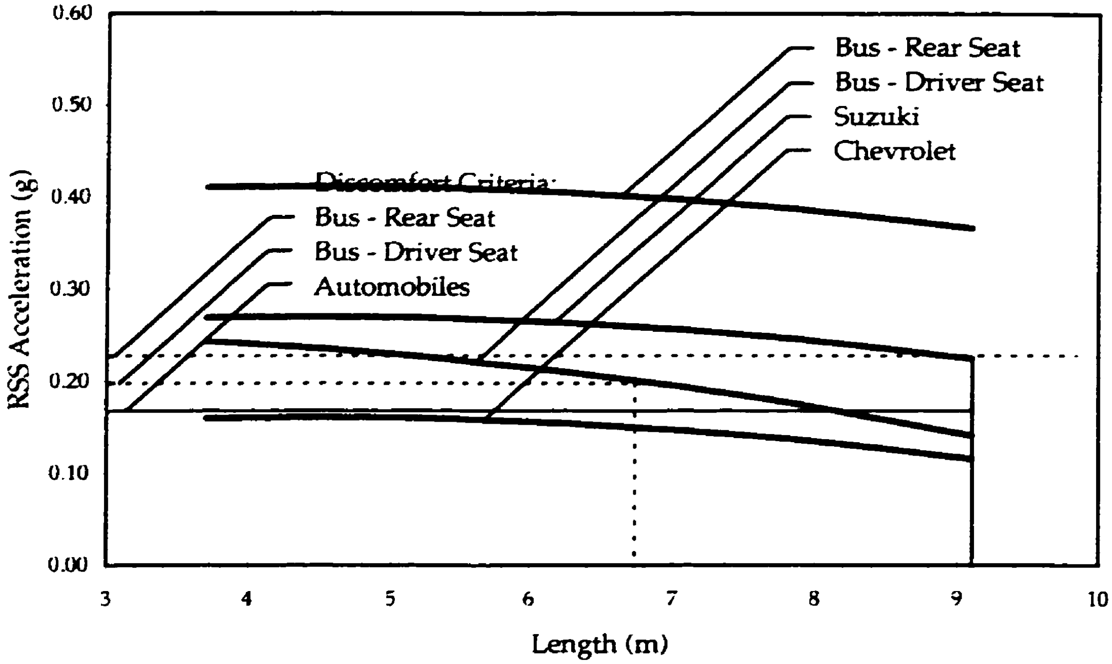
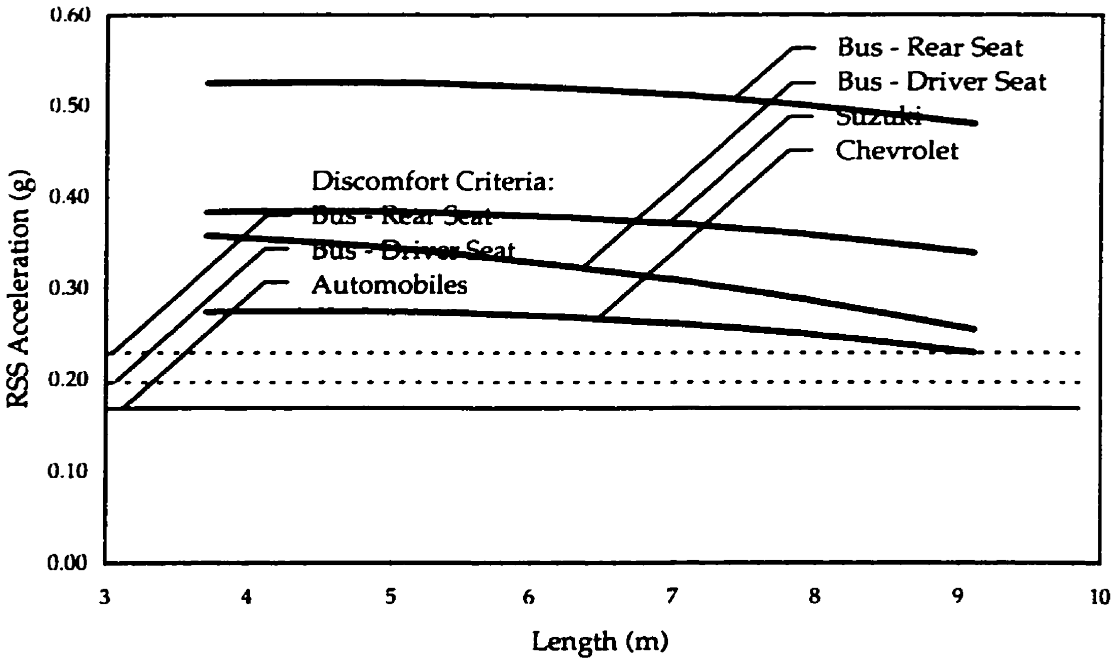


Figure 7.6
Length Regression Curves for H = 100 mm and S = 45 km/h



The optimal speed hump designs are summarized in Tables 7.5 and 7.6. The model predicted that humps designed to reduce transit bus speeds to 25 km/h will permit automobiles to traverse them at 35 km/h. The regression model was sensitive to small changes in discomfort levels, which could result in fairly wide ranges in lengths.

It may be desirable to specify speed humps with lengths easily converted to feet, such as 7.9 m (26 feet) instead of 8.0 m. While humps were not recommended specifically for buses at 45 km/h, they could be employed close to bus stops, where speeds are low.

Table 7.5
Optimal Speed Hump Designs for Automobiles

Hump-Crossing Speed (km/h)	Speed Hump Dimensions (m, mm)
25	5.2 x 100
35	8.0 x 100
45	9.1 x 75

Table 7.6
Optimal Speed Hump Designs for Transit Buses

Hump-Crossing Speed (km/h)	Speed Hump Dimensions (m, mm)
25	7.9 x 100
35	5.7 x 75
45	Not Found

7.2.3 Recommended Designs

On bus routes a compromise would have to be made between the dynamic responses of transit buses and automobiles. Using the regression curves for a hump-crossing speed of 25 km/h, the recommended design was a 6.1 m (20 feet) by 100 mm speed hump. The length is between 5.2 and 7.9 m, but is closer to the former to reflect the greater number of automobiles likely on most streets. Compromise was more difficult at higher speeds due to larger spreads between regression curves. For speeds of 35 km/h, the regression model predicted that the 75 mm high Watts Profile and 8.8 m (29 feet) by 100 mm humps would create acceptable acceleration levels for most light and heavy vehicles.

However, it was observed during the speed study and field tests that Watts Profile humps caused scraping bumpers and licence plates in several vehicles. Due to the objectives of cause no vehicle damage and minimize undue noise or displacement, the Watts Profile hump was not recommended. A better design for bus routes was therefore the 8.8 m by 100 mm hump.

The recommended speed humps for bus routes and non-bus routes are listed in Tables 7.7 and 7.8, and shown in Figure 7.7. These lengths and heights can be recommended for speed cushions as well.

Table 7.7
Recommended Speed Humps for Non-Bus Routes

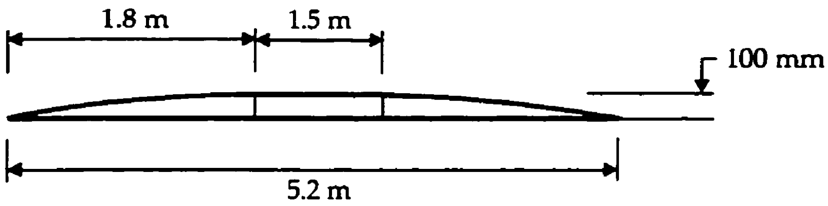
Desired Speed (km/h)	Hump-Crossing Speed (km/h)	Speed Hump Dimensions (m, mm) (ft, in.)
30	25	5.2 x 100 (17 x 4)
40	35	7.9 x 100 (26 x 4)
50	45	9.1 x 75 (30 x 3)

Table 7.8
Recommended Speed Humps for Bus Routes

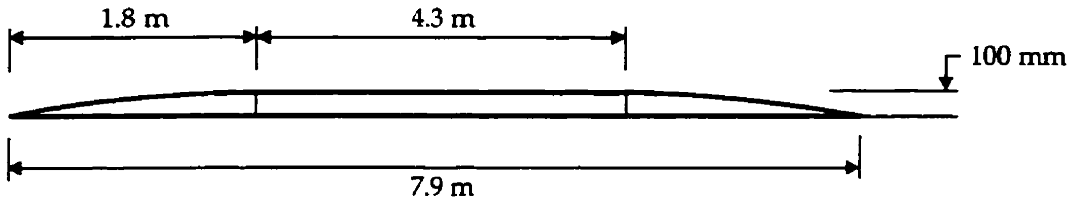
Desired Speed (km/h)	Hump-Crossing Speed (km/h)	Speed Hump Dimensions (m, mm) (ft, in.)
30	25	6.1 x 100 (20 x 4)
40	35	8.8 x 100 (29 x 4)
50	45	See Below

The recommended humps for bus routes were compromises that will slow transit buses and other heavy vehicles to speeds slightly below those specified at the hump. Automobiles will be slowed to speeds slightly above those specified. By working through the regression equations in reverse, it was determined that the 6.1 m by 100 mm and 8.8 m by 100 mm humps will allow automobile speeds to be at most about 5 km/h higher than the hump-crossing speeds.

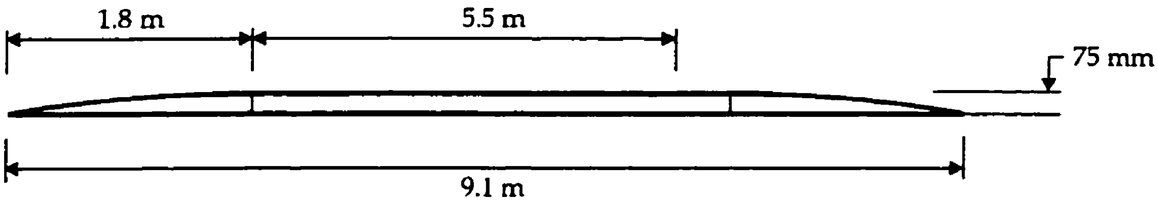
Figure 7.7
Profiles of Recommended Speed Humps



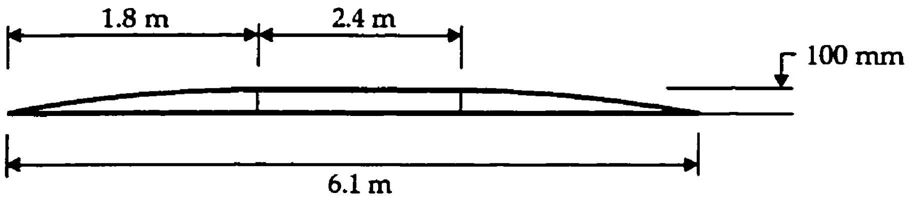
Desired Speed = 30 km/h (Non-Bus Routes)



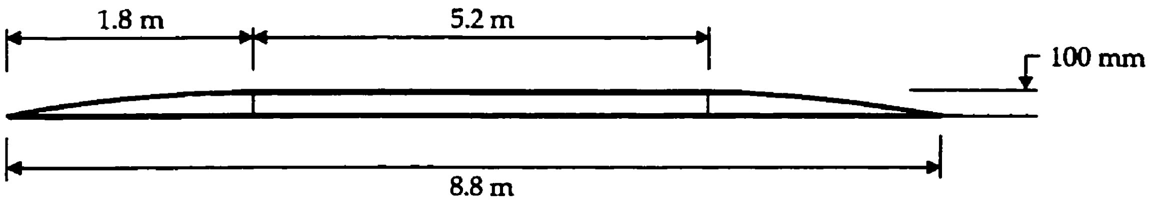
Desired Speed = 40 km/h (Non-Bus Routes)



Desired Speed = 50 km/h (Non-Bus Routes)



Desired Speed = 30 km/h (Bus Routes)



Desired Speed = 40 km/h (Bus Routes)

Where it is not desirable to have *any* vehicles exceeding the desired speed, the humps designed solely for automobiles should be employed. Other vehicles will be slowed to a greater degree, but speed humps could then be used on bus routes having a posted speed of 50 km/h.

Engineering judgement should be used to determine from the regression curves which speed hump designs would make effective traffic calming measures under different conditions. Appropriate streets for traffic calming may have a higher percentage of buses and heavy vehicles, or different desired speeds than those used in this study.

7.2.4 Comments

Unfortunately, there was a high degree of uncertainty with the recommended lengths because of the experimental errors associated with the discomfort criteria. For example, in the case of H = 100 mm and S = 25 km/h the discomfort criterion of 0.17g intercepted the Suzuki regression curve at a length of 3.7 m (see Figure 7.2). The criterion was actually 0.17g ± 0.04g, and its lower bound intercepted the same curve at approximately 9 metres. An even greater degree of uncertainty was associated with discomfort criteria for transit buses.

Another problem was that some of the optimal designs, such as the 5.7 m by 75 mm hump for transit buses at 35 km/h, had as much as a 4 metre spread between the averaged lengths. Speed humps of this design will likely produce ideal levels of discomfort for only some transit bus passengers, with lower levels at the driver seat and much higher levels towards the rear.

On the other hand the stepwise centred regression model, with its adjusted R^2 of 97%, turned out to be very precise. The determination of discomfort was much less precise.

The model was not used to predict lengths below 3.7 m or above 9.1 m, as these were outside the range of speed humps tested. If speed humps as much as 12 metres long had been tested, which exist in the Netherlands and Australia, it is possible an optimal design could have been found for buses and heavy vehicles at 45 km/h.

An opportunity arose to implement one of the recommended designs in an actual project. In the fall of 1997 the Supreme Court of Canada commissioned a traffic calming study to reduce motor vehicle volumes and speeds in the Judicial area, and make it safer for pedestrians. The recommended plan included two speed humps along Vittoria Way adjacent to the Supreme Court Building. Each hump is to be 5.2 m long and 100 mm high, as per the recommended design for non-bus routes at a desired speed of 30 km/h [Braaksma, 1998].

CHAPTER 8 – CONCLUSIONS

8.1 SPEED HUMPS IN PRACTICE

Watts Profile speed humps are the most common type in Canada and around the world. Despite their popularity, it was concluded that longer humps were better suited for speed reduction. The Watts Profile humps at Algonquin College in Ottawa and in Montgomery County, Maryland, induced scraped undercarriages on several vehicles travelling over them between 25 and 35 km/h.

The original Watts tests were only carried out on speed bumps and humps up to 3.7 m long. It has been shown in other studies that longer humps, particularly those that isolate the effects of vehicles entering and exiting the hump, create a more linear relationship between dynamic responses and increasing speeds [Moinat, 1991; Jarvis, 1992].

Seminole Profile speed humps were found to be more effective speed reducers than Watts Profile humps. While the Seminole Profile hump was not specifically recommended in this study, the regression model predicted it would produce RSS accelerations slightly below the discomfort criterion for automobiles for a height of 75 mm, and above the criterion for a height of 100 mm, at hump-crossing speeds of 35 km/h.

The optimal speed hump designs found in this study were compared with those specified for streets in Denmark. There, circular humps 100 mm high and 4.0, 6.5 and 9.5 m long are recommended for automobiles for desired speeds of 30, 40 and 50 km/h [Vejdirektoratet, 1991]. The results of this study indicated that 5.2 and 8.0 m by 100 mm humps, and a 9.1 m by 75 mm hump, would be effective at these speeds for automobiles on streets in North America.

Whatever the final design, speed humps, as with all traffic calming measures, should enhance and not detract from the appearance of a street. If possible, materials should be of high quality and the design should not look temporary. It has been shown the environmental design of traffic calming measures are often the means by which they are ultimately accepted by the public [Pharaoh & Russell, 1991].

It has also been shown that traffic calming measures such as speed humps can affect not only motorist behaviour but motorist attitudes as well. This can hold true even at a distance from the measures.

> "An interesting evaluation of nine streets in Nordrhein-Westfalen (Germany) measured the reactions of drivers to a pair of badminton players in the street. These measurements were made before and after traffic calming measures were introduced. The 'before' observations found that drivers approached the players quickly, slowing at the last second, and often reminding the players of the driver's right of way by sounding the horn. 'After' studies found a big change in behaviour, with drivers slowing as much as 40 metres before the game, and giving the players time to move away" [Pharaoh & Russell, 1991].

8.2 CONCLUSIONS OF STUDY

In many instances streets should be more than just efficient pathways for motor vehicles. They should be safe for pedestrians and children, accessible for cyclists, convenient for shoppers and quiet for residents. As traffic calming measures, speed humps can help improve conditions for these street users.

The purpose of this study was to work towards the development of speed hump standards for Canada. The goal was to recommend hump designs for bus routes and non-bus routes with posted speeds of 30, 40 and 50 km/h. Again, the objectives were:

- reduce automobile and heavy vehicle speeds
- produce acceptable levels of discomfort for vehicle occupants
- result in no vehicle damage
- maximize overall road safety
- minimize vehicle noise and displacement
- minimize installation and maintenance costs.

The optimal speed hump designs all met the first objective of reducing automobile or transit bus speeds to the design speeds. The recommended speed humps for bus routes were compromises that came reasonably close to the optimal designs for automobiles and transit buses.

By meeting the first objective, the recommended speed humps were acceptable to motorists by virtue of the discomfort criteria, and should not result in vehicle damage. They should also be safe if the design speeds are not exceeded by an excessive amount, and should not produce undue noise and displacement.

The last objective was not required, as there were no two designs that met the first five objectives at the same speed. Had it been necessary, a smaller speed hump would have been recommended over a larger one in order to minimize installation and maintenance costs.

The analytical method used in determining the discomfort criteria was deemed successful in finding appropriate acceleration levels for most motorists. The use of RSS accelerations in representing that discomfort was deemed moderately successful, because high amounts of vehicle pitching did not always result in high RSS accelerations.

It can also be concluded that a factorial design is an efficient way to organize a large number of experimental tests, and that multiple regression analysis is an effective way to evaluate the results.

8.3 RECOMMENDATIONS

A number of recommendations can be made through the research and testing carried out in this study:

- that factorial designs be used to set up experiments, and reduce the number of tests required
- that analytical methods be considered to assess subjective measures such as discomfort, to further reduce the number of tests needed
- that measures other than peak vertical accelerations, such as root sum of squares (RSS) accelerations, be used to represent discomfort
- that multiple regression be used to analyze and model experimental results.

It is recommended that these geometric designs be considered as input into Special Project 208, the Transportation Association of Canada (TAC) and Canadian Institute of Transportation Engineers (CITE) traffic calming standards currently under development. The recommended speed humps are again summarized in Tables 8.1 and 8.2.

Table 8.1
Recommended Speed Humps for Non-Bus Routes

Desired Speed (km/h)	Speed Hump Dimensions (m, mm)	(ft, in.)
30	5.2 x 100	(17 x 4)
40	7.9 x 100	(26 x 4)
50	9.1 x 75	(30 x 3)

Table 8.2
Recommended Speed Humps for Bus Routes

Desired Speed (km/h)	Speed Hump Dimensions (m, mm) (ft, in.)
30	6.1 x 100 (20 x 4)
40	8.8 x 100 (29 x 4)
50	See Below

The speed humps are intended for implementation on appropriate bus routes and non-bus routes in Canada. If speed humps are needed to slow automobiles to certain desired speeds on bus routes, the humps recommended for non-bus routes should be used. This will result in lower speeds for buses and other heavy vehicles.

8.4 SUGGESTIONS FOR FURTHER RESEARCH

While random error was low in this study, more data would be helpful in reducing experimental error. The discomfort criteria could be more accurately determined by obtaining speed readings for more existing humps, and in different geographic areas. In particular, many more readings are needed to determine accurate discomfort criteria for transit buses and other heavy vehicles, including large fire trucks and low floor buses. Minivans and sport utility vehicles should be tested as well.

More research should be done on how discomfort is interpreted by the occupants of motor vehicles. Maybe one reason certain motorists purchase large or small automobiles is that they accept different levels of discomfort. Drivers of smaller automobiles, and passengers choosing to sit near the back of transit buses, may do so because they tolerate higher acceleration levels. Perhaps discomfort criteria should be determined separately for certain classes of automobile, rather than averaged for all automobiles. Also, perhaps RSS accelerations in buses should be measured only at the driver seat since it is bus operators, and not passengers, that judge appropriate hump-crossing speeds.

While they are much more difficult to calculate, the use of pitching accelerations should be considered in future speed hump experiments. It was found that large vehicle displacements did not necessarily correspond to high horizontal or vertical accelerations.

An analytical method of comparing hump-crossing speeds to acceleration levels was used in this study. The use of subjective methods, such as a rating system, should also be considered as a means of gaining a different perspective on the assessment of discomfort among individuals.

Since both Watts and Seminole Profile speed humps of the same height have the same ramp slopes, further experiments should be carried out on designs with different ramp slopes, including circular, trapezoidal and sinusoidal humps. Speed humps with more gradual slopes, sinusoidal humps and perhaps speed cushions may be better suited for heavy vehicles.

Finally, the suitability of the speed humps recommended in this study should be verified with on-road tests. A good starting point would be to determine the 85th percentile speed for the planned humps on Vittoria Way adjacent to the Supreme Court of Canada. The speed measurements could be supplemented with tests to determine the best compromises between transit bus comfort and automobile effectiveness for speed humps on bus routes.

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GLOSSARY OF TERMS

85th Percentile Speed – measure of the upper limit of "reasonable" speeds for most traffic conditions, used to establish posted speed limits. Traffic calming measures are usually designed to reduce 85th percentile speeds to predetermined levels.

Accelerometer – a device that measures the instantaneous acceleration of an object.

Bollards – small posts, sometimes flexible, placed between traffic calming measures such as speed humps to prevent automobiles from driving on boulevards or sidewalks.

Bulb – a small curb extension, usually placed at intersections to narrow roadway width and shorten pedestrian crossing distances.

Centred Data – data that is normalized to lessen the effects of multicollinearity.

Chicane – a series of angular curb extensions, usually placed mid-block to narrow roadway width to cause a lateral shift for motorists.

CITE – Canadian Institute of Transportation Engineers.

Confidence Interval – the distance between the mean value of a variable and its actual values.

Dependent Variable – output variable.

Discomfort Criteria – a baseline acceleration level, measured during field tests to compare discomfort without subjective assessments.

Displacement – the vertical motion of a vehicle.

Enter – a method of selecting independent variables for inclusion into a multiple regression model. Variables are "forced" in all at once.

Experimental Error – error attributable to known factors in an experiment.

Factorial Design – a statistical technique that allows independent variables in an experiment to be assessed simultaneously rather than individually. Fewer tests are required, but computational difficulty is increased.

Field Test – an off-road or on-road experiment. Off-road tests are performed under controlled conditions, while on-road tests are carried out on streets with regular traffic.

'g' – acceleration due to gravity (9.81 m/s^2).

Gateway – an entrance feature to a traffic calmed area to signal drivers that they are entering a different environment and need to reduce speeds. It usually consists of vertical members to lessen the appearance of width.

Independent Variable – input variable.

Ischial Tuberosities – lower portions of the hip bone, where vibrations are "felt" by seated individuals.

ISO – International Standards Organization.

ITE – Institute of Transportation Engineers.

Mini-Traffic Circle – a small island built in the middle of an intersection to cause a lateral shift for motorists.

Multicollinearity – identical information about a dependent variable supplied by several independent variables. A redundancy that can reduce precision and obscure important information in a multiple regression model.

Narrowing – an intersection or mid-block reduction in roadway width. This can be achieved by introducing chicanes, bulbs, boulevards, bicycle lanes, pavement markings, etc.

Noise – unwanted sound, sometimes produced by vehicles as they traverse speed humps.

Pitching – the front-to-back motion of a vehicle. This occurs at speed humps when a vehicle has a wheelbase similar to the length of the hump.

Platform – a raised area similar to a raised intersection, but smaller and usually placed mid-block at major pedestrian routes.

Prediction Interval – the distance between an individual value of a variable and its actual values. This interval will be larger than the confidence interval because of random error.

Raised Intersection – a lifting of an entire intersection to sidewalk level. Ramps on the roadway allow smooth but slow passage for vehicles.

Random Error – error attributable to unknown factors in an experiment.

SAE – Society of Automotive Engineers.

SAE Pad – a semi-rigid circular pad, housing an accelerometer, that is sat on by an individual while recording accelerations. It can help isolate variability between test subjects.

Seminole Profile Speed Hump – a speed hump with a 3 metre flat top and circular ramps, 6.7 m in total length and 75 to 100 mm high.

Simulation Study – mathematical or computer experiment using no field tests.

Speed Bump – an abrupt raised section of roadway up to one metre in length, placed at right angles to the flow of traffic.

Speed Cushion – a gradual raised section of roadway narrower than a speed hump, which can be bypassed by wide vehicles.

Speed Hump – a gradual raised section of roadway ranging from 3 to 12 metres in total length and 75 to 100 mm high, placed at right angles to the flow of traffic.

Stepwise – a method of selecting independent variables for inclusion into a multiple regression model. Variables are selected one at a time, and if they do not meet certain criteria they are not included in the model. After each variable is selected all the others are reassessed.

TAC – Transportation Association of Canada.

Traffic Calming – a strategy for changing driver behaviour (speeding, short-cutting, choosing to drive) by physically changing the driving environment. The change is done by constructing geometric features on or near the roadway in such a way that driver behaviour is self-enforced.

Traffic Calming Measures – geometric features constructed on or near the roadway designed to change driver behaviour. The measures could consist of speed humps, raised intersections, chicanes, bulbs, mini-traffic circles, etc.

Watts Profile Speed Hump – a speed hump with a circular profile, 3.7 m in total length and 75 to 100 mm high.

LIST OF SYMBOLS

α – statistical significance level.

ε – random error.

a_i – individual acceleration value per unit of time.

a_n – acceleration long axis *n*.

B_k – the *k*th variable coefficient.

D1, D2 and D3 – dummy variables representing vehicle type. D1 = 1 is the Suzuki Swift, D2 = 1 is the driver seat of the transit bus, and D3 = 1 is the rear seat of the transit bus. D1 = D2 = D3 = 0 is the Chevrolet Monte Carlo.

f – acceleration frequency.

H – speed hump height.

L – speed hump length.

L_c – centred speed hump length.

rmq(a_x) – root-mean-quad acceleration along horizontal axis.

rmq(a_z) – root-mean-quad acceleration along vertical axis.

rms(a_x) – root-mean-square acceleration along horizontal axis.

rms(a_z) – root-mean-square acceleration along vertical axis.

RSQ(a_{xz}) – root sum quad acceleration for the horizontal and vertical axes.

RSS(a_{xz}) – root sum of squares acceleration for the horizontal and vertical axes.

S – hump-crossing speed.

S_c – centred hump-crossing speed.

T – waveform duration.

V – vehicle type.

x_k – the *k*th independent variable.

Y – dependent variable.

APPENDIX A
FACTORIAL DESIGNS

Table A.1
Aliasing for Completely Confounded $4^2 \times 3 \times 2$ Factorial Design

Main Effects

Effect	Defining Factor	Alias
L	$L^3HS^2V^3$	HS^2V^3
L^2	$L^3HS^2V^3$	LHS^2V^3
L^3	$L^3HS^2V^3$	$L^2HS^2V^3$
H	$L^3HS^2V^3$	$L^3S^2V^3$
S	$L^3HS^2V^3$	L^3HV^3
S^2	$L^3HS^2V^3$	L^3HSV^3
V	$L^3HS^2V^3$	L^3HS^2
V^2	$L^3HS^2V^3$	L^3HS^2V
V^3	$L^3HS^2V^3$	$L^3HS^2V^2$

2-Factor Interactions

Effect	Defining Factor	Alias
LH	$L^3HS^2V^3$	S^2V^3
L^2H	$L^3HS^2V^3$	LS^2V^3
L^3H	$L^3HS^2V^3$	$L^2S^2V^3$
LS	$L^3HS^2V^3$	HV^3
L^2S	$L^3HS^2V^3$	LHV^3
L^3S	$L^3HS^2V^3$	L^2HV^3
LS^2	$L^3HS^2V^3$	HSV^3
L^2S^2	$L^3HS^2V^3$	$LHSV^3$
L^3S^2	$L^3HS^2V^3$	L^2HSV^3
LV	$L^3HS^2V^3$	HS^2
L^2V	$L^3HS^2V^3$	LHS^2
L^3V	$L^3HS^2V^3$	L^2HS^2
LV^2	$L^3HS^2V^3$	HS^2V
L^2V^2	$L^3HS^2V^3$	LHS^2V
L^3V^2	$L^3HS^2V^3$	L^2HS^2V
LV^3	$L^3HS^2V^3$	HS^2V^2
L^2V^3	$L^3HS^2V^3$	LHS^2V^2
L^3V^3	$L^3HS^2V^3$	$L^2HS^2V^2$
HS	$L^3HS^2V^3$	L^3V^3
HS^2	$L^3HS^2V^3$	L^3SV^3
HV	$L^3HS^2V^3$	L^3S^2
HV^2	$L^3HS^2V^3$	L^3S^2V
HV^3	$L^3HS^2V^3$	$L^3S^2V^2$
SV	$L^3HS^2V^3$	L^3H
S^2V	$L^3HS^2V^3$	L^3HS
SV^2	$L^3HS^2V^3$	L^3HV
S^2V^2	$L^3HS^2V^3$	L^3HSV
SV^3	$L^3HS^2V^3$	L^3HV^2
S^2V^3	$L^3HS^2V^3$	L^3HSV^2

3-Factor Interactions

Effect	Defining Factor	Alias
LHS	$L^3HS^2V^3$	V^3
L^2HS	$L^3HS^2V^3$	LV^3
L^3HS	$L^3HS^2V^3$	L^2V^3
LHS^2	$L^3HS^2V^3$	SV^3
L^2HS^2	$L^3HS^2V^3$	LSV^3
L^3HS^2	$L^3HS^2V^3$	L^2SV^3
LHV	$L^3HS^2V^3$	S^2
L^2HV	$L^3HS^2V^3$	LS^2
L^3HV	$L^3HS^2V^3$	L^2S^2
LHV^2	$L^3HS^2V^3$	S^2V
L^2HV^2	$L^3HS^2V^3$	LS^2V
L^3HV^2	$L^3HS^2V^3$	L^2S^2V
LHV^3	$L^3HS^2V^3$	S^2V^2
L^2HV^3	$L^3HS^2V^3$	LS^2V^2
L^3HV^3	$L^3HS^2V^3$	$L^2S^2V^2$
LSV	$L^3HS^2V^3$	H
L^2SV	$L^3HS^2V^3$	LH
L^3SV	$L^3HS^2V^3$	L^2H
LS^2V	$L^3HS^2V^3$	HS
L^2S^2V	$L^3HS^2V^3$	LHS
L^3S^2V	$L^3HS^2V^3$	L^2HS
LSV^2	$L^3HS^2V^3$	HV
L^2SV^2	$L^3HS^2V^3$	LHV
L^3SV^2	$L^3HS^2V^3$	L^2HV
LS^2V^2	$L^3HS^2V^3$	HSV
$L^2S^2V^2$	$L^3HS^2V^3$	$LHSV$
$L^3S^2V^2$	$L^3HS^2V^3$	L^2HSV
LSV^3	$L^3HS^2V^3$	HV^2
L^2SV^3	$L^3HS^2V^3$	LHV^2
L^3SV^3	$L^3HS^2V^3$	L^2HV^2
LS^2V^3	$L^3HS^2V^3$	HSV^2

4-Factor Interactions

Effect	Defining Factor	Alias
$LHSV$	$L^3HS^2V^3$	1
L^2HSV	$L^3HS^2V^3$	L
L^3HSV	$L^3HS^2V^3$	L^2
LHS^2V	$L^3HS^2V^3$	S
L^2HS^2V	$L^3HS^2V^3$	LS
L^3HS^2V	$L^3HS^2V^3$	L^2S
$LHSV^2$	$L^3HS^2V^3$	V
L^2HSV^2	$L^3HS^2V^3$	LV
L^3HSV^2	$L^3HS^2V^3$	L^2V
LHS^2V^2	$L^3HS^2V^3$	SV
$L^2HS^2V^2$	$L^3HS^2V^3$	LSV
$L^3HS^2V^2$	$L^3HS^2V^3$	L^2SV
$LHSV^3$	$L^3HS^2V^3$	V^2
L^2HSV^3	$L^3HS^2V^3$	LV^2
L^3HSV^3	$L^3HS^2V^3$	L^2V^2
LHS^2V^3	$L^3HS^2V^3$	SV^2
$L^2HS^2V^3$	$L^3HS^2V^3$	LSV^2
$L^3HS^2V^3$	$L^3HS^2V^3$	L^2SV^2
$L^2S^2V^3$	$L^3HS^2V^3$	$LHSV^2$
$L^3S^2V^3$	$L^3HS^2V^3$	L^2HSV^2
HSV	$L^3HS^2V^3$	L^3
HS^2V	$L^3HS^2V^3$	L^3S
HSV^2	$L^3HS^2V^3$	L^3V
HS^2V^2	$L^3HS^2V^3$	L^3SV
HSV^3	$L^3HS^2V^3$	L^3V^2
HS^2V^3	$L^3HS^2V^3$	L^3SV^2

Indicates Effect is of Experimental Interest

Table A.2

Confounding for $4^2 \times 3 \times 2$ Factorial Design

Treatment Combination	L (i)	H (j)	S (k)	V (l)	$L^3HS^2V^3$ ($3i+j+2k+3l$)	Block (mod 4)
1	0	0	0	0	0	0
2	0	0	0	1	3	3
3	0	0	0	2	6	2
4	0	0	0	3	9	1
5	0	0	1	0	2	2
6	0	0	1	1	5	1
7	0	0	1	2	8	0
8	0	0	1	3	11	3
9	0	0	2	0	4	0
10	0	0	2	1	7	3
11	0	0	2	2	10	2
12	0	0	2	3	13	1
13	1	0	0	0	3	3
14	1	0	0	1	6	2
15	1	0	0	2	9	1
16	1	0	0	3	12	0
17	1	0	1	0	5	1
18	1	0	1	1	8	0
19	1	0	1	2	11	3
20	1	0	1	3	14	2
21	1	0	2	0	7	3
22	1	0	2	1	10	2
23	1	0	2	2	13	1
24	1	0	2	3	16	0
25	2	0	0	0	6	2
26	2	0	0	1	9	1
27	2	0	0	2	12	0
28	2	0	0	3	15	3
29	2	0	1	0	8	0
30	2	0	1	1	11	3
31	2	0	1	2	14	2
32	2	0	1	3	17	1
33	2	0	2	0	10	2
34	2	0	2	1	13	1
35	2	0	2	2	16	0
36	2	0	2	3	19	3
37	3	0	0	0	9	1
38	3	0	0	1	12	0
39	3	0	0	2	15	3
40	3	0	0	3	18	2
41	3	0	1	0	11	3
42	3	0	1	1	14	2
43	3	0	1	2	17	1
44	3	0	1	3	20	0
45	3	0	2	0	13	1
46	3	0	2	1	16	0
47	3	0	2	2	19	3
48	3	0	2	3	22	2
49	0	1	0	0	1	1
50	0	1	0	1	4	0
51	0	1	0	2	7	3
52	0	1	0	3	10	2
53	0	1	1	0	3	3
54	0	1	1	1	6	2
55	0	1	1	2	9	1
56	0	1	1	3	12	0
57	0	1	2	0	5	1
58	0	1	2	1	8	0
59	0	1	2	2	11	3
60	0	1	2	3	14	2
61	1	1	0	0	4	0
62	1	1	0	1	7	3
63	1	1	0	2	10	2
64	0	1	2	0	5	1

Table A.2

Confounding for $4^2 \times 3 \times 2$ Factorial Design

	Factor and Level				Confounding	
Treatment Combination	L (i)	H (j)	S (k)	V (l)	$L^3HS^2V^3$ ($3i+j+2k+3l$)	Block (mod 4)
65	1	1	1	0	6	2
66	1	1	1	1	9	1
67	1	1	1	2	12	0
68	1	1	1	3	15	3
69	1	1	2	0	8	0
70	1	1	2	1	11	3
71	1	1	2	2	14	2
72	1	1	2	3	17	1
73	2	1	0	0	7	3
74	2	1	0	1	10	2
75	2	1	0	2	13	1
76	2	1	0	3	16	0
77	2	1	1	0	9	1
78	2	1	1	1	12	0
79	2	1	1	2	15	3
80	2	1	1	3	18	2
81	2	1	2	0	11	3
82	2	1	2	1	14	2
83	2	1	2	2	17	1
84	2	1	2	3	20	0
85	3	1	0	0	10	2
86	3	1	0	1	13	1
87	3	1	0	2	16	0
88	3	1	0	3	19	3
89	3	1	1	0	12	0
90	3	1	1	1	15	3
91	3	1	1	2	18	2
92	3	1	1	3	21	1
93	3	1	2	0	14	2
94	3	1	2	1	17	1
95	3	1	2	2	20	0
96	3	1	2	3	23	3

Table A.3

Blocking for $4^2 \times 3 \times 2$ Factorial Design

Block 0				Block 1				Block 2				Block 3			
Factor and Level				Factor and Level				Factor and Level				Factor and Level			
L	H	S	V	L	H	S	V	L	H	S	V	L	H	S	V
0	0	0	0	0	0	0	3	0	0	0	2	0	0	0	1
0	0	1	2	0	0	1	1	0	0	1	0	0	0	1	3
0	0	2	0	0	0	2	3	0	0	2	2	0	0	2	1
1	0	0	3	1	0	0	2	1	0	0	1	1	0	0	0
1	0	1	1	1	0	1	0	1	0	1	3	1	0	1	2
1	0	2	3	1	0	2	2	1	0	2	1	1	0	2	0
2	0	0	2	2	0	0	1	2	0	0	0	2	0	0	3
2	0	1	0	2	0	1	3	2	0	1	2	2	0	1	1
2	0	2	2	2	0	2	1	2	0	2	0	2	0	2	3
3	0	0	1	3	0	0	0	3	0	0	3	3	0	0	2
3	0	1	3	3	0	1	2	3	0	1	1	3	0	1	0
3	0	2	1	3	0	2	0	3	0	2	3	3	0	2	2
0	1	0	1	0	1	0	0	0	1	0	3	0	1	0	2
0	1	1	3	0	1	1	2	0	1	1	1	0	1	1	0
0	1	2	1	0	1	2	0	0	1	2	3	0	1	2	2
1	1	0	0	0	1	2	0	1	1	0	2	1	1	0	1
1	1	1	2	1	1	1	1	1	1	1	0	1	1	0	1
1	1	2	0	1	1	2	3	1	1	2	2	1	1	2	1
2	1	0	3	2	1	0	2	2	1	0	1	2	1	0	0
2	1	1	1	2	1	1	0	2	1	1	3	2	1	1	2
2	1	2	3	2	1	2	2	2	1	2	1	2	1	2	0
3	1	0	2	3	1	0	1	3	1	0	0	3	1	0	3
3	1	1	0	3	1	1	3	3	1	1	2	3	1	1	1
3	1	2	2	3	1	2	1	3	1	2	0	3	1	2	3

APPENDIX B
MEASURING ACCELERATIONS

Figure B.1
SAE Pad Detail

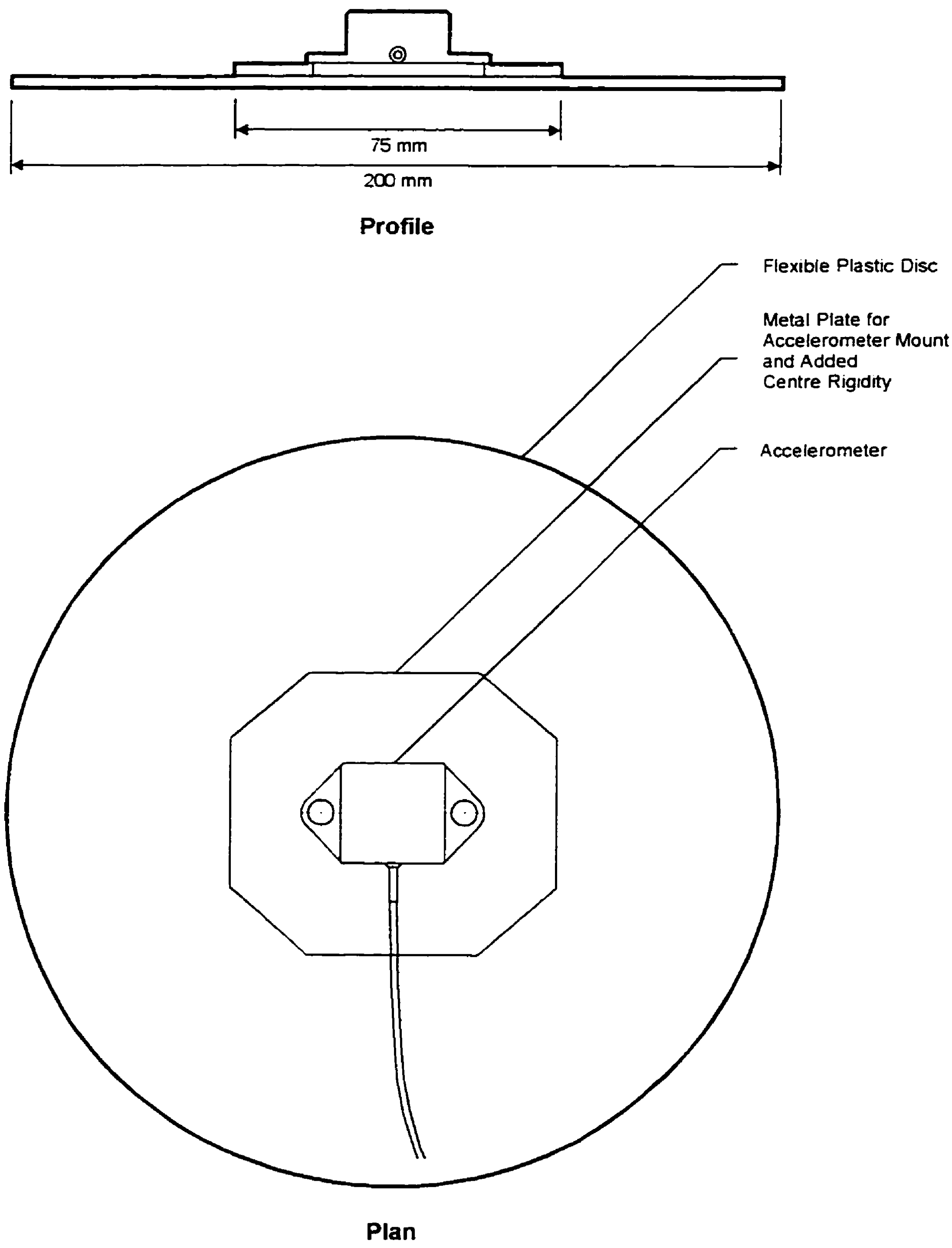


Table B.1
Accelerometer Calibration (X-Axes)

X-Axis Up						X-Axis Down					
x-axis	**y-axis**	**z-axis**	**x-axis**	**y-axis**	**z-axis**	**x-axis**	**y-axis**	**z-axis**	**x-axis**	**y-axis**	**z-axis**
-821	82	-62		⋮		832	118	-57		⋮	
-818	76	-62				824	124	-50			
-806	72	-58	-822	86	-49	820	130	-62	832	130	-46
-806	76	-58	-822	82	-58	828	130	-57	836	130	-46
-806	82	-58	-822	66	-61	828	124	-50	832	130	-46
-806	82	-49	-822	82	-62	832	124	-50	832	130	-50
-818	76	-58	-818	86	-62	832	129	-46	832	120	-53
-822	76	-62	-818	83	-62	832	124	-46	832	120	-58
-822	70	-62	-806	86	-58	832	124	-46	832	128	-54
-822	76	-50	-806	86	-62	832	124	-50	828	124	-46
-822	76	-58	-817	88	-62	832	124	-46	828	130	-50
-822	71	-53	-818	82	-62	832	119	-46	832	130	-57
-822	72	-57	-818	82	-69	836	128	-46	824	129	-62
-818	71	-62	-818	82	-69	832	120	-58	816	118	-62
-822	82	-62	-818	82	-69	832	124	-50	820	115	-53
-822	82	-61	-818	76	-66	832	120	-50	828	124	-46
-822	76	-58	-822	70	-66	832	124	-46	832	118	-46
-822	76	-58	-818	72	-65	832	130	-46	832	124	-46
-822	70	-62	-818	70	-58	832	124	-50	828	128	-46
-822	70	-54	-817	66	-50	828	124	-46	832	129	-46
-818	82	-50	-817	66	-58	828	124	-46	832	128	-46
-818	82	-49	-822	66	-62	832	118	-42	832	130	-46
-822	82	-50	-822	66	-61	832	114	-50	836	128	-42
-822	82	-62	-822	71	-61	828	118	-58	832	124	-33
-806	82	-62	-822	76	-62	832	119	-46	832	120	-34
-821	76	-62	-817	82	-62	832	124	-49	832	118	-38
-822	66	-62	-818	82	-62	832	128	-46	828	114	-46
-823	71	-62	-821	82	-62	836	124	-42	832	114	-50
-822	82	-58	-818	82	-62	832	119	-42	836	114	-50
-822	82	-58	-818	66	-54	836	129	-50	832	108	-58
-818	76	-66	-822	67	-46	836	128	-46	836	115	-50
-806	76	-62	-807	66	-42	840	124	-49	832	128	-50
-806	72	-62	-806	66	-45	832	130	-45	828	118	-58
-806	71	-62	-806	66	-42	832	128	-49	824	114	-53
-806	82	-61	-806	70	-46	832	129	-42	828	114	-46
-822	82	-62	-801	66	-50	832	114	-46	828	114	-46
-822	86	-49	-821	76	-62	832	108	-49	832	115	-57
-822	72	-62	-822	66	-62	832	108	-58	828	119	-58
-822	82	-58	-823	71	-62	832	108	-58	832	124	-45
-837	71	-50	-822	82	-58	832	118	-58	836	128	-57
-822	70	-50	-818	71	-62	832	124	-46	832	124	-62
-822	76	-46	-822	82	-62	832	130	-46	832	130	-57
	⋮		*Averages:*				⋮		*Averages:*		
			-817.1	**77.4**	**-58.2**				**830.5**	**122.2**	**-49.7**

Date: June 8, 1997

Weather: +28 °C, Sunny

Table B.2
Accelerometer Calibration (Y-Axes)

Y-Axis Up						Y-Axis Down					
x-axis	y-axis	z-axis	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
38	930	-69		⋮		-26	-718	-10		⋮	
28	934	-70				-26	-722	-14			
18	930	-66	22	930	-62	-18	-714	-10	-14	-737	12
28	919	-62	18	924	-66	-25	-714	-10	-14	-730	-1
34	924	-62	12	924	-62	-18	-722	-14	-14	-729	-1
34	919	-62	28	930	-62	-18	-722	-14	-14	-722	-2
34	920	-62	34	930	-65	-14	-730	-18	-26	-726	-2
34	924	-62	28	918	-62	-10	-730	-14	-29	-718	-14
34	924	-62	28	920	-62	-14	-730	-26	-26	-702	-14
28	924	-62	28	924	-66	-10	-734	-25	-26	-714	-14
34	934	-62	28	920	-65	-14	-734	-18	-18	-718	-14
28	934	-73	24	915	-66	-22	-730	-14	-21	-718	-14
34	931	-66	18	914	-74	-18	-734	-18	-21	-722	-18
38	930	-62	12	915	-74	-18	-730	-26	-18	-725	-18
34	934	-62	18	908	-65	-18	-722	-14	-26	-734	-18
28	931	-62	22	914	-66	-26	-722	-18	-18	-733	-14
23	934	-62	22	914	-66	-30	-721	-18	-17	-730	-14
22	936	-66	28	915	-66	-26	-722	-30	-18	-730	-10
18	940	-73	28	915	-65	-22	-722	-21	-14	-730	-5
28	934	-77	22	919	-62	-26	-725	-14	-10	-725	-14
19	930	-66	28	924	-62	-26	-730	-14	-9	-730	-10
19	914	-65	28	930	-62	-14	-730	-14	-14	-722	-14
18	903	-66	28	936	-66	-14	-730	-10	-18	-730	-14
18	914	-66	28	935	-62	-14	-730	-9	-14	-730	-14
22	919	-62	34	940	-62	-18	-730	-10	-21	-718	-14
28	930	-62	34	940	-62	-18	-725	-14	-26	-722	-10
18	930	-73	23	934	-62	-13	-730	-14	-21	-726	-1
34	930	-66	24	934	-62	-14	-730	-26	-26	-730	-14
23	930	-62	23	934	-73	-10	-738	-14	-25	-729	-18
23	930	-62	23	934	-65	-14	-738	-14	-14	-722	-14
28	924	-66	22	930	-62	-14	-738	-18	-14	-722	-18
28	924	-66	28	930	-66	-14	-734	-18	-26	-721	-26
28	930	-62	34	930	-62	-18	-730	-17	-18	-718	-18
34	930	-62	28	924	-62	-14	-718	-14	-21	-722	-18
22	930	-62	28	924	-62	-18	-722	-18	-21	-718	-25
18	934	-62	28	924	-66	-18	-722	-22	-18	-722	-26
22	934	-62	19	930	-66	-1	-722	-14	-14	-718	-30
22	930	-65	24	930	-74	-10	-722	-14	-14	-721	-21
28	918	-62	28	930	-74	-18	-730	-14	-18	-729	-25
24	914	-62	28	935	-74	-18	-730	-13	-14	-730	-18
24	920	-62	34	934	-78	-25	-734	-14	-14	-734	-14
24	930	-77	40	940	-69	-21	-738	-10	-14	-722	-14
	⋮		*Averages:* 26.6	928.2	-65.8		⋮		*Averages:* -17.1	-723	-17.2

Date: June 8, 1997

Weather: +28 °C, Sunny

Table B.3
Accelerometer Calibration (Z-Axes)

Z-Axis Up						Z-Axis Down					
x-axis	**y-axis**	**z-axis**	**x-axis**	**y-axis**	**z-axis**	**x-axis**	**y-axis**	**z-axis**	**x-axis**	**y-axis**	**z-axis**
92	66	-854		⋮		-90	130	784		⋮	
99	70	-854				-62	139	772			
98	66	-854	98	70	-870	-66	135	772	-78	146	776
98	66	-854	99	76	-869	-66	142	772	-82	142	780
98	70	-854	103	70	-870	-82	130	772	-78	142	784
98	76	-856	98	66	-869	-78	143	772	-78	134	784
98	76	-854	98	66	-866	-78	143	768	-81	142	784
92	70	-854	98	66	-866	-82	142	768	-78	142	780
98	70	-854	99	66	-870	-78	146	768	-82	142	780
98	76	-854	98	70	-855	-78	146	780	-78	146	780
98	76	-866	88	66	-854	-77	139	784	-78	142	784
98	67	-854	92	70	-854	-78	139	780	-78	135	780
92	66	-840	92	66	-854	-82	142	788	-78	134	784
92	66	-850	88	66	-855	-94	142	784	-78	139	784
92	66	-854	92	66	-856	-90	130	784	-82	135	784
87	66	-854	98	66	-854	-78	130	796	-78	146	784
92	66	-854	88	66	-866	-78	130	788	-74	146	772
82	66	-854	82	71	-870	-85	130	784	-78	142	784
86	66	-854	76	76	-854	-78	130	780	-81	134	784
86	70	-854	76	67	-854	-78	134	780	-78	139	784
92	67	-854	87	70	-854	-78	142	776	-78	138	792
92	66	-854	86	66	-854	-78	143	768	-78	142	796
98	66	-854	86	60	-870	-78	135	772	-78	134	792
102	66	-855	88	66	-870	-90	142	768	-74	135	788
88	66	-866	92	70	-855	-86	142	780	-78	139	780
92	66	-866	98	66	-855	-90	146	788	-78	146	780
98	66	-854	86	66	-865	-94	139	788	-78	146	772
99	66	-866	82	66	-854	-90	130	784	-78	146	772
98	67	-854	86	66	-866	-86	142	784	-78	142	780
87	72	-854	98	66	-856	-89	131	784	-85	139	772
92	66	-854	92	66	-854	-82	131	784	-81	142	780
98	72	-850	92	60	-854	-90	143	784	-89	143	772
92	70	-854	92	60	-854	-78	134	784	-90	142	784
98	67	-854	92	66	-854	-81	135	788	-86	143	780
88	66	-854	99	66	-854	-90	139	784	-90	142	784
88	60	-854	102	66	-854	-82	146	784	-89	142	784
98	66	-854	98	72	-854	-78	146	780	-90	134	796
98	66	-854	99	76	-854	-82	146	772	-90	130	788
82	76	-866	98	66	-854	-78	146	772	-82	130	784
98	72	-854	98	66	-866	-78	146	780	-82	134	780
98	76	-856	98	66	-854	-81	146	784	-78	131	784
98	66	-866	92	70	-854	-82	146	780	-78	130	788
	⋮		*Averages:*				⋮		*Averages:*		
			95.1	**68.3**	**-860.3**				**-82.6**	**138.7**	**782.2**

Date: June 8, 1997

Weather: +28 °C, Sunny

Exhibit B.1
Sample Conversion of Accelerometer Output

Pilot study example using the Watts Profile speed hump at Algonquin College:

For the first test run at 19 km/h, the unadjusted maximum and minimum horizontal (x-axis) and vertical (z-axis) accelerations are shown below. The peak accelerations are adjusted by interpolation using the calibration values from Tables B.1 to B.3.

Time (s)	Horiz. Accel.	Vert. Accel.
1.566	188	924
1.567	200	912
1.568	208	895
1.569	196	894
1.570	196	891
2.012	2	1083
2.013	3	1083
2.014	2	1086
2.015	6	1078
2.016	2	1079

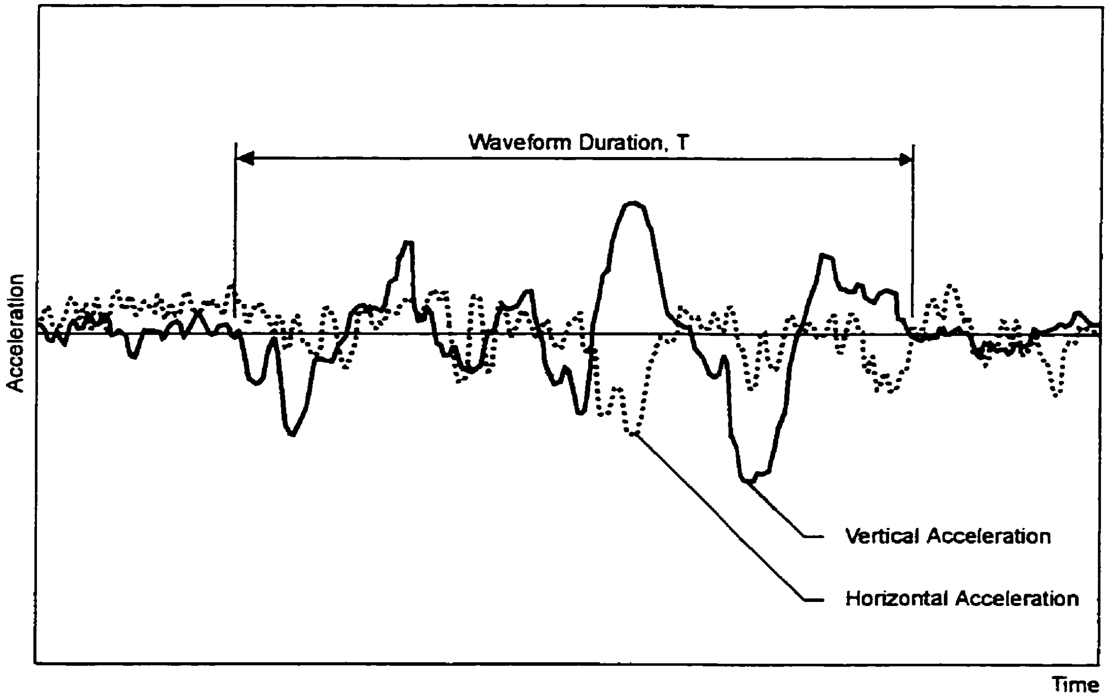
$$\frac{2\,(830.5 - 208)}{(830.5 + 817.1)} - 1 = -0.24g$$

$$\frac{2\,(782.2 - 1086)}{(782.2 + 860.3)} = -0.37g$$

Exhibit B.2
Sample Determination of Waveform Duration

The calculation of rms and rmq accelerations depend on the duration of the acceleration waveforms.

The duration period was taken as the time from when the speed hump was entered (the initial negative peak) to when the vertical acceleration waveform crossed the origin after decaying to half its peak value.



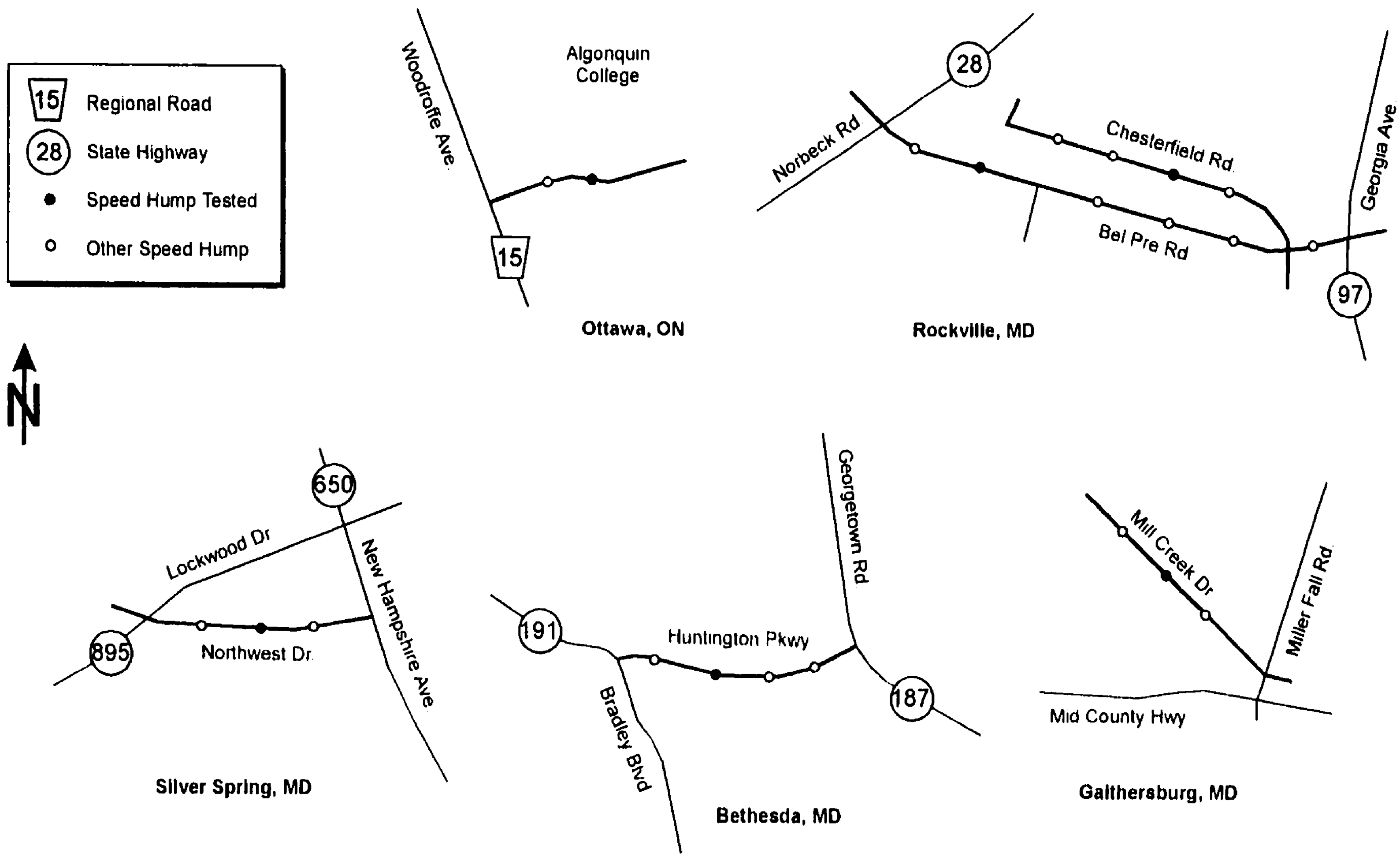
APPENDIX C
DETERMINING DISCOMFORT

Table C.1
Vehicle Speeds for Algonquin College Pilot Study, Ottawa, Ontario

West Speed Hump						East Speed Hump					
Eastbound			Westbound			Eastbound			Westbound		
Speed (km/h)	Vehicle (If Not Car)	Comments	Speed (km/h)	Vehicle (If Not Car)	Comments	Speed (km/h)	Vehicle (If Not Car)	Comments	Speed (km/h)	Vehicle (If Not Car)	Comments
29			18			18	Para Transit	No undue noise	22		
31	Pickup		26			24			21		
22			25			24	Pickup		25		
23	Minivan		25			21			42		No adverse effects
23			32		Scraped bumper	26			26		
24			20			25			22		
25			19			19	Sport Utility		24		
29			22			23			21		
22			28			15			26		
25	Para Transit	No undue noise	26			19			21		
21			23			21	Minivan		19		
25			22			25			21		
26			22			26			24	Pickup	
21			21			21			19		
25			24			22			35		Scraped bumper
26			26	Minivan		20			28	Pickup	
22			26			24			21		
17	24' Van	No undue noise	23			20			19		
20			27			26			28		
29			23			26			19		
23			22			17	School Bus	No undue noise	23		
24			19			23	Pickup		20		
27			27			25			19		
19			26			20			22		
23			26	Minivan		21			23		
20			24			25			26		
26			29	Sport Utility		24			25		
27			26			21			26		
26			26			22			25		
26			27			22			21		

Date: Nov. 19, 1996 Weather: +3 °C, Overcast Road Surface: Mainly Dry Time Period: 1:20 -- 3:30 pm

Figure C.1
Existing Speed Hump Locations



C2

Table C.2
Peak Acceleration Data for Algonquin College Pilot Study

				Acceleration Readings				Calibrated Accelerations (g)				Peak Accelerations (g)		
Run	Undulation	Speed (km/h)	Vehicle	Min. a_x	Max. a_x	Min. a_z	Max. a_z	Max. a_x	Min. a_x	Max. a_z	Min. a_z	Peak a_x	Peak a_z	Comments
1	Speed Hump	19	Suzuki	-128	208	504	1086	0.164	-0.244	0.339	-0.370	0.244	0.370	
2	Speed Hump	19	Suzuki	-114	232	508	1012	0.147	-0.273	0.334	-0.280	0.273	0.334	
3	Speed Hump	23	Suzuki	-161	220	522	1260	0.204	-0.259	0.317	-0.582	0.259	0.582	
4	Speed Hump	23	Suzuki	-196	180	534	1216	0.246	-0.210	0.302	-0.528	0.246	0.528	
5	Speed Hump	25	Suzuki	-213	378	514	1276	0.267	-0.451	0.327	-0.601	0.451	0.601	
6	Speed Hump	25	Suzuki	-302	366	460	1228	0.375	-0.436	0.392	-0.543	0.436	0.543	
7	Level Crossing	60	Suzuki	-278	366	522	1272	0.346	-0.436	0.317	-0.596	0.436	0.596	
8	Speed Bump	15	Suzuki	-398	586	366	1244	0.491	-0.703	0.507	-0.562	0.703	0.562	

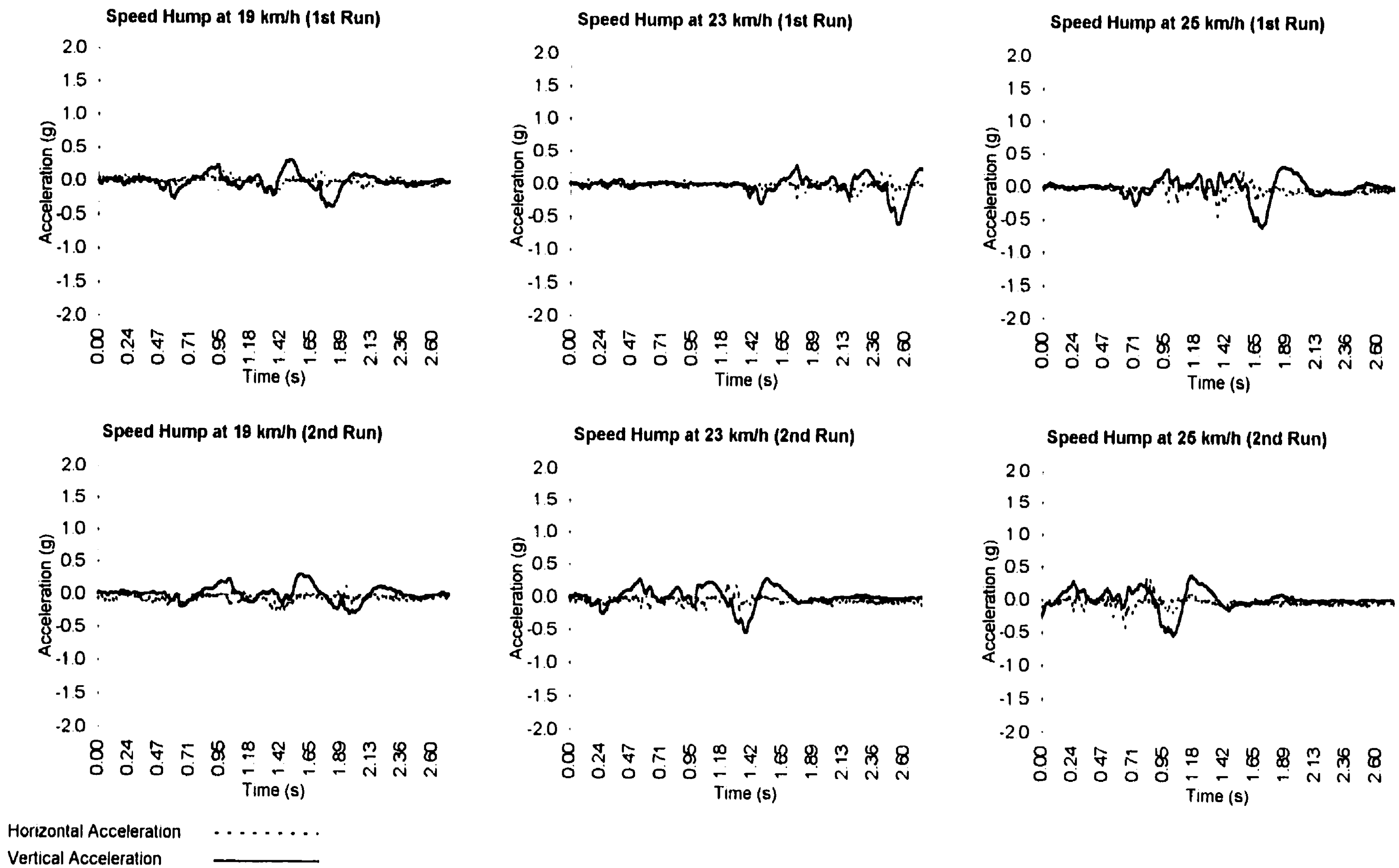
Date: Aug. 17-18, 1997 Road Surface: Dry Weather +24 °C, Sunny

Table C.3
RMS and RMQ Acceleration Data for Algonquin College Pilot Study

					RMS Accelerations (g)				RMQ Accelerations (g)				Root Sums (g)	
Run	Undulation	Speed (km/h)	Vehicle	Time (s)	Avg. a_x^2	Avg. a_z^2	rms (a_x)	rms (a_z)	Avg. a_x^4	Avg. a_z^4	rmq (a_x)	rmq (a_z)	RSS	RSQ
1	Speed Hump	19	Suzuki	1.46	0.0039	0.0248	0.052	0.130	0.0001	0.0018	0.091	0.187	0.099	0.134
2	Speed Hump	19	Suzuki	1.57	0.0081	0.0204	0.072	0.114	0.0002	0.0011	0.106	0.163	0.095	0.120
3	Speed Hump	23	Suzuki	1.37	0.0054	0.0335	0.063	0.156	0.0001	0.0046	0.092	0.241	0.119	0.171
4	Speed Hump	23	Suzuki	1.60	0.0062	0.0316	0.062	0.141	0.0001	0.0031	0.089	0.210	0.109	0.150
5	Speed Hump	25	Suzuki	1.45	0.0100	0.0454	0.083	0.177	0.0006	0.0072	0.143	0.265	0.138	0.191
6	Speed Hump	25	Suzuki	1.38	0.0106	0.0437	0.088	0.178	0.0007	0.0058	0.150	0.255	0.140	0.185
7	Level Crossing	60	Suzuki	0.98	0.0092	0.0377	0.097	0.196	0.0005	0.0051	0.150	0.269	0.155	0.194
8	Speed Bump	15	Suzuki	0.80	0.0299	0.0481	0.193	0.245	0.0057	0.0070	0.291	0.306	0.221	0.251

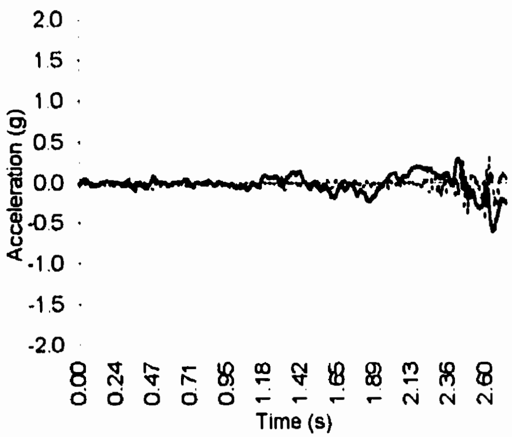
Date: Aug. 17-18, 1997 Road Surface: Dry Weather: +24 °C, Sunny

Figures C.2 to C.7
Acceleration Plots for Algonquin College Pilot Study

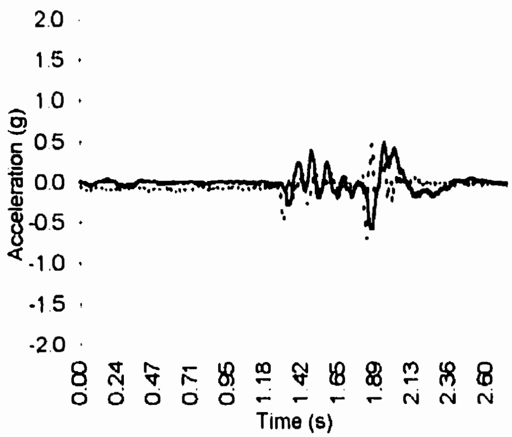


Figures C.8 and C.9
Acceleration Plots for Algonquin College Pilot Study

Railway Level Crossing at 60 km/h



Speed Bump at 15 km/h



Horizontal Acceleration . . . .
Vertical Acceleration ————

Table C.4
Automobile Speeds for Algonquin College, Ottawa, Ontario

Watts Profile Hump -- 3.7 m x 100 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments
24		26	
24		25	
21		26	
26		21	
25		25	
19		23	
23		19	
15		22	
17		20	
21		21	
24		19	
25		21	
26		18	
21		25	
22		24	
20		19	
24		21	
26		19	
20		19	
21		21	
18		26	
26		21	
17		24	
23		22	
25		22	
20		26	
15		42	No adverse effects
21		25	
22		21	
19		20	

Watts Profile Hump -- 3.7 m x 100 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments

For Each Direction...			
Mean Speed =	22 km/h	Mean Speed =	23 km/h
85th Percentile Speed =	25 km/h	85th Percentile Speed =	26 km/h
15th Percentile Speed =	18 km/h	15th Percentile Speed =	19 km/h
Standard Deviation =	3 km/h	Standard Deviation =	4 km/h
Totalling for Both Directions...			
		Mean Speed =	**22 km/h**
		85th Percentile Speed =	**25 km/h**
		15th Percentile Speed =	**19 km/h**
		Standard Deviation =	**4 km/h**

Date: Nov 19, 1996 Weather: +3 °C, Overcast Road Surface: Mainly Dry Time Period: 3:00 -- 3:50 pm

Table C.5
Automobile and Bus Speeds for Bel Pre Road, Rockville, Maryland

Seminole Profile Hump -- 6.7 m x 80 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments
36		46	
35		26	
35		38	
40		29	
43		36	
35		27	
32		37	
28		43	
35		20	
22		37	
56	No adverse effects	37	
59	No adverse effects	31	
30		44	
22		39	
36		43	
36		43	
39		38	
39		44	
35		33	
43		39	
35		46	
39		33	
38		45	
29		22	
44		48	
31		52	No adverse effects
37		44	
34		34	
35		26	
41		53	No adverse effects

Seminole Profile Hump -- 6.7 m x 80 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments
34	Metro Bus	32	Metro Bus
33	Metro Bus	36	Metro Bus
24	Metro Bus	27	Metro Bus
30	Metro Bus	25	Metro Bus
27	Metro Bus	27	Metro Bus

Totalling for Both Directions

Mean Speed for Buses = 30 km/h

For Each Direction

Eastbound		Westbound	
Mean Speed =	37 km/h	Mean Speed =	38 km/h
85th Percentile Speed =	42 km/h	85th Percentile Speed =	46 km/h
15th Percentile Speed =	30 km/h	15th Percentile Speed =	28 km/h
Standard Deviation =	8 km/h	Standard Deviation =	8 km/h

Totalling for Both Directions

Mean Speed = 37 km/h
85th Percentile Speed = 44 km/h
15th Percentile Speed = 29 km/h
Standard Deviation = 8 km/h

Date: Jan. 15, 1997 Weather: +5 °C, Sunny Road Surface: Dry Time Period: 9:40 -- 10:30 am

Table C.6
Automobile Speeds for Chesterfield Road, Rockville, Maryland

Watts Profile Hump -- 3.7 m x 80 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments
24		24	
32		26	
24		27	Scraped licence plate
17		21	
20		35	
21		24	
22		19	
26		25	
18		21	
23		20	
32		26	
22		19	
19		20	
25		23	
19		17	
31		17	
22		24	
17		26	
23		19	
23		22	
30	Scraped bumper	24	
35		27	
26		24	
24		25	
23		19	
26		22	
20		19	
23		21	
18		19	
28		23	

Watts Profile Hump -- 3.7 m x 80 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments

For Each Direction

Eastbound		Westbound	
Mean Speed =	24 km/h	Mean Speed =	23 km/h
85th Percentile Speed =	29 km/h	85th Percentile Speed =	26 km/h
15th Percentile Speed =	19 km/h	15th Percentile Speed =	19 km/h
Standard Deviation =	5 km/h	Standard Deviation =	4 km/h

Totalling for Both Directions

Mean Speed = 23 km/h
85th Percentile Speed = 28 km/h
15th Percentile Speed = 19 km/h
Standard Deviation = 4 km/h

Date. Jan. 15, 1997 Weather. +5 °C, Sunny Road Surface Mainly Dry Time Period: 10:50 am -- 12:40 pm

8

Table C.7
Automobile Speeds for Northwest Drive, Silver Spring, Maryland

Watts Profile Hump -- 3.7 m x 80 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments
20		33	
15		24	
26		23	
21		27	
37		32	
32		38	
27		13	
22		17	
20		37	
27		29	
22		21	
15		22	
18		23	
25		29	
29		28	
15		33	
25		27	
26		23	
28		17	
20		33	
25		28	
24		19	
23		20	
21		22	
26		22	
28		28	
26		25	
24		19	
31		21	
26		34	

Watts Profile Hump -- 3.7 m x 80 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments

For Each Direction...

	Eastbound	Westbound
Mean Speed =	24 km/h	26 km/h
85th Percentile Speed =	28 km/h	33 km/h
15th Percentile Speed =	20 km/h	19 km/h
Standard Deviation =	5 km/h	6 km/h

Totalling for Both Directions...

Mean Speed = 25 km/h
85th Percentile Speed = 31 km/h
15th Percentile Speed = 20 km/h
Standard Deviation = 6 km/h

Date: Jan. 15, 1997 Weather: +6 °C, Sunny Road Surface: Partly Dry Time Period: 1:20 -- 3:00 pm

Table C.8

Automobile Speeds for Huntington Parkway, Bethesda, Maryland

Seminole Profile Hump -- 6.7 m x 100 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments
24		34	
26		22	
34		24	
30		46	
28		35	
22		27	
32		37	
42		24	
31		36	
33		35	
28		40	
28		43	
37		27	
40		37	
39		30	
32		28	
30		32	
25		48	
24		41	Scraped licence plate
18		32	
33		36	
34		43	
44		37	
42		19	
22		31	
31		43	
27		23	
35		28	
36		24	
26		34	

Seminole Profile Hump -- 6.7 m x 100 mm			
Eastbound		Westbound	
Speed (km/h)	Comments	Speed (km/h)	Comments

For Each Direction...

Eastbound		Westbound	
Mean Speed =	31 km/h	Mean Speed =	33 km/h
85th Percentile Speed =	38 km/h	85th Percentile Speed =	42 km/h
15th Percentile Speed =	24 km/h	15th Percentile Speed =	24 km/h
Standard Deviation =	6 km/h	Standard Deviation =	7 km/h

Totalling for Both Directions

Mean Speed = 32 km/h
85th Percentile Speed = 40 km/h
15th Percentile Speed = 24 km/h
Standard Deviation = 7 km/h

Date: Jan. 15, 1997 Weather: +6 °C, Sunny Road Surface: Dry Time Period: 3:30 -- 4:30 pm

Table C.9

Automobile Speeds for Mill Creek Road, Gaithersburg, Maryland

Watts Profile Hump -- 3.7 m x 75 mm			
Northbound		Southbound	
Speed (km/h)	Comments	Speed (km/h)	Comments
27		16	
24		21	
22		25	
19		20	
20		27	
24		32	Scraped bumper
21		24	
29		28	
24		21	
23		26	
18		23	
22		24	
24		23	
26		24	
23		27	
18		40	No adverse effects
18		37	
23		24	
18		25	
18		22	
28		23	
31		22	
18		21	
29		28	
25		25	
21		25	
19		29	
25		18	
26		24	
21		20	

Watts Profile Hump -- 3.7 m x 75 mm			
Northbound		Southbound	
Speed (km/h)	Comments	Speed (km/h)	Comments

For Each Direction...

Northbound		Southbound	
Mean Speed =	23 km/h	Mean Speed =	25 km/h
85th Percentile Speed =	27 km/h	85th Percentile Speed =	28 km/h
15th Percentile Speed =	18 km/h	15th Percentile Speed =	21 km/h
Standard Deviation =	4 km/h	Standard Deviation =	5 km/h

Totalling for Both Directions...

Mean Speed = 24 km/h

85th Percentile Speed = 27 km/h

15th Percentile Speed = 20 km/h

Standard Deviation = 4 km/h

Date: Jan. 16, 1997 | Weather: +8 °C, Mainly Sunny | Road Surface: Wet | Time Period: 10:30 am -- 12:50 pm

APPENDIX D
FIELD TESTING

Figure D.1
3" High Ramp Sections

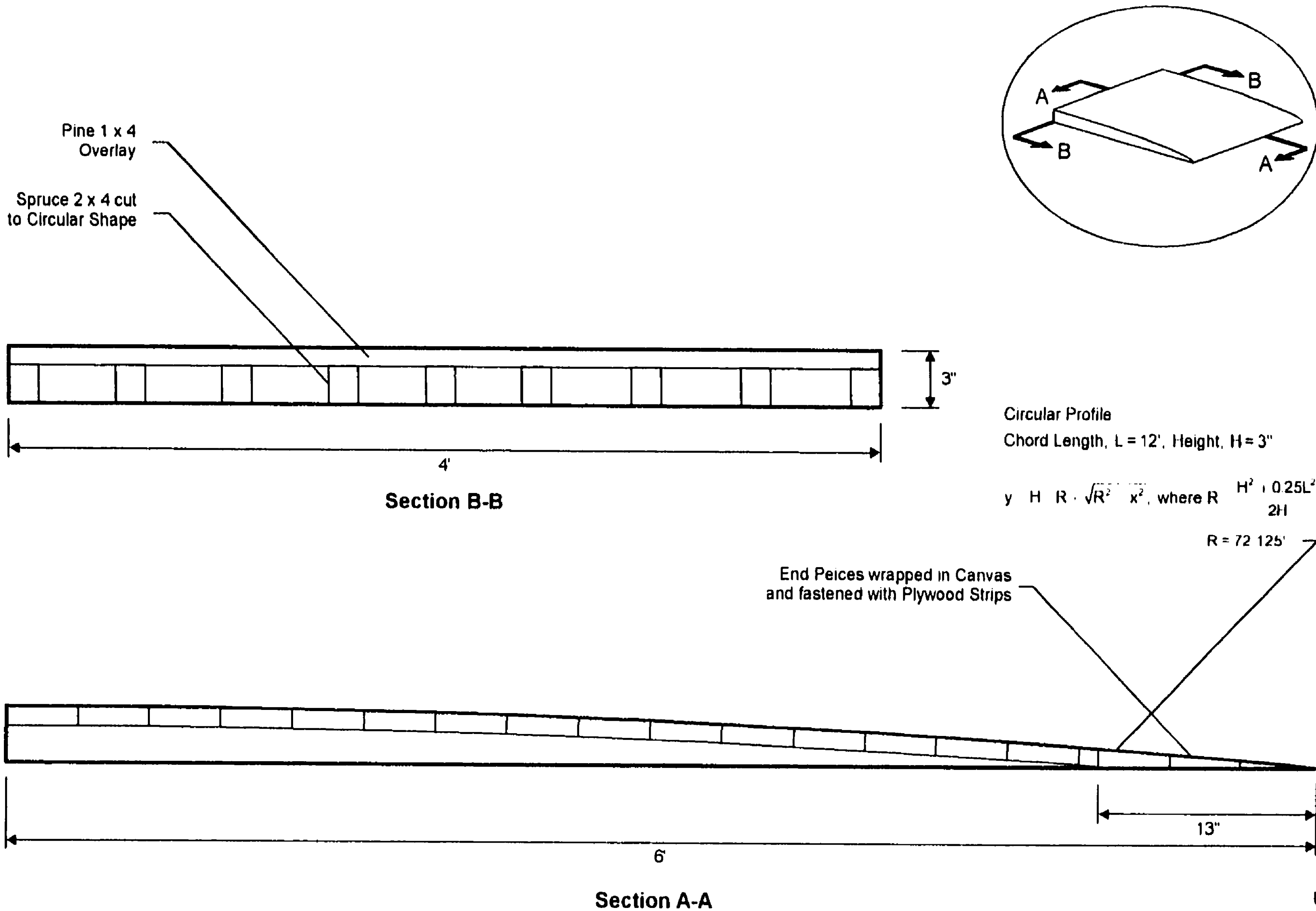


Figure D.2
4" High Ramp Sections

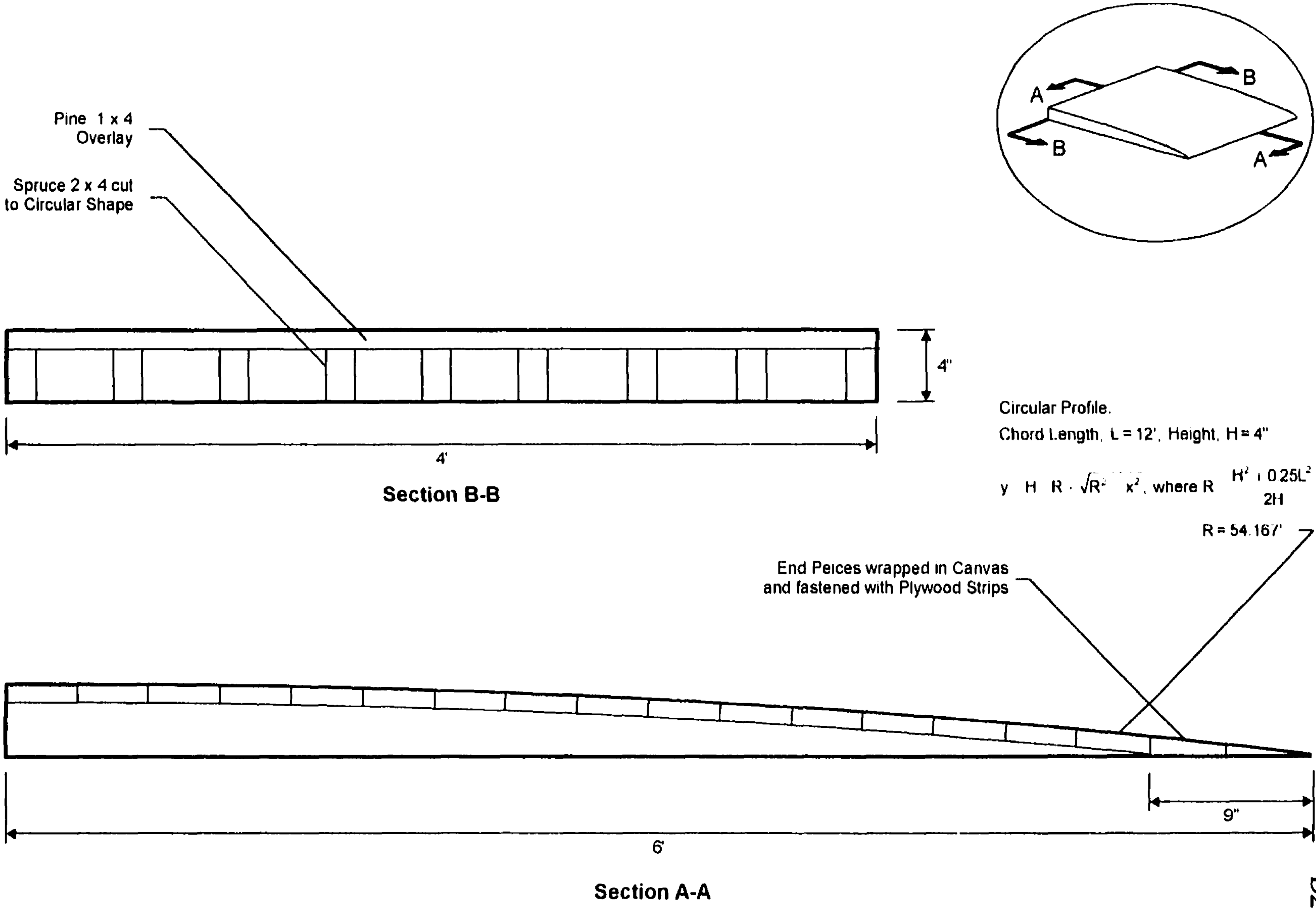


Figure D.3
Test Hump Plan Views (3" and 4" High)

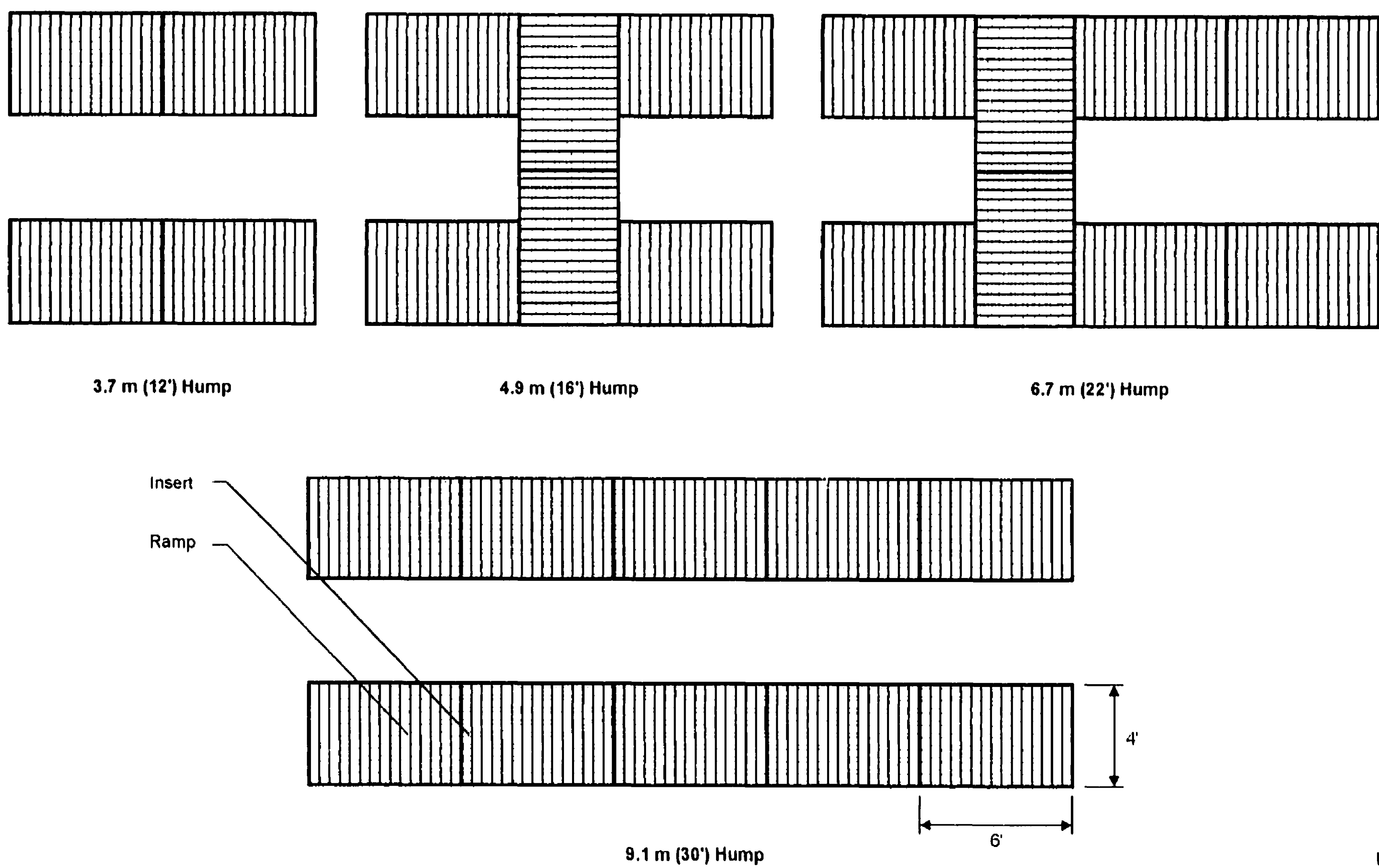


Table D.1

Peak Acceleration Data for Automobile Test Runs

Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Acceleration Readings: Min. a_x	Acceleration Readings: Max. a_x	Acceleration Readings: Min. a_z	Acceleration Readings: Max. a_z	Calibrated Accelerations (g): Max. a_x	Calibrated Accelerations (g): Min. a_x	Calibrated Accelerations (g): Max. a_z	Calibrated Accelerations (g): Min. a_z	Peak Accelerations (g): Peak a_x	Peak Accelerations (g): Peak a_z	Comments
1	3.7 x 75	20	Suzuki	-53	164	531	1024	0.072	-0.191	0.306	-0.294	0.191	0.306	
2	3.7 x 75	20	Suzuki	-62	140	515	1046	0.083	-0.162	0.325	-0.321	0.162	0.325	
3	3.7 x 75	24	Suzuki	-118	184	504	1094	0.151	-0.215	0.339	-0.380	0.215	0.380	
4	3.7 x 75	24	Suzuki	-90	188	500	1070	0.117	-0.220	0.344	-0.350	0.220	0.350	
5	3.7 x 75	25	Suzuki	-106	192	512	1111	0.137	-0.225	0.329	-0.400	0.225	0.400	
6	3.7 x 75	25	Suzuki	-128	184	508	1099	0.164	-0.215	0.334	-0.386	0.215	0.386	
7	3.7 x 75	29	Suzuki	-73	208	480	1212	0.097	-0.244	0.368	-0.523	0.244	0.523	
8	3.7 x 75	29	Suzuki	-98	224	452	1268	0.127	-0.264	0.402	-0.592	0.264	0.592	
9	3.7 x 75	45	Suzuki	-208	298	168	1378	0.261	-0.354	0.748	-0.725	0.354	0.748	
10	3.7 x 75	45	Suzuki	-240	420	172	1362	0.299	-0.502	0.743	-0.706	0.502	0.743	
11	3.7 x 75	20	Chevrolet	-118	86	476	1016	0.151	-0.096	0.373	-0.285	0.151	0.373	
12	3.7 x 75	20	Chevrolet	-126	74	488	1042	0.161	-0.082	0.358	-0.316	0.161	0.358	
13	3.7 x 75	24	Chevrolet	-126	110	472	1016	0.161	-0.125	0.378	-0.285	0.161	0.378	
14	3.7 x 75	24	Chevrolet	-136	79	444	1070	0.173	-0.088	0.412	-0.350	0.173	0.412	
15	3.7 x 75	29	Chevrolet	-126	140	522	1026	0.161	-0.162	0.317	-0.297	0.162	0.317	
16	3.7 x 75	29	Chevrolet	-106	126	534	1070	0.137	-0.145	0.302	-0.350	0.145	0.350	
17	4.9 x 75	35	Chevrolet	-160	208	298	1038	0.202	-0.244	0.590	-0.311	0.244	0.590	
18	4.9 x 75	35	Chevrolet	-106	168	310	1062	0.137	-0.196	0.575	-0.341	0.196	0.575	
19	6.7 x 75	29	Suzuki	-117	196	492	1083	0.150	-0.230	0.353	-0.366	0.230	0.366	
20	6.7 x 75	29	Suzuki	-126	180	492	1042	0.161	-0.210	0.353	-0.316	0.210	0.353	
21	6.7 x 75	35	Suzuki	-122	200	424	1067	0.156	-0.235	0.436	-0.347	0.235	0.436	
22	6.7 x 75	35	Suzuki	-168	262	420	1090	0.212	-0.310	0.441	-0.375	0.310	0.441	
23	6.7 x 75	37	Suzuki	-192	274	400	1107	0.241	-0.324	0.465	-0.395	0.324	0.465	
24	6.7 x 75	37	Suzuki	-192	258	392	1095	0.241	-0.305	0.475	-0.381	0.305	0.475	
25	6.7 x 75	44	Suzuki	-152	310	286	1196	0.193	-0.368	0.604	-0.504	0.368	0.604	
26	6.7 x 75	44	Suzuki	-289	322	274	1326	0.359	-0.383	0.619	-0.662	0.383	0.662	
27	6.7 x 75	29	Chevrolet	-106	152	515	1024	0.137	-0.176	0.325	-0.294	0.176	0.325	
28	6.7 x 75	29	Chevrolet	-74	196	514	1016	0.098	-0.230	0.327	-0.285	0.230	0.327	
29	6.7 x 75	37	Chevrolet	-140	252	496	1034	0.178	-0.298	0.348	-0.307	0.298	0.348	
30	6.7 x 75	37	Chevrolet	-132	220	512	1070	0.168	-0.259	0.329	-0.350	0.259	0.350	
31	6.7 x 75	44	Chevrolet	-148	224	346	1090	0.188	-0.264	0.531	-0.375	0.264	0.531	
32	6.7 x 75	44	Chevrolet	-212	248	370	1099	0.265	-0.293	0.502	-0.386	0.293	0.502	

Table D.1
Peak Acceleration Data for Automobile Test Runs

Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Acceleration Readings: Min. a_x	Max. a_x	Min. a_z	Max. a_z	Calibrated Accelerations (g): Max. a_x	Min. a_x	Max. a_z	Min. a_z	Peak Accelerations (g): Peak a_x	Peak a_z	Comments
33	9.1 x 75	25	Chevrolet	-128	86	468	1035	0.164	-0.096	0.383	-0.308	0.164	0.383	
34	9.1 x 75	25	Chevrolet	-128	74	488	1020	0.164	-0.082	0.358	-0.290	0.164	0.358	
35	9.1 x 75	45	Chevrolet	-236	164	448	1126	0.295	-0.191	0.407	-0.419	0.295	0.419	
36	9.1 x 75	45	Chevrolet	-176	200	420	1098	0.222	-0.235	0.441	-0.385	0.235	0.441	
37	3.7 x 100	19	Suzuki	-102	252	464	1196	0.132	-0.298	0.387	-0.504	0.298	0.504	
38	3.7 x 100	19	Suzuki	-93	244	504	1160	0.121	-0.288	0.339	-0.460	0.288	0.460	
39	3.7 x 100	23	Suzuki	-164	275	424	1232	0.207	-0.326	0.436	-0.548	0.326	0.548	
40	3.7 x 100	23	Suzuki	-144	306	420	1172	0.183	-0.363	0.441	-0.475	0.363	0.475	
41	3.7 x 100	25	Suzuki	-338	286	420	1347	0.418	-0.339	0.441	-0.688	0.418	0.688	
42	3.7 x 100	25	Suzuki	-248	330	378	1315	0.309	-0.392	0.492	-0.649	0.392	0.649	
43	3.7 x 100	19	Chevrolet	-160	107	440	1111	0.202	-0.122	0.417	-0.400	0.202	0.417	
44	3.7 x 100	19	Chevrolet	-127	99	448	1150	0.162	-0.112	0.407	-0.448	0.162	0.448	
45	3.7 x 100	23	Chevrolet	-110	140	314	1184	0.142	-0.162	0.570	-0.489	0.162	0.570	Scraped air dam
46	3.7 x 100	23	Chevrolet	-152	90	354	1180	0.193	-0.101	0.521	-0.484	0.193	0.521	Scraped air dam
47	3.7 x 100	25	Chevrolet	-128	140	310	1192	0.164	-0.162	0.575	-0.499	0.164	0.575	Scraped air dam
48	3.7 x 100	25	Chevrolet	-136	122	322	1212	0.173	-0.140	0.560	-0.523	0.173	0.560	Scraped air dam
49	3.7 x 100	45	Chevrolet	-486	352	128	1568	0.598	-0.419	0.797	-0.957	0.598	0.957	
50	3.7 x 100	45	Chevrolet	-682	376	72	1698	0.836	-0.448	0.865	-1.115	0.836	1.115	
51	4.9 x 100	25	Suzuki	-194	236	374	1083	0.244	-0.278	0.497	-0.366	0.278	0.497	
52	4.9 x 100	25	Suzuki	-178	216	350	1176	0.224	-0.254	0.526	-0.480	0.254	0.526	
53	4.9 x 100	45	Suzuki	-246	363	-158	1639	0.307	-0.433	1.145	-1.043	0.433	1.145	Became airborne
54	4.9 x 100	45	Suzuki	-210	346	-214	1508	0.263	-0.412	1.213	-0.884	0.412	1.213	Became airborne
55	6.7 x 100	24	Suzuki	-202	244	452	1176	0.253	-0.288	0.402	-0.480	0.288	0.480	
56	6.7 x 100	24	Suzuki	-209	224	420	1184	0.262	-0.264	0.441	-0.489	0.264	0.489	
57	6.7 x 100	32	Suzuki	-226	240	275	1130	0.282	-0.283	0.618	-0.424	0.283	0.618	
58	6.7 x 100	32	Suzuki	-186	248	258	1118	0.234	-0.293	0.638	-0.409	0.293	0.638	
59	6.7 x 100	40	Suzuki	-174	294	228	1240	0.219	-0.349	0.675	-0.557	0.349	0.675	
60	6.7 x 100	40	Suzuki	-210	275	192	1236	0.263	-0.326	0.719	-0.553	0.326	0.719	
61	6.7 x 100	24	Chevrolet	-110	118	456	1074	0.142	-0.135	0.397	-0.355	0.142	0.397	
62	6.7 x 100	24	Chevrolet	-128	127	468	1058	0.164	-0.146	0.383	-0.336	0.164	0.383	
63	6.7 x 100	32	Chevrolet	-161	156	472	1204	0.204	-0.181	0.378	-0.514	0.204	0.514	
64	6.7 x 100	32	Chevrolet	-134	156	464	1212	0.171	-0.181	0.387	-0.523	0.181	0.523	

Table D.1
Peak Acceleration Data for Automobile Test Runs

Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Acceleration Readings				Calibrated Accelerations (g)				Peak Accelerations (g)		Comments
				Min. a_x	Max. a_x	Min. a_z	Max. a_z	Max. a_x	Min. a_x	Max. a_z	Min. a_z	Peak a_x	Peak a_z	
65	6.7 x 100	35	Chevrolet	-134	212	424	1280	0.171	-0.249	0.436	-0.606	0.249	0.606	
66	6.7 x 100	35	Chevrolet	-162	220	428	1294	0.205	-0.259	0.431	-0.623	0.259	0.623	
67	6.7 x 100	40	Chevrolet	-130	204	346	1303	0.166	-0.239	0.531	-0.634	0.239	0.634	
68	6.7 x 100	40	Chevrolet	-170	204	314	1280	0.214	-0.239	0.570	-0.606	0.239	0.606	
69	9.1 x 100	35	Suzuki	-197	258	252	1378	0.247	-0.305	0.646	-0.725	0.305	0.725	
70	9.1 x 100	35	Suzuki	-226	244	212	1367	0.282	-0.288	0.694	-0.712	0.288	0.712	

Date: Sept. 21, 1997 Road Surface: Dry Weather: +12 °C, Sunny and Windy

: Indicates Test Run is from Factorial Design

Table D.2
Peak Acceleration Data for Transit Bus Test Runs

Run	Hump Shape (m,mm)	Speed (km/h)	Position	Acceleration Readings: Min. a_x	Max. a_x	Min. a_z	Max. a_z	Calibrated Accelerations (g): Max. a_x	Min. a_x	Max. a_z	Min. a_z	Peak Accelerations (g): Peak a_x	Peak a_z	Comments
1	3.7 x 75	35	Driver Seat	-148	335	38	1363	0.188	-0.399	0.906	-0.707	0.399	0.906	
2	3.7 x 75	35	Driver Seat	-148	350	2	1370	0.188	-0.417	0.950	-0.716	0.417	0.950	
3	4.9 x 75	25	Rear Seat	32	368	384	1519	-0.031	-0.439	0.485	-0.897	0.439	0.897	
4	4.9 x 75	25	Rear Seat	42	400	343	1492	-0.043	-0.477	0.535	-0.864	0.477	0.864	
5	4.9 x 75	45	Rear Seat	-147	564	-12	2075	0.187	-0.676	0.967	-1.574	0.676	1.574	
6	4.9 x 75	45	Rear Seat	-215	637	-89	2125	0.269	-0.765	1.061	-1.635	0.765	1.635	
7	6.7 x 75	25	Driver Seat	-70	204	384	1400	0.093	-0.239	0.485	-0.752	0.239	0.752	
8	6.7 x 75	25	Driver Seat	-66	208	384	1392	0.088	-0.244	0.485	-0.743	0.244	0.743	
9	6.7 x 75	30	Driver Seat	-54	220	364	1420	0.074	-0.259	0.509	-0.777	0.259	0.777	
10	6.7 x 75	30	Driver Seat	-58	240	364	1408	0.079	-0.283	0.509	-0.762	0.283	0.762	
11	6.7 x 75	45	Driver Seat	-206	372	292	1752	0.258	-0.443	0.597	-1.181	0.443	1.181	
12	6.7 x 75	45	Driver Seat	-174	340	288	1684	0.219	-0.405	0.602	-1.098	0.405	1.098	
13	6.7 x 75	30	Rear Seat	-6	384	292	1348	0.015	-0.458	0.597	-0.689	0.458	0.689	
14	6.7 x 75	30	Rear Seat	48	448	256	1528	-0.050	-0.536	0.641	-0.908	0.526	0.908	
15	9.1 x 75	35	Rear Seat	-82	400	248	1300	0.108	-0.477	0.650	-0.631	0.477	0.650	
16	9.1 x 75	35	Rear Seat	-61	440	256	1244	0.082	-0.526	0.641	-0.562	0.526	0.641	
17	3.7 x 100	35	Rear Seat	-318	676	-410	2371	0.394	-0.812	1.452	-1.935	0.812	1.935	
18	3.7 x 100	35	Rear Seat	-138	576	-38	2000	0.176	-0.691	0.999	-1.483	0.691	1.483	
19	4.9 x 100	35	Driver Seat	-250	492	136	1896	0.312	-0.589	0.787	-1.356	0.589	1.356	
20	4.9 x 100	35	Driver Seat	-137	580	172	1900	0.174	-0.696	0.743	-1.361	0.696	1.361	
21	6.7 x 100	25	Rear Seat	-34	488	180	1500	0.049	-0.584	0.733	-0.874	0.584	0.874	
22	6.7 x 100	25	Rear Seat	16	500	184	1512	-0.011	-0.599	0.728	-0.889	0.599	0.889	
23	6.7 x 100	45	Rear Seat	-574	1212	-297	2962	0.705	-1.463	1.314	-2.654	1.463	2.654	Lifted off seat
24	6.7 x 100	45	Rear Seat	-546	1104	-214	2779	0.671	-1.332	1.213	-2.431	1.332	2.431	Lifted off seat
25	9.1 x 100	25	Driver Seat	-113	404	88	1952	0.145	-0.482	0.845	-1.424	0.482	1.424	
26	9.1 x 100	25	Driver Seat	-118	360	116	1952	0.151	-0.429	0.811	-1.424	0.429	1.424	
27	9.1 x 100	45	Driver Seat	-254	500	156	1768	0.316	-0.599	0.762	-1.200	0.599	1.200	
28	9.1 x 100	45	Driver Seat	-234	460	184	1984	0.292	-0.550	0.728	-1.463	0.550	1.463	

Date: Oct. 14, 1997 Road Surface: Dry to Partly Dry Weather: +17 °C, Variable

Indicates Test Run is from Factorial Design

Table D.3
RMS and RMQ Acceleration Data for Automobile Test Runs

Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Time (s)	RMS Accelerations (g)				RMQ Accelerations (g)				Root Sums (g)	
					Avg. a_x^2	Avg. a_z^2	rms (a_x)	rms (a_z)	Avg. a_x^4	Avg. a_z^4	rmq (a_x)	rmq (a_z)	RSS	RSQ
1	3.7 x 75	20	Suzuki	1.57	0.0033	0.0200	0.046	0.113	0.0000	0.0010	0.000	0.159	0.086	0.112
2	3.7 x 75	20	Suzuki	1.55	0.0040	0.0206	0.051	0.115	0.0000	0.0011	0.000	0.163	0.089	0.115
3	3.7 x 75	24	Suzuki	1.32	0.0066	0.0271	0.071	0.143	0.0001	0.0019	0.093	0.195	0.113	0.140
4	3.7 x 75	24	Suzuki	1.31	0.0084	0.0274	0.080	0.145	0.0001	0.0018	0.093	0.193	0.117	0.138
5	3.7 x 75	25	Suzuki	1.27	0.0066	0.0297	0.072	0.153	0.0001	0.0022	0.094	0.204	0.120	0.146
6	3.7 x 75	25	Suzuki	1.27	0.0082	0.0314	0.080	0.157	0.0001	0.0022	0.094	0.204	0.125	0.146
7	3.7 x 75	29	Suzuki	1.39	0.0071	0.0494	0.071	0.189	0.0001	0.0061	0.092	0.257	0.143	0.183
8	3.7 x 75	29	Suzuki	1.36	0.0078	0.0548	0.076	0.201	0.0002	0.0077	0.110	0.274	0.152	0.195
9	3.7 x 75	45	Suzuki	1.26	0.0105	0.1661	0.091	0.363	0.0004	0.0199	0.133	0.355	0.265	0.252
10	3.7 x 75	45	Suzuki	1.28	0.0176	0.1368	0.117	0.327	0.0012	0.0377	0.175	0.414	0.246	0.295
11	3.7 x 75	20	Chevrolet	1.60	0.0025	0.0259	0.040	0.127	0.0000	0.0013	0.000	0.169	0.094	0.119
12	3.7 x 75	20	Chevrolet	1.65	0.0024	0.0278	0.038	0.130	0.0000	0.0016	0.000	0.176	0.096	0.125
13	3.7 x 75	24	Chevrolet	1.30	0.0021	0.0298	0.040	0.151	0.0000	0.0017	0.000	0.190	0.111	0.134
14	3.7 x 75	24	Chevrolet	1.39	0.0022	0.0335	0.040	0.155	0.0000	0.0024	0.000	0.204	0.113	0.144
15	3.7 x 75	29	Chevrolet	1.18	0.0030	0.0268	0.050	0.151	0.0000	0.0015	0.000	0.189	0.112	0.134
16	3.7 x 75	29	Chevrolet	1.23	0.0032	0.0344	0.051	0.167	0.0000	0.0021	0.000	0.203	0.124	0.144
17	4.9 x 75	35	Chevrolet	1.51	0.0036	0.0466	0.049	0.176	0.0001	0.0051	0.090	0.241	0.129	0.171
18	4.9 x 75	35	Chevrolet	1.58	0.0037	0.0449	0.048	0.169	0.0000	0.0050	0.000	0.237	0.124	0.168
19	6.7 x 75	29	Suzuki	1.68	0.0032	0.0317	0.044	0.137	0.0000	0.0022	0.000	0.190	0.102	0.135
20	6.7 x 75	29	Suzuki	1.79	0.0033	0.0284	0.043	0.126	0.0000	0.0017	0.000	0.176	0.094	0.124
21	6.7 x 75	35	Suzuki	1.67	0.0049	0.0366	0.054	0.148	0.0001	0.0028	0.088	0.202	0.111	0.144
22	6.7 x 75	35	Suzuki	1.58	0.0057	0.0434	0.060	0.166	0.0002	0.0040	0.106	0.224	0.125	0.161
23	6.7 x 75	37	Suzuki	1.55	0.0061	0.0502	0.063	0.180	0.0002	0.0048	0.107	0.236	0.135	0.169
24	6.7 x 75	37	Suzuki	1.49	0.0064	0.0500	0.066	0.183	0.0002	0.0053	0.108	0.244	0.138	0.174
25	6.7 x 75	44	Suzuki	1.57	0.0086	0.0826	0.074	0.229	0.0003	0.0135	0.118	0.305	0.170	0.217
26	6.7 x 75	44	Suzuki	1.42	0.0088	0.1023	0.079	0.268	0.0004	0.0214	0.130	0.350	0.198	0.249
27	6.7 x 75	29	Chevrolet	1.70	0.0041	0.0239	0.049	0.119	0.0000	0.0012	0.000	0.163	0.091	0.115
28	6.7 x 75	29	Chevrolet	1.56	0.0069	0.0259	0.067	0.129	0.0001	0.0012	0.089	0.167	0.103	0.120
29	6.7 x 75	37	Chevrolet	1.28	0.0095	0.0398	0.086	0.176	0.0002	0.0030	0.112	0.220	0.139	0.158
30	6.7 x 75	37	Chevrolet	1.35	0.0073	0.0434	0.074	0.179	0.0002	0.0030	0.110	0.217	0.137	0.156
31	6.7 x 75	44	Chevrolet	1.60	0.0069	0.0589	0.066	0.192	0.0001	0.0076	0.089	0.263	0.143	0.186
32	6.7 x 75	44	Chevrolet	1.58	0.0077	0.0540	0.070	0.185	0.0002	0.0058	0.106	0.246	0.140	0.176

Table D.3
RMS and RMQ Acceleration Data for Automobile Test Runs

Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Time (s)	RMS Accelerations (g)				RMQ Accelerations (g)				Root Sums (g)	
					Avg. a_x^2	Avg. a_z^2	rms (a_x)	rms (a_z)	Avg. a_x^4	Avg. a_z^4	rmq (a_x)	rmq (a_z)	RSS	RSQ
33	9.1 x 75	25	Chevrolet	2.28	0.0029	0.0238	0.036	0.102	0.0000	0.0014	0.000	0.157	0.077	0.111
34	9.1 x 75	25	Chevrolet	2.17	0.0022	0.0213	0.032	0.099	0.0000	0.0011	0.000	0.150	0.074	0.106
35	9.1 x 75	45	Chevrolet	1.35	0.0052	0.0467	0.062	0.186	0.0001	0.0046	0.093	0.242	0.139	0.172
36	9.1 x 75	45	Chevrolet	1.47	0.0050	0.0365	0.058	0.158	0.0001	0.0035	0.091	0.221	0.119	0.157
37	3.7 x 100	19	Suzuki	1.44	0.0081	0.0479	0.075	0.182	0.0002	0.0048	0.109	0.240	0.139	0.172
38	3.7 x 100	19	Suzuki	1.47	0.0107	0.0413	0.085	0.168	0.0003	0.0035	0.120	0.221	0.133	0.159
39	3.7 x 100	23	Suzuki	1.57	0.0127	0.0566	0.090	0.190	0.0005	0.0069	0.134	0.257	0.149	0.185
40	3.7 x 100	23	Suzuki	1.52	0.0170	0.0457	0.106	0.173	0.0008	0.0046	0.151	0.235	0.144	0.173
41	3.7 x 100	25	Suzuki	1.47	0.0153	0.0772	0.102	0.229	0.0008	0.0144	0.153	0.315	0.177	0.225
42	3.7 x 100	25	Suzuki	1.45	0.0186	0.0714	0.113	0.222	0.0009	0.0122	0.158	0.303	0.176	0.218
43	3.7 x 100	19	Chevrolet	1.70	0.0053	0.0523	0.056	0.175	0.0001	0.0052	0.088	0.235	0.130	0.167
44	3.7 x 100	19	Chevrolet	1.77	0.0035	0.0540	0.044	0.175	0.0000	0.0051	0.000	0.232	0.127	0.164
45	3.7 x 100	23	Chevrolet	1.43	0.0027	0.0628	0.043	0.210	0.0000	0.0097	0.000	0.287	0.151	0.203
46	3.7 x 100	23	Chevrolet	1.43	0.0035	0.0727	0.049	0.225	0.0000	0.0099	0.000	0.288	0.163	0.204
47	3.7 x 100	25	Chevrolet	1.37	0.0037	0.0875	0.052	0.253	0.0000	0.0151	0.000	0.324	0.182	0.229
48	3.7 x 100	25	Chevrolet	1.34	0.0033	0.0849	0.050	0.252	0.0000	0.0137	0.000	0.318	0.181	0.225
49	3.7 x 100	45	Chevrolet	1.31	0.0243	0.1489	0.136	0.337	0.0028	0.0529	0.215	0.448	0.257	0.321
50	3.7 x 100	45	Chevrolet	1.31	0.0212	0.1585	0.127	0.348	0.0035	0.0798	0.227	0.497	0.262	0.355
51	4.9 x 100	25	Suzuki	1.70	0.0057	0.0588	0.058	0.186	0.0001	0.0064	0.088	0.248	0.138	0.176
52	4.9 x 100	25	Suzuki	1.69	0.0051	0.0761	0.055	0.212	0.0001	0.0112	0.088	0.285	0.155	0.202
53	4.9 x 100	45	Suzuki	1.27	0.0220	0.3531	0.132	0.527	0.0013	0.2213	0.179	0.646	0.384	0.458
54	4.9 x 100	45	Suzuki	0.98	0.0188	0.3061	0.139	0.559	0.0011	0.1880	0.183	0.662	0.407	0.469
55	6.7 x 100	24	Suzuki	2.04	0.0040	0.0432	0.044	0.146	0.0001	0.0045	0.084	0.217	0.108	0.154
56	6.7 x 100	24	Suzuki	2.09	0.0039	0.0386	0.043	0.136	0.0001	0.0035	0.083	0.202	0.101	0.144
57	6.7 x 100	32	Suzuki	1.46	0.0066	0.0681	0.067	0.216	0.0002	0.0115	0.108	0.298	0.160	0.212
58	6.7 x 100	32	Suzuki	1.41	0.0063	0.0697	0.067	0.222	0.0002	0.0124	0.109	0.306	0.164	0.217
59	6.7 x 100	40	Suzuki	1.50	0.0125	0.1038	0.091	0.263	0.0006	0.0220	0.141	0.348	0.197	0.248
60	6.7 x 100	40	Suzuki	1.50	0.0092	0.1197	0.078	0.282	0.0003	0.0305	0.119	0.378	0.207	0.268
61	6.7 x 100	24	Chevrolet	1.95	0.0037	0.0394	0.044	0.142	0.0000	0.0030	0.000	0.198	0.105	0.140
62	6.7 x 100	24	Chevrolet	1.87	0.0036	0.0419	0.044	0.150	0.0000	0.0031	0.000	0.202	0.110	0.143
63	6.7 x 100	32	Chevrolet	1.53	0.0038	0.0609	0.050	0.200	0.0000	0.0066	0.000	0.256	0.145	0.181
64	6.7 x 100	32	Chevrolet	1.54	0.0036	0.0603	0.048	0.198	0.0000	0.0066	0.000	0.256	0.144	0.181

Table D.3

RMS and RMQ Acceleration Data for Automobile Test Runs

					RMS Accelerations (g)				RMQ Accelerations (g)				Root Sums (g)	
Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Time (s)	Avg. a_x^2	Avg. a_z^2	rms (a_x)	rms (a_z)	Avg. a_x^4	Avg. a_z^4	rmq (a_x)	rmq (a_z)	RSS	RSQ
65	6.7 x 100	35	Chevrolet	1.59	0.0049	0.0716	0.056	0.212	0.0001	0.0109	0.089	0.288	0.155	0.204
66	6.7 x 100	35	Chevrolet	1.33	0.0060	0.0808	0.067	0.246	0.0001	0.0129	0.093	0.314	0.181	0.222
67	6.7 x 100	40	Chevrolet	1.51	0.0051	0.0921	0.058	0.247	0.0001	0.0164	0.090	0.323	0.179	0.229
68	6.7 x 100	40	Chevrolet	1.55	0.0060	0.0860	0.062	0.236	0.0001	0.0152	0.090	0.315	0.172	0.223
69	9.1 x 100	35	Suzuki	1.99	0.0068	0.1176	0.058	0.243	0.0002	0.0260	0.100	0.338	0.177	0.240
70	9.1 x 100	35	Suzuki	1.97	0.0050	0.1279	0.050	0.255	0.0001	0.0310	0.084	0.354	0.184	0.251

Date: Sept. 21, 1997 Road Surface: Dry Weather: +12 °C, Sunny and Windy

Indicates Test Run is from Factorial Design

Table D.4
RMS and RMQ Acceleration Data for Transit Bus Test Runs

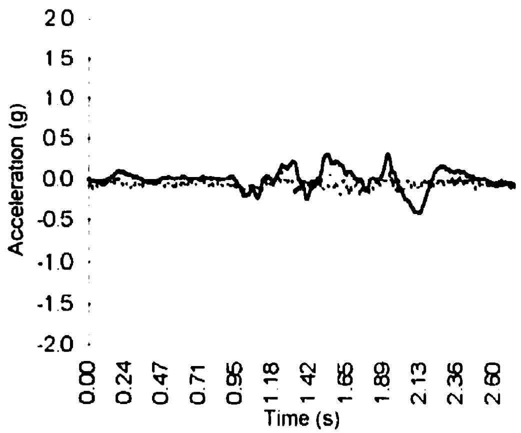
					RMS Accelerations (g)				RMQ Accelerations (g)				Root Sums (g)	
Run	Hump Shape (m,mm)	Speed (km/h)	Position	Time (s)	Avg. a_x^2	Avg. a_z^2	rms (a_x)	rms (a_z)	Avg. a_x^4	Avg. a_z^4	rmq (a_x)	rmq (a_z)	RSS	RSQ
1	3.7 x 75	35	Driver Seat	2.11	0.015	0.146	0.083	0.263	0.001	0.049	0.140	0.391	0.195	0.278
2	3.7 x 75	35	Driver Seat	2.08	0.015	0.155	0.085	0.273	0.001	0.053	0.140	0.400	0.202	0.284
3	4.9 x 75	25	Rear Seat	1.98	0.045	0.103	0.151	0.228	0.003	0.028	0.197	0.345	0.193	0.250
4	4.9 x 75	25	Rear Seat	1.82	0.054	0.114	0.173	0.250	0.004	0.029	0.220	0.354	0.215	0.259
5	4.9 x 75	45	Rear Seat	1.49	0.094	0.417	0.251	0.529	0.018	0.425	0.330	0.731	0.414	0.522
6	4.9 x 75	45	Rear Seat	1.65	0.100	0.424	0.246	0.507	0.021	0.472	0.337	0.731	0.399	0.523
7	6.7 x 75	25	Driver Seat	1.82	0.005	0.075	0.053	0.203	0.000	0.016	0.086	0.306	0.149	0.217
8	6.7 x 75	25	Driver Seat	1.76	0.005	0.077	0.055	0.209	0.000	0.017	0.087	0.315	0.153	0.223
9	6.7 x 75	30	Driver Seat	1.56	0.007	0.112	0.065	0.267	0.000	0.033	0.089	0.381	0.195	0.270
10	6.7 x 75	30	Driver Seat	1.54	0.006	0.113	0.061	0.271	0.000	0.034	0.090	0.384	0.196	0.272
11	6.7 x 75	45	Driver Seat	2.38	0.014	0.175	0.077	0.271	0.001	0.073	0.131	0.419	0.199	0.297
12	6.7 x 75	45	Driver Seat	2.40	0.014	0.170	0.075	0.266	0.001	0.064	0.120	0.403	0.195	0.286
13	6.7 x 75	30	Rear Seat	1.76	0.046	0.107	0.161	0.247	0.003	0.023	0.208	0.339	0.208	0.248
14	6.7 x 75	30	Rear Seat	1.73	0.069	0.141	0.200	0.286	0.008	0.042	0.261	0.394	0.247	0.291
15	9.1 x 75	35	Rear Seat	2.05	0.041	0.094	0.142	0.214	0.003	0.019	0.194	0.311	0.182	0.228
16	9.1 x 75	35	Rear Seat	2.12	0.090	0.079	0.206	0.193	0.011	0.015	0.268	0.289	0.200	0.235
17	3.7 x 100	35	Rear Seat	1.75	0.085	0.473	0.221	0.520	0.023	0.693	0.339	0,793	0.399	0.566
18	3.7 x 100	35	Rear Seat	1.78	0.076	0.346	0.206	0.441	0.014	0.298	0.296	0.640	0.344	0.457
19	4.9 x 100	35	Driver Seat	2.35	0.029	0.346	0.112	0.384	0.005	0.223	0.214	0.555	0.283	0.395
20	4.9 x 100	35	Driver Seat	2.47	0.028	0.331	0.106	0.366	0.003	0.215	0.188	0.543	0.269	0.386
21	6.7 x 100	25	Rear Seat	1.85	0.045	0.156	0.156	0.291	0.005	0.057	0.226	0.420	0.233	0.303
22	6.7 x 100	25	Rear Seat	1.91	0.080	0.144	0.205	0.275	0.010	0.051	0.270	0.405	0.242	0.300
23	6.7 x 100	45	Rear Seat	1.50	0.097	0.682	0.255	0.674	0.053	1.214	0.433	0.948	0.510	0.678
24	6.7 x 100	45	Rear Seat	1.59	0.147	0.784	0.304	0.702	0.110	1.833	0.513	1.036	0.541	0.743
25	9.1 x 100	25	Driver Seat	3.11	0.010	0.197	0.055	0.252	0.001	0.160	0.113	0.476	0.182	0.337
26	9.1 x 100	25	Driver Seat	3.09	0.010	0.202	0.057	0.256	0.000	0.164	0.107	0.480	0.185	0.339
27	9.1 x 100	45	Driver Seat	2.11	0.023	0.235	0.105	0.334	0.002	0.161	0.184	0.525	0.248	0.373
28	9.1 x 100	45	Driver Seat	2.42	0.022	0.248	0.095	0.320	0.002	0.208	0.160	0.542	0.236	0.384

Date: Oct. 14, 1997 Road Surface Dry to Partly Dry Weather +17 °C, Variable

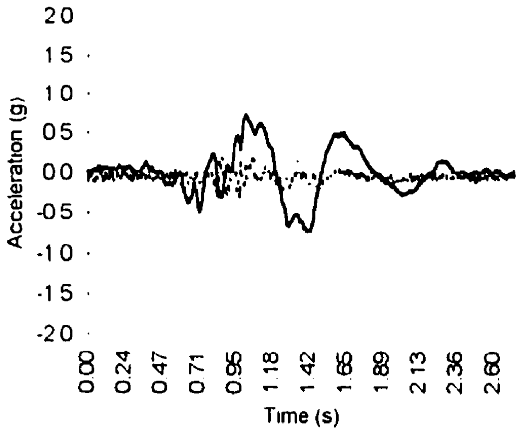
Indicates Test Run is from Factorial Design

Figures D.4 to D.9
Acceleration Plots for Suzuki Swift (Factorial Design)

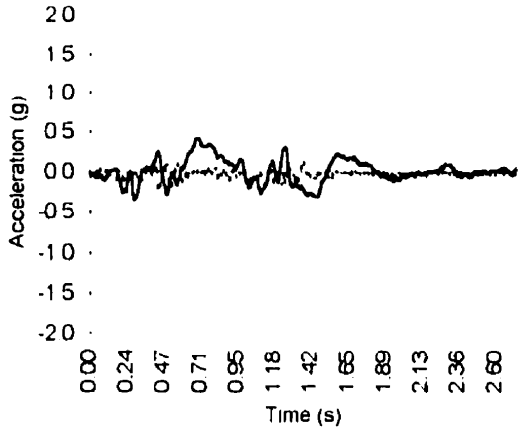
3.7 x 75 Hump at 25 km/h (1st Run)



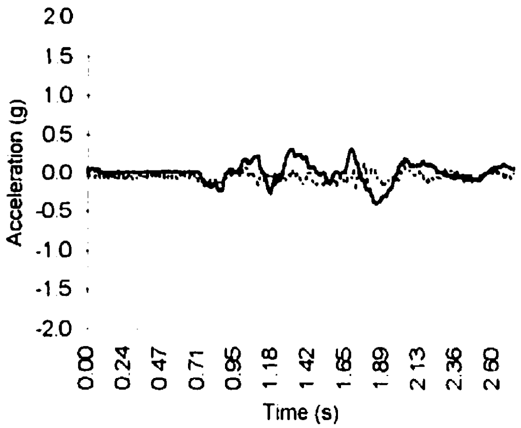
3.7 x 75 Hump at 45 km/h (1st Run)



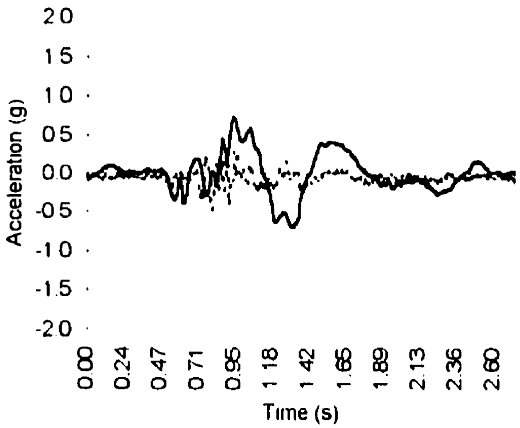
6.7 x 75 Hump at 35 km/h (1st Run)



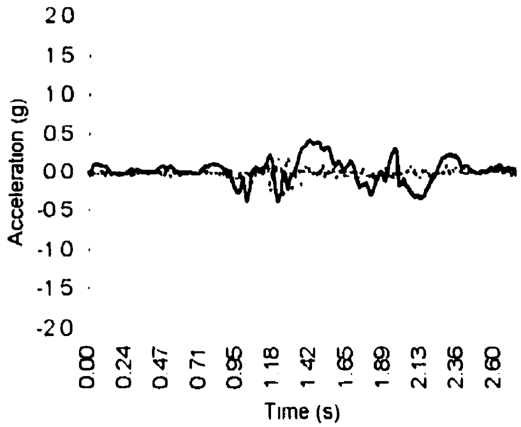
3.7 x 75 Hump at 25 km/h (2nd Run)



3.7 x 75 Hump at 45 km/h (2nd Run)



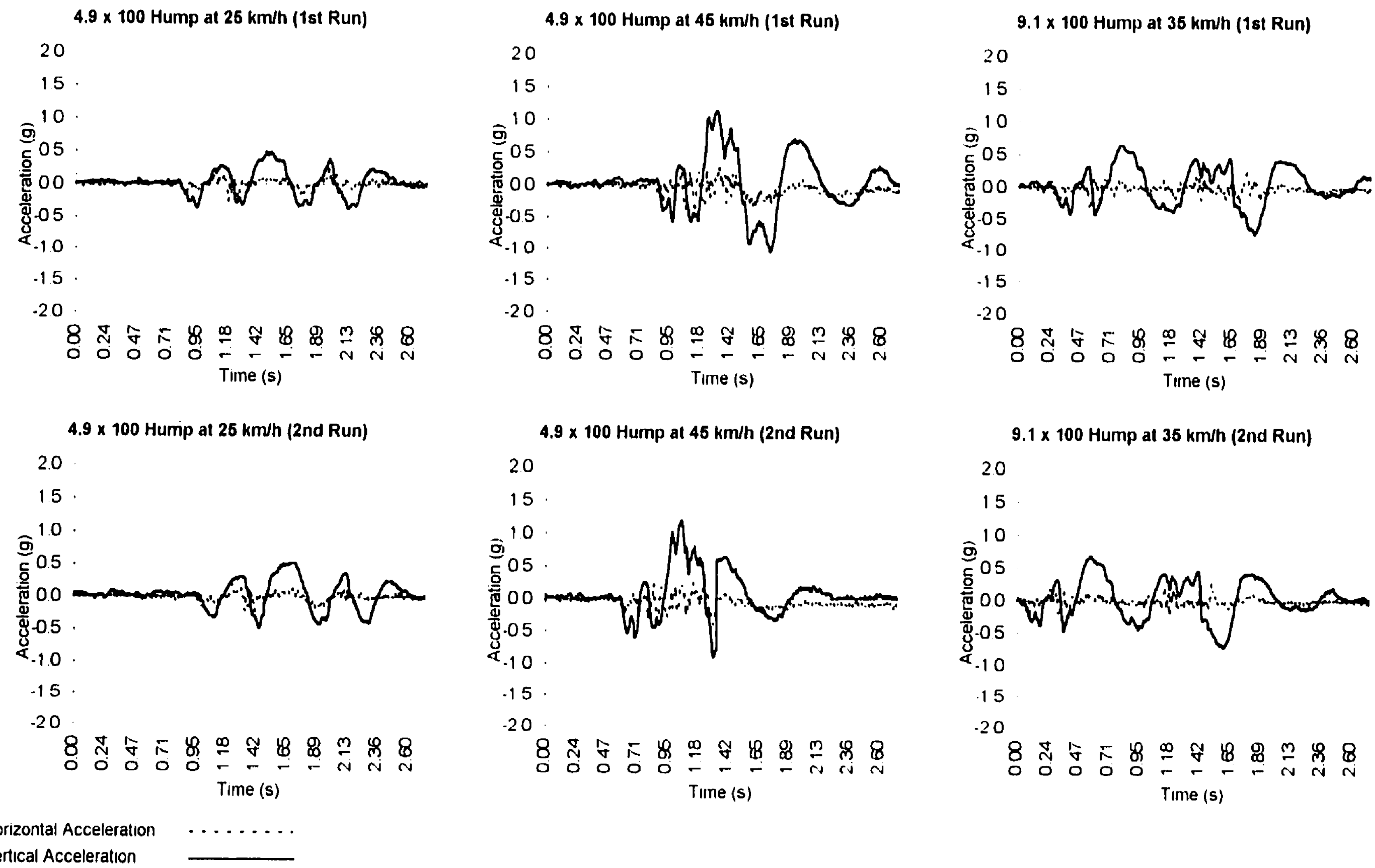
6.7 x 75 Hump at 35 km/h (2nd Run)



Horizontal Acceleration - - - - - - - -

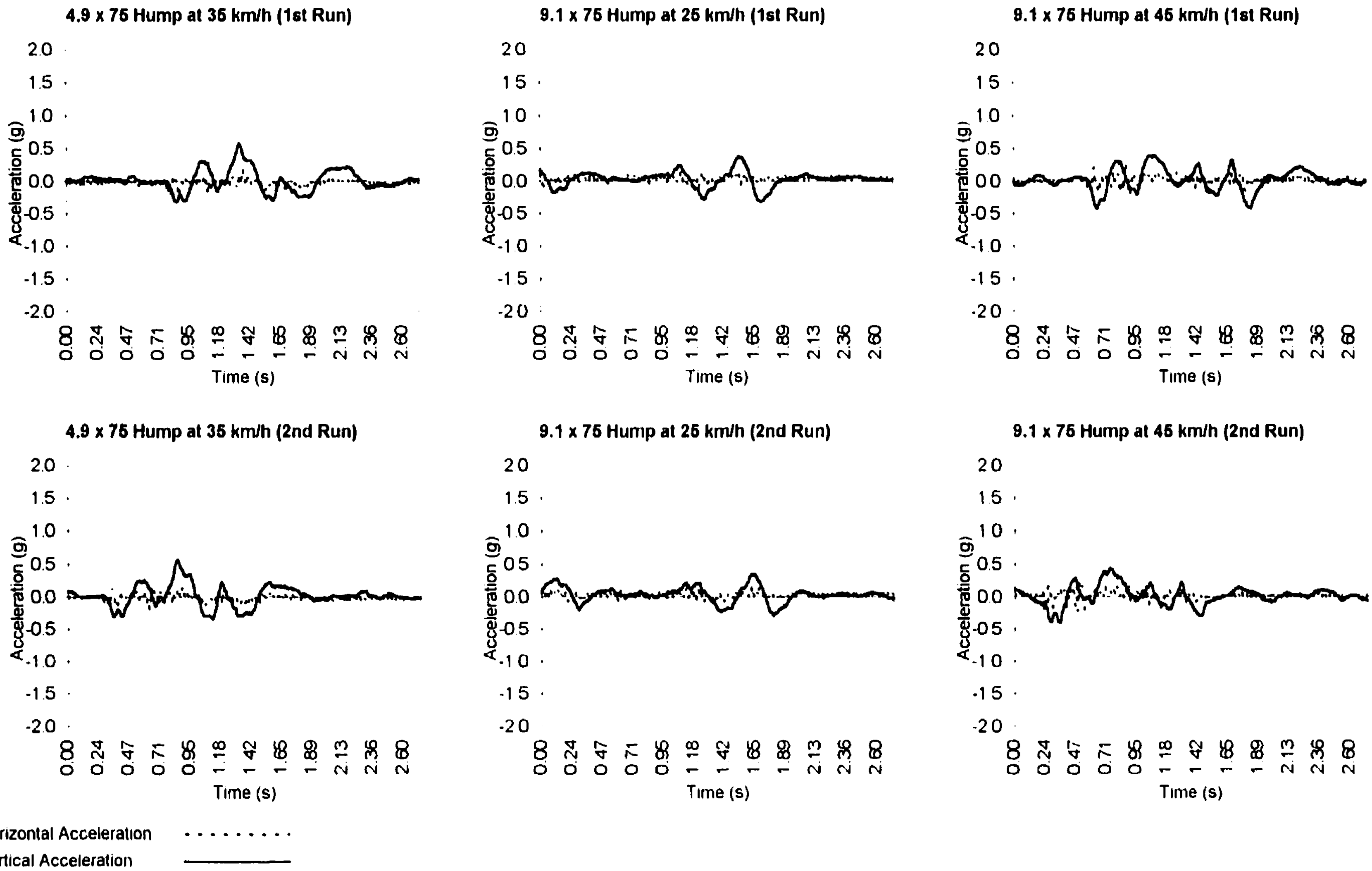
Vertical Acceleration ————

Figures D.10 to D.15
Acceleration Plots for Suzuki Swift (Factorial Design)



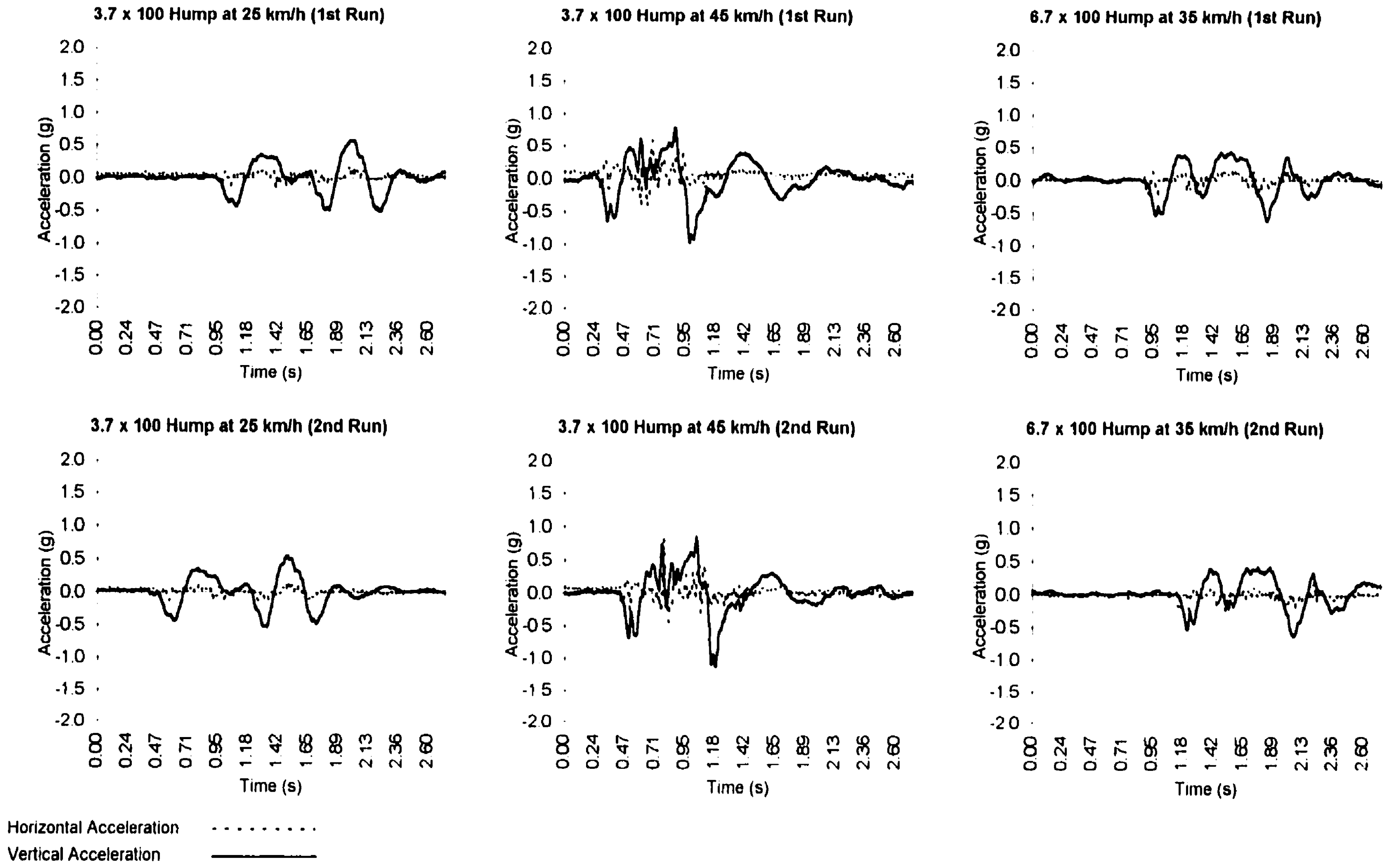
Figures D.16 to D.21

Acceleration Plots for Chevrolet Monte Carlo (Factorial Design)



Figures D.22 to D.27

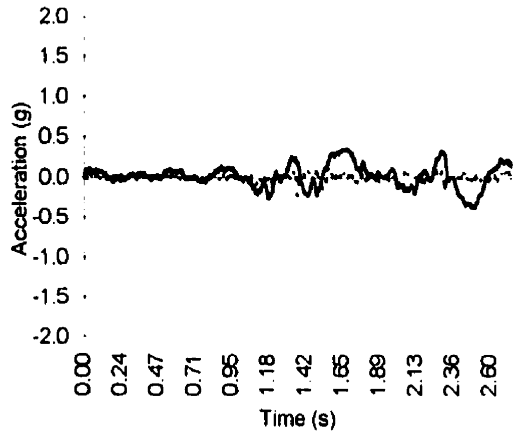
Acceleration Plots for Chevrolet Monte Carlo (Factorial Design)



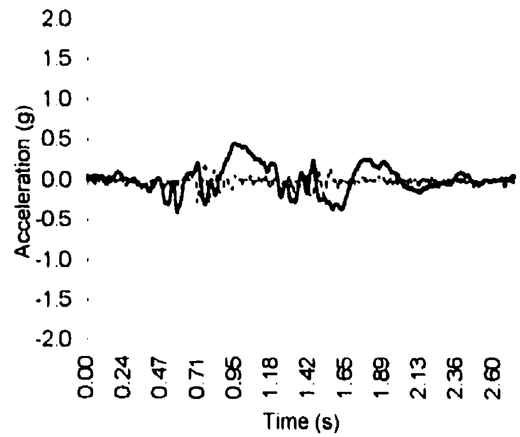
Figures D.28 to D.33

Acceleration Plots for Suzuki Swift (Discomfort Criteria)

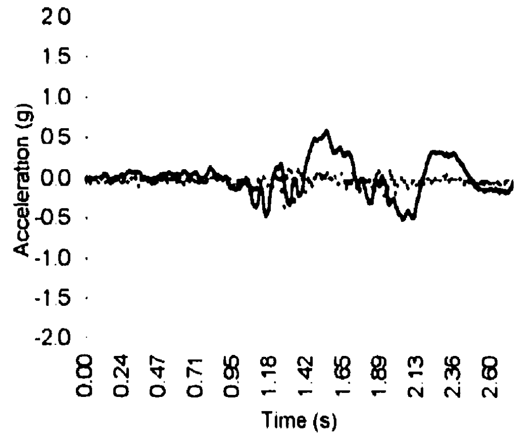
6.7 x 75 Hump at 29 km/h (1st Run)



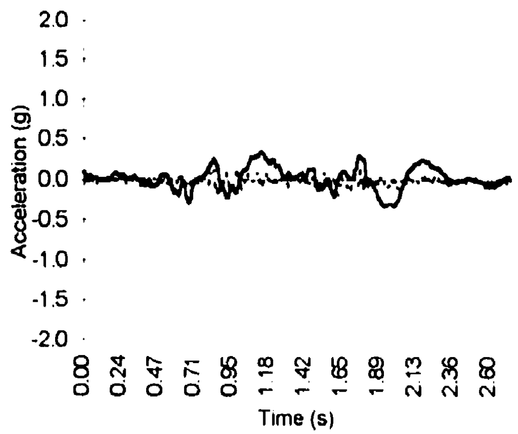
6.7 x 75 Hump at 37 km/h (1st Run)



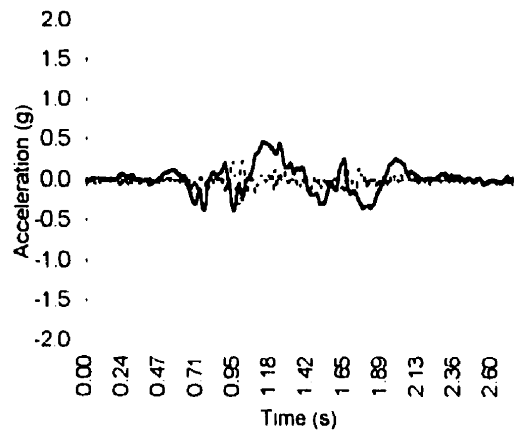
6.7 x 75 Hump at 44 km/h (1st Run)



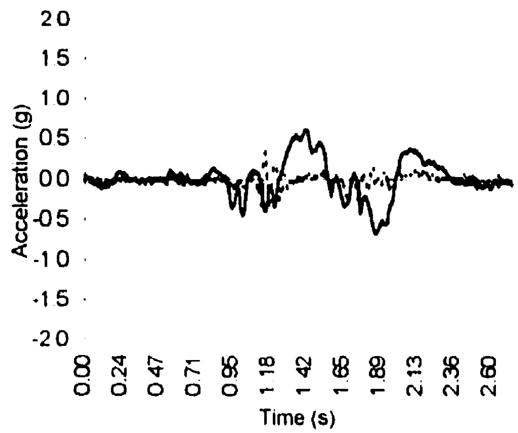
6.7 x 75 Hump at 29 km/h (2nd Run)



6.7 x 75 Hump at 37 km/h (2nd Run)



6.7 x 75 Hump at 44 km/h (2nd Run)

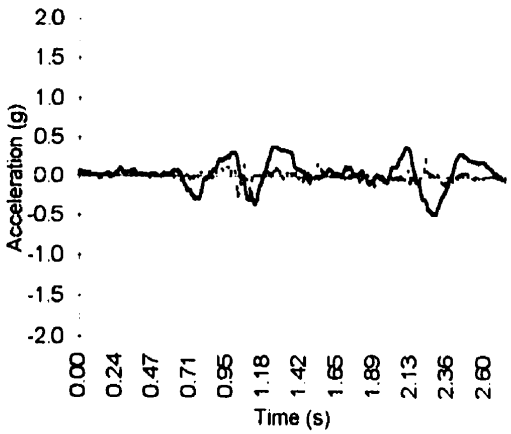


Horizontal Acceleration . . . .
Vertical Acceleration ————

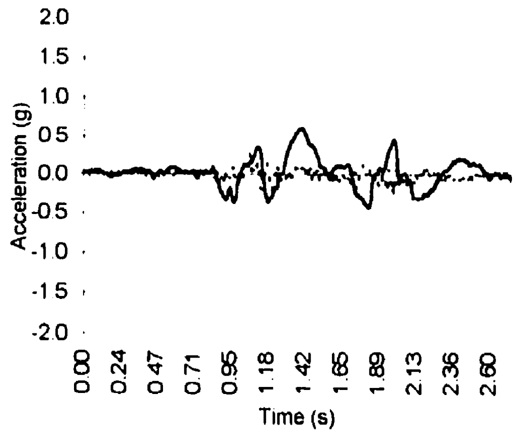
Figures D.34 to D.39

Acceleration Plots for Suzuki Swift (Discomfort Criteria)

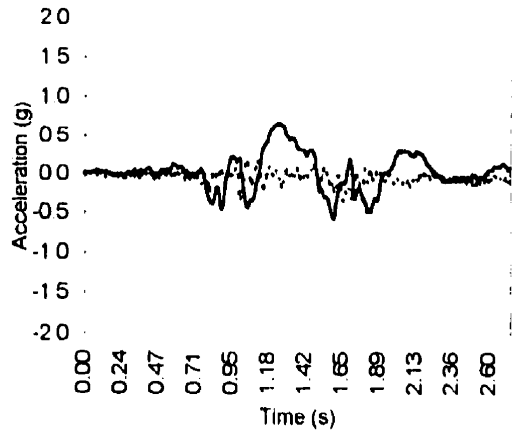
6.7 x 100 Hump at 24 km/h (1st Run)



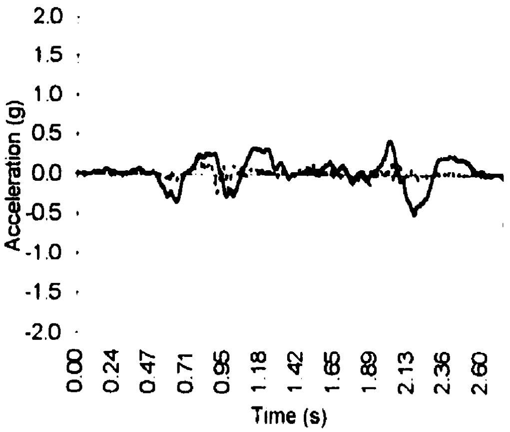
6.7 x 100 Hump at 32 km/h (1st Run)



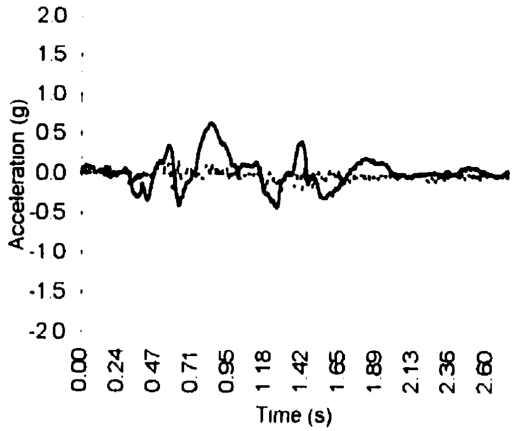
6.7 x 100 Hump at 40 km/h (1st Run)



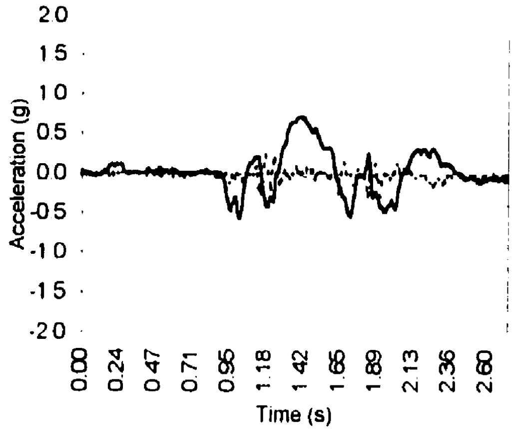
6.7 x 100 Hump at 24 km/h (2nd Run)



6.7 x 100 Hump at 32 km/h (2nd Run)



6.7 x 100 Hump at 40 km/h (2nd Run)

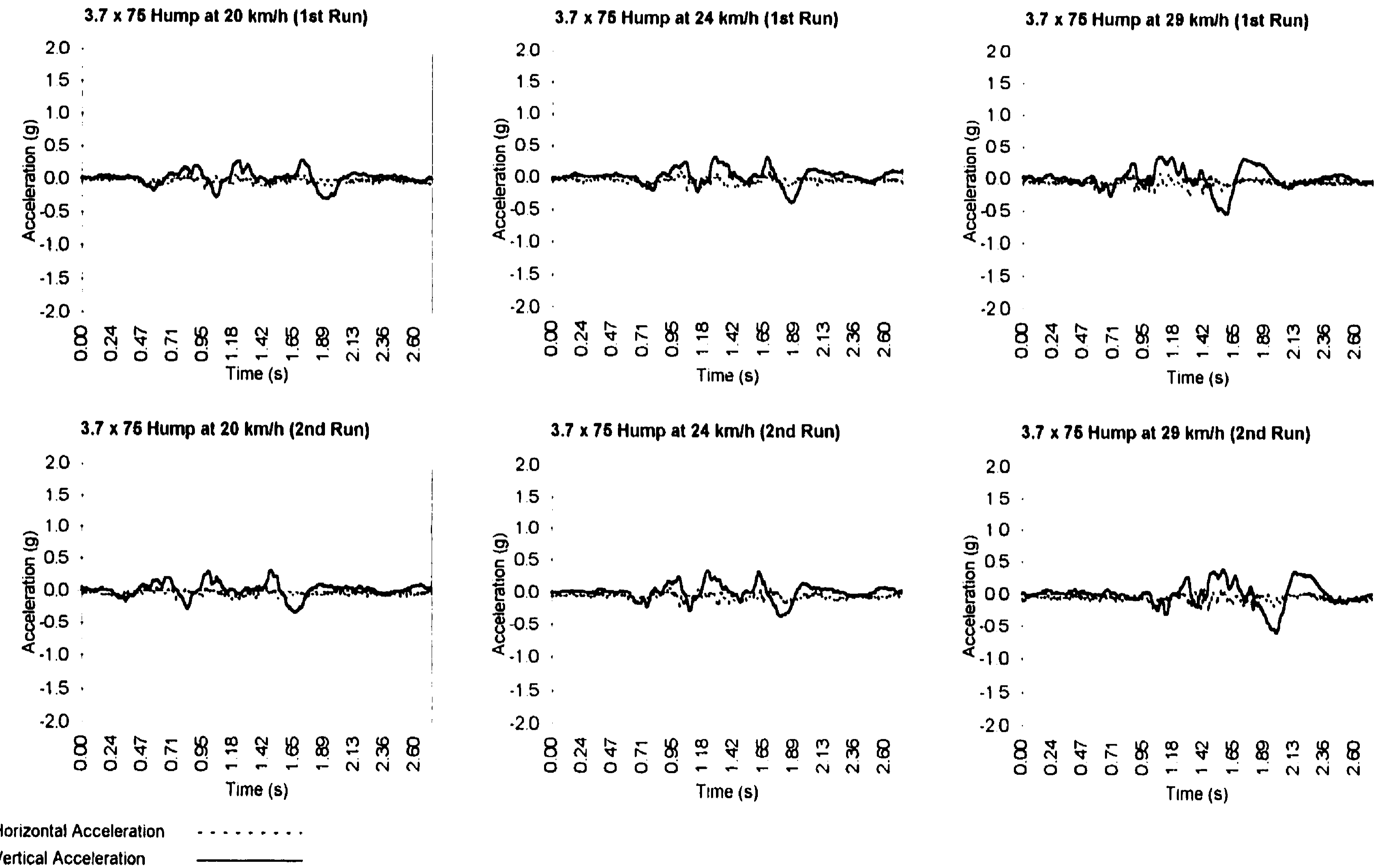


Horizontal Acceleration . . . .

Vertical Acceleration ————

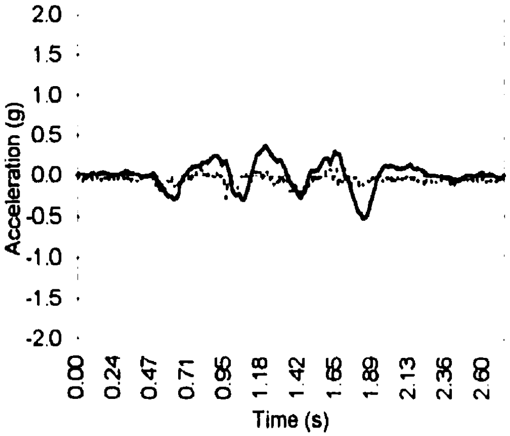
Figures D.40 to D.45

Acceleration Plots for Suzuki Swift (Discomfort Criteria)

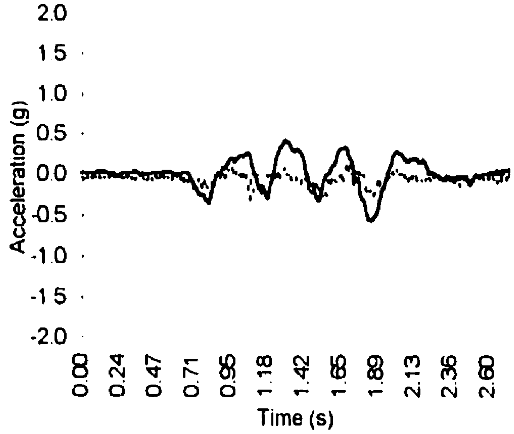


Figures D.46 to D.51
Acceleration Plots for Suzuki Swift (Discomfort Criteria)

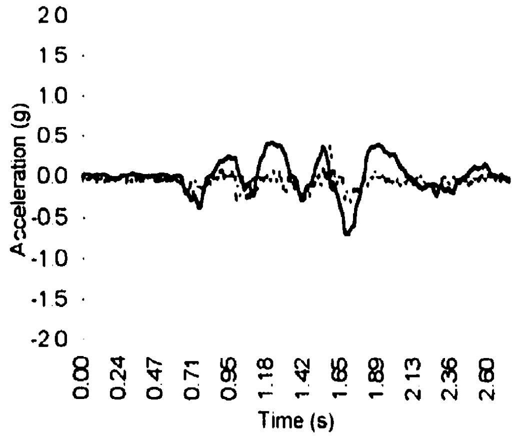
3.7 x 100 Hump at 19 km/h (1st Run)



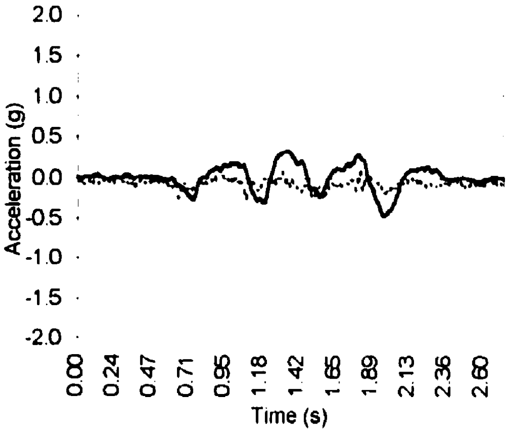
3.7 x 100 Hump at 23 km/h (1st Run)



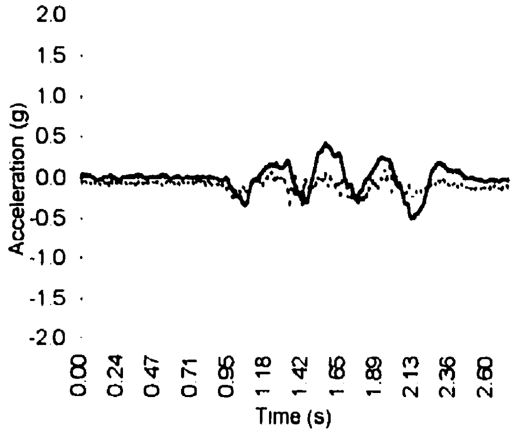
3.7 x 100 Hump at 26 km/h (1st Run)



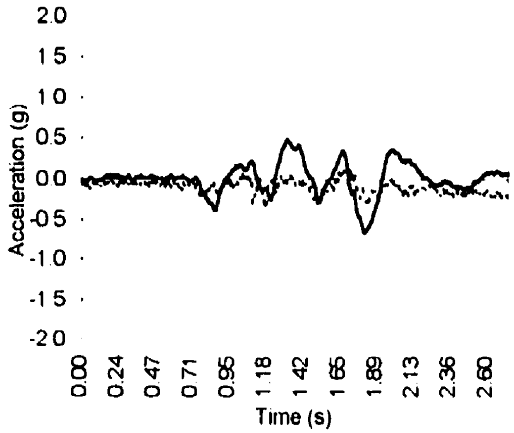
3.7 x 100 Hump at 19 km/h (2nd Run)



3.7 x 100 Hump at 23 km/h (2nd Run)

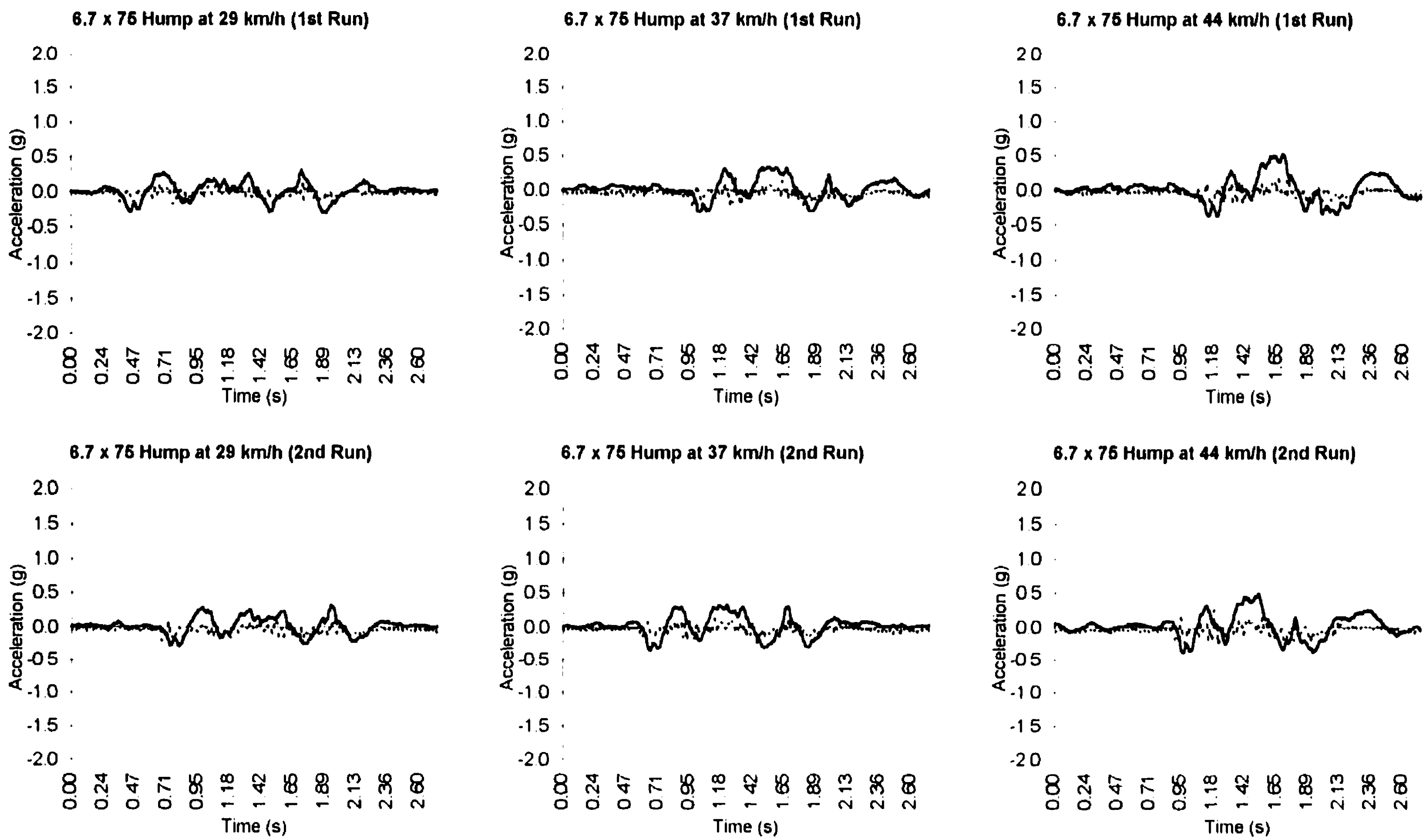


3.7 x 100 Hump at 26 km/h (2nd Run)



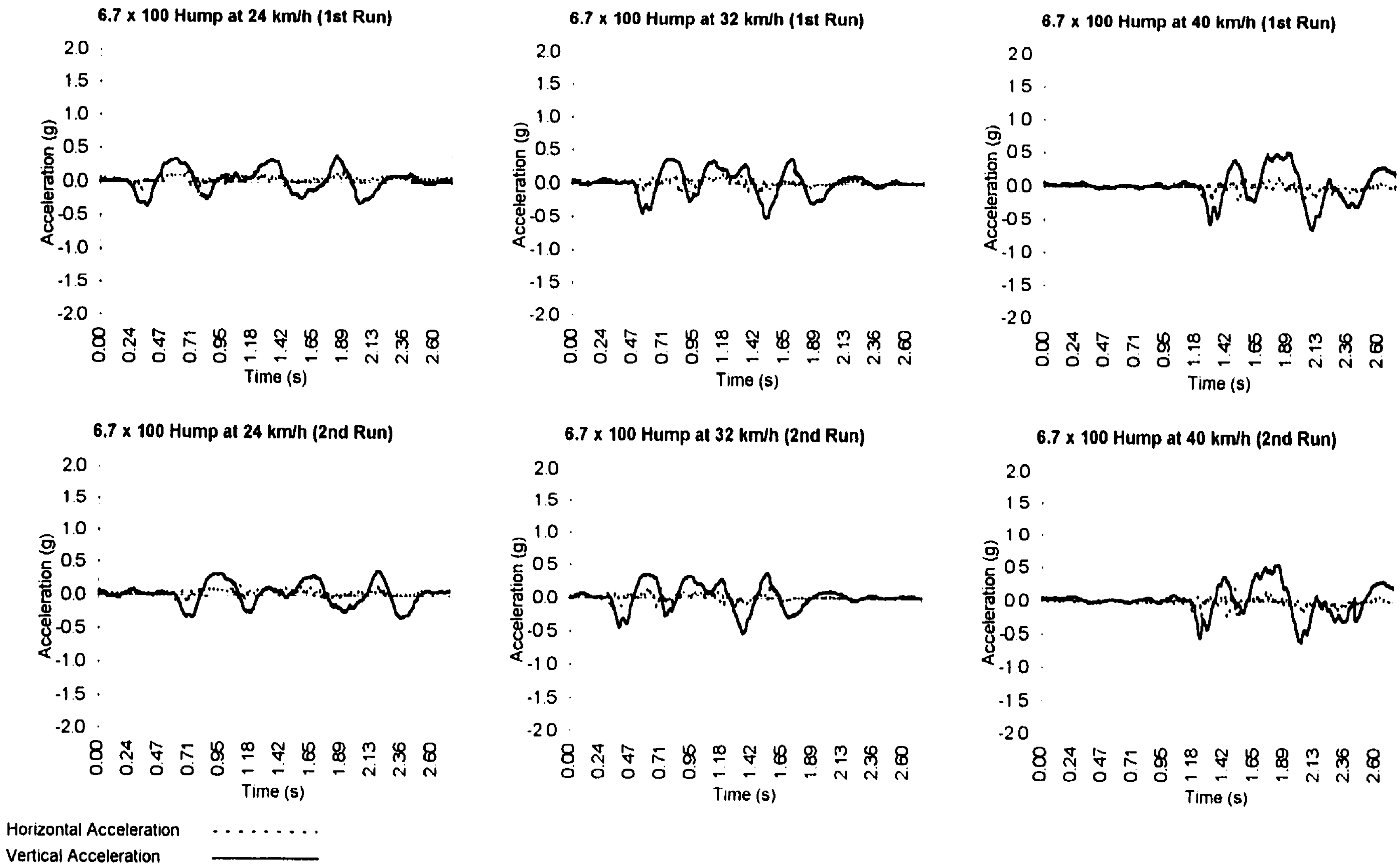
Horizontal Acceleration . . . .
Vertical Acceleration ————

Figures D.52 to D.57
Acceleration Plots for Chevrolet Monte Carlo (Discomfort Criteria)

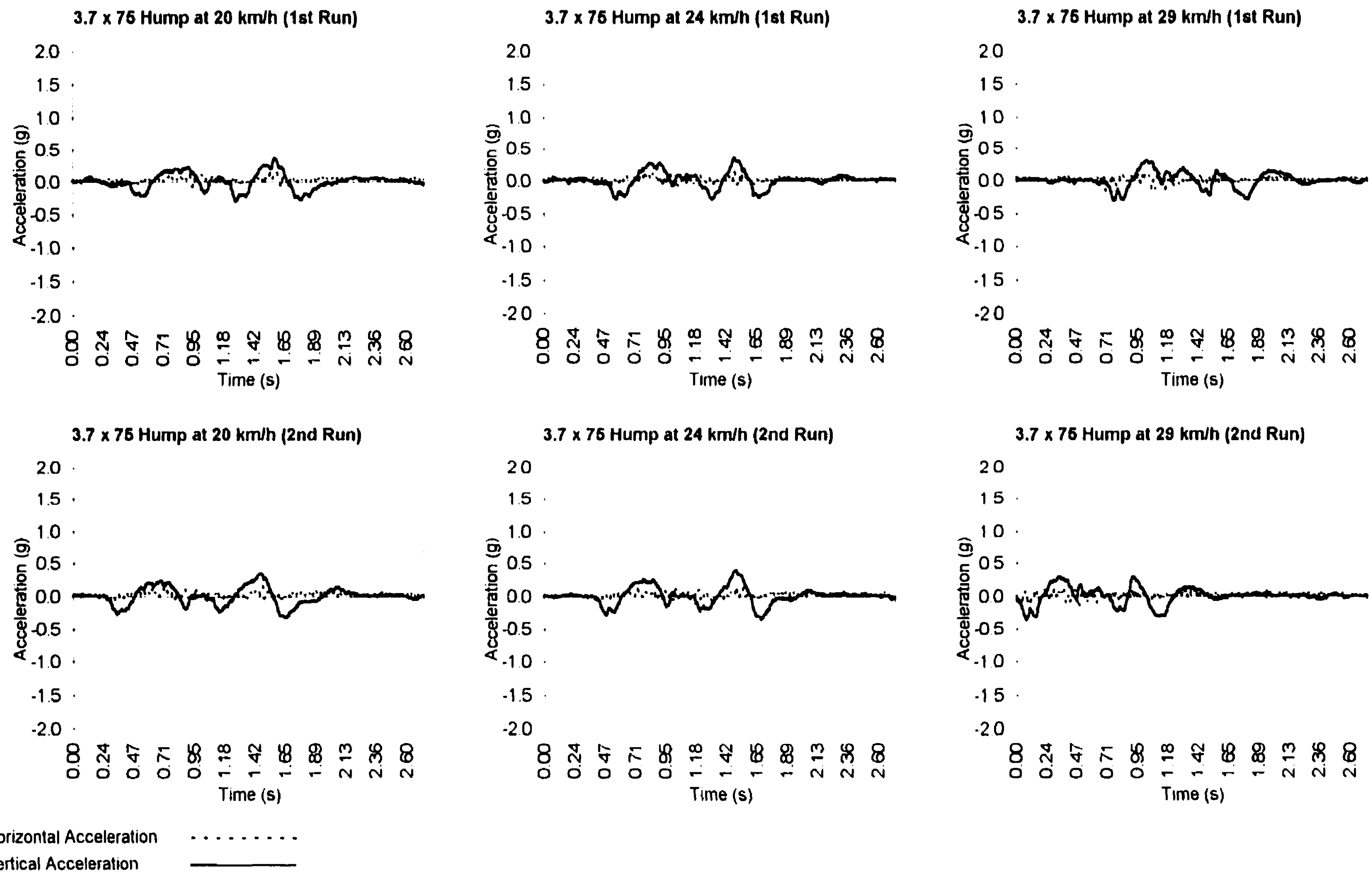


Horizontal Acceleration
Vertical Acceleration

Figures D.58 to D.63
Acceleration Plots for Chevrolet Monte Carlo (Discomfort Criteria)

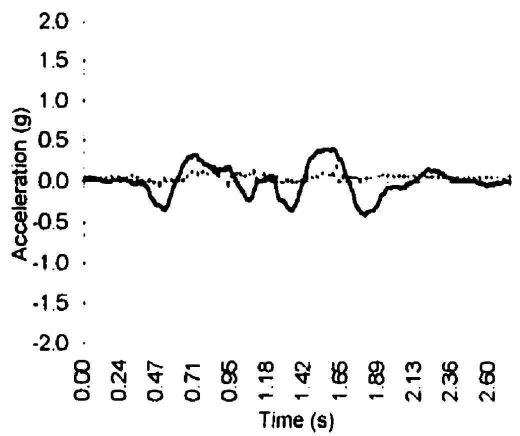


Figures D.64 to D.69
Acceleration Plots for Chevrolet Monte Carlo (Discomfort Criteria)

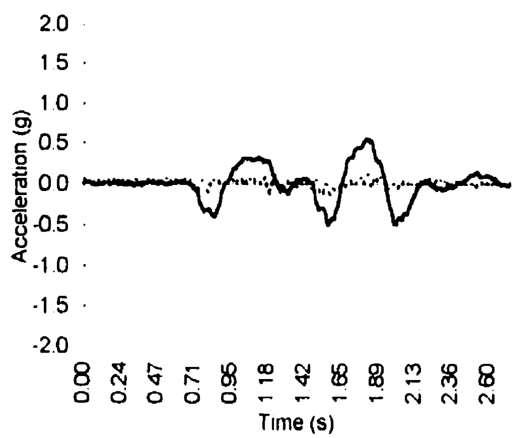


Figures D.70 to D.73
Acceleration Plots for Chevrolet Monte Carlo (Discomfort Criteria)

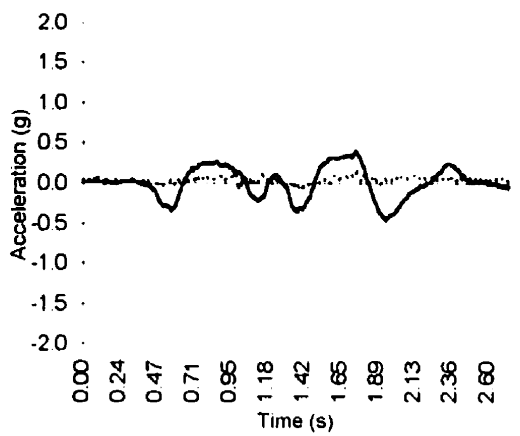
3.7 x 100 Hump at 19 km/h (1st Run)



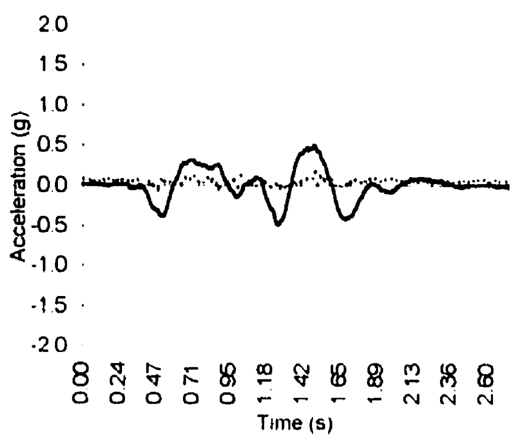
3.7 x 100 Hump at 23 km/h (1st Run)



3.7 x 100 Hump at 19 km/h (2nd Run)



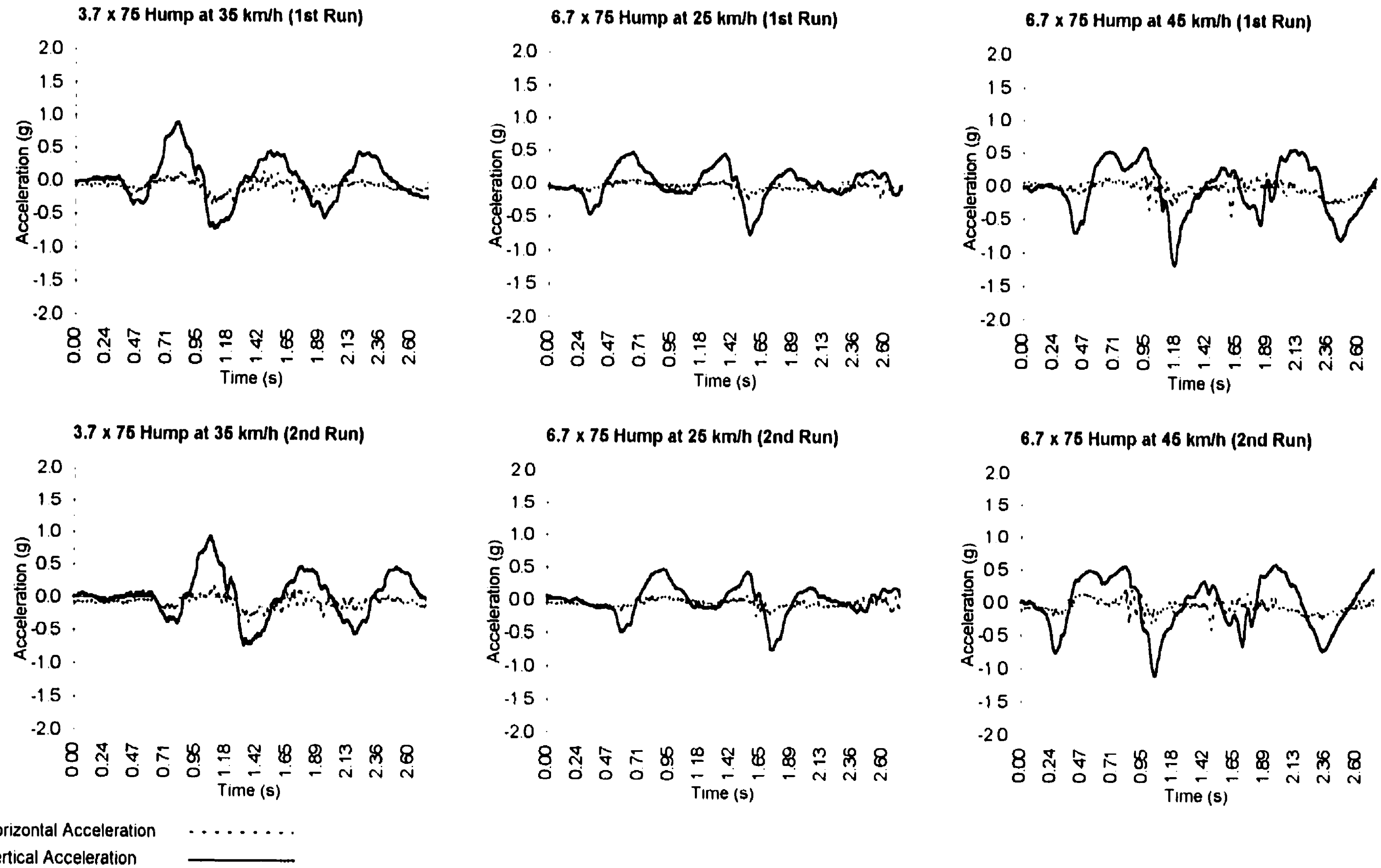
3.7 x 100 Hump at 23 km/h (2nd Run)



Horizontal Acceleration . . . .
Vertical Acceleration ————

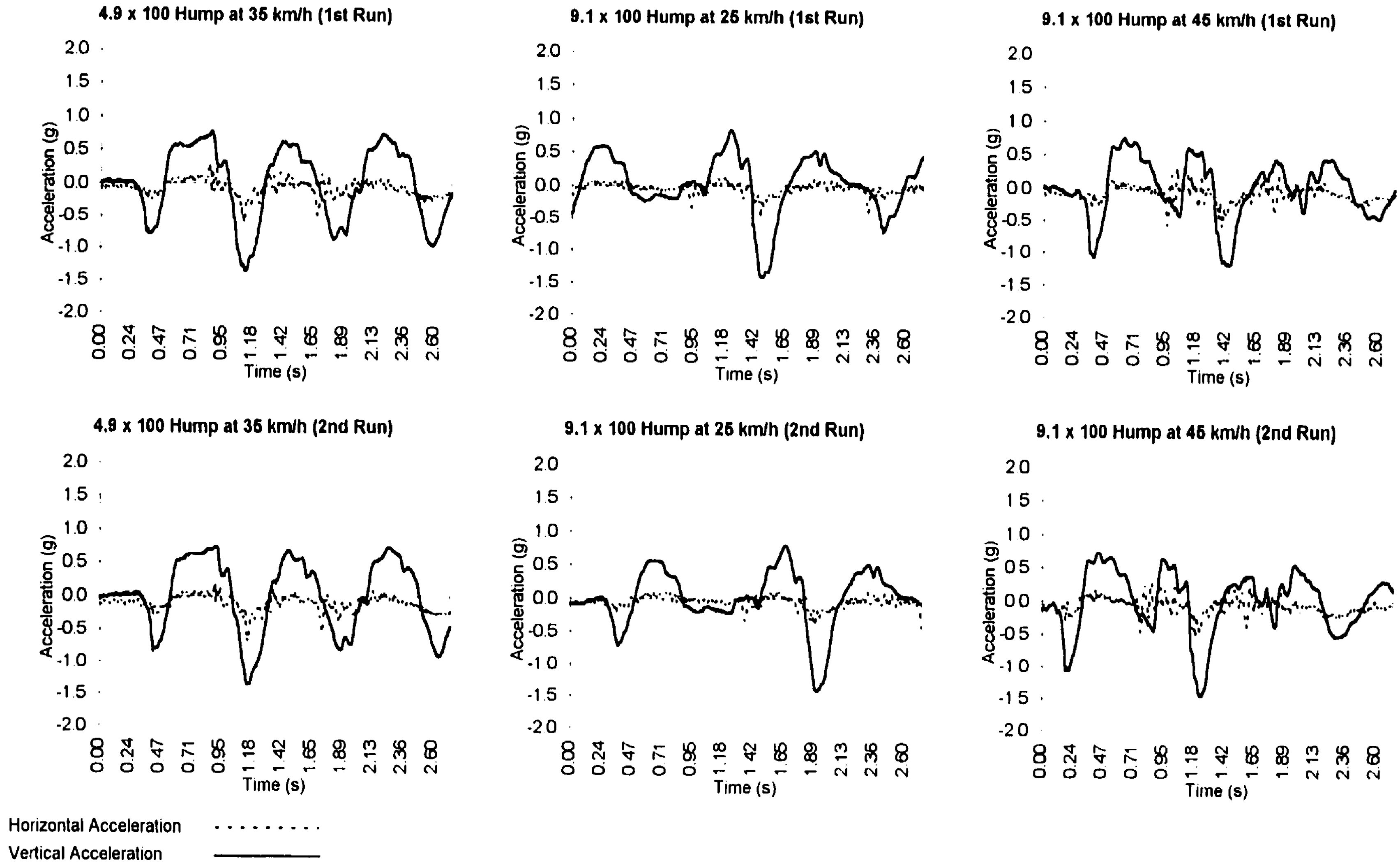
Figures D.74 to D.79

Acceleration Plots for GM Classic -- Driver Seat (Factorial Design)



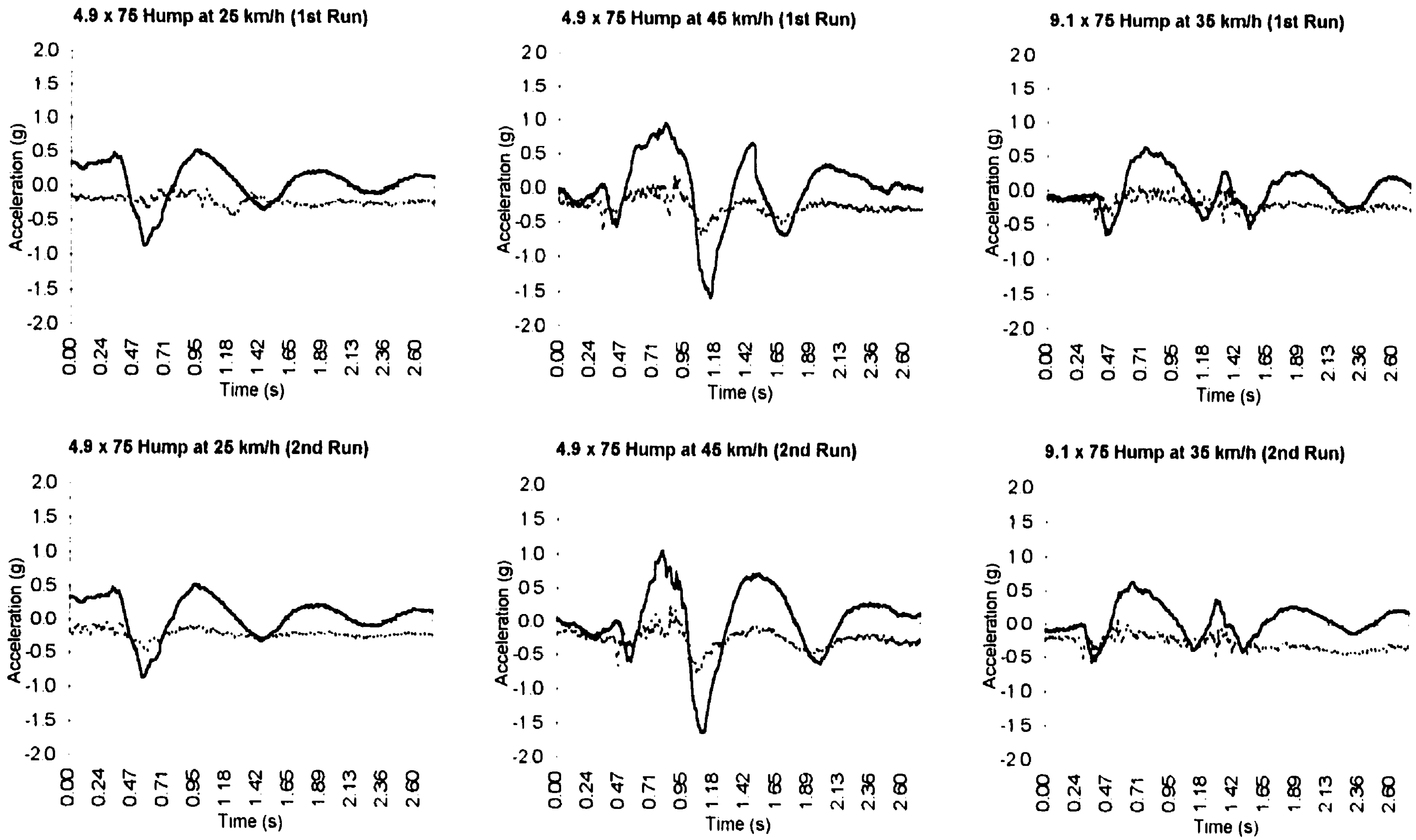
Figures D.80 to D.85

Acceleration Plots for GM Classic -- Driver Seat (Factorial Design)



Figures D.86 to D.91

Acceleration Plots for GM Classic -- Rear Seat (Factorial Design)

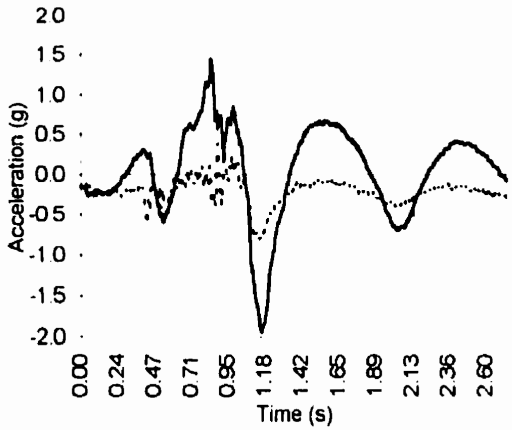


Horizontal Acceleration . . . .

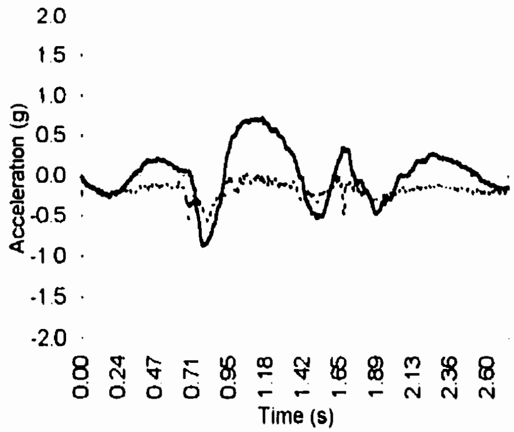
Vertical Acceleration ————

Figures D.92 to D.97
Acceleration Plots for GM Classic -- Rear Seat (Factorial Design)

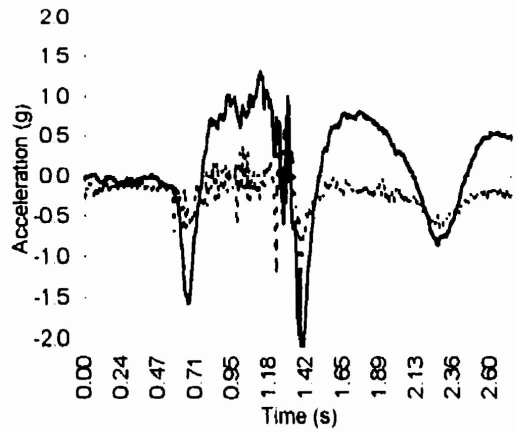
3.7 x 100 Hump at 36 km/h (1st Run)



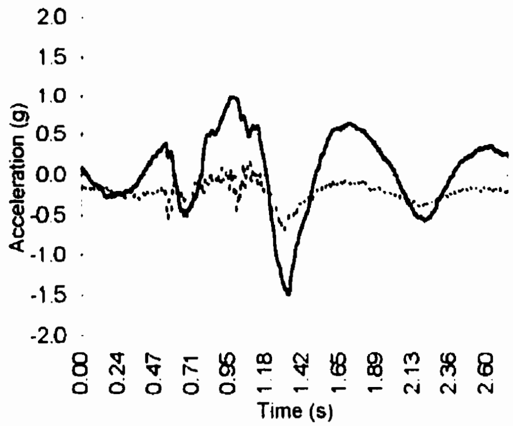
6.7 x 100 Hump at 25 km/h (1st Run)



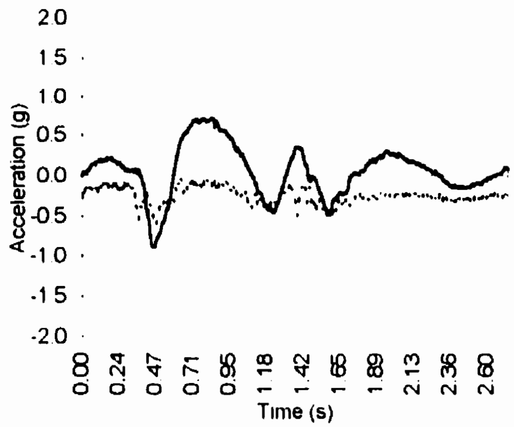
6.7 x 100 Hump at 45 km/h (1st Run)



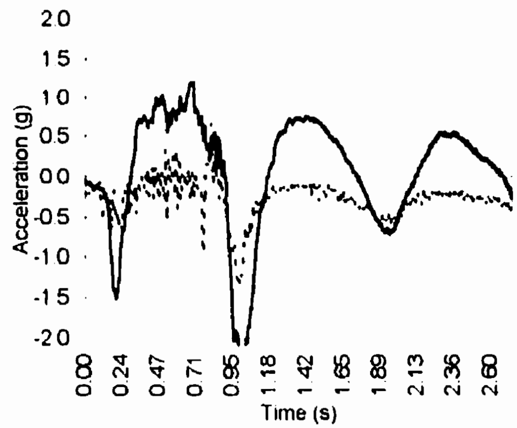
3.7 x 100 Hump at 36 km/h (2nd Run)



6.7 x 100 Hump at 25 km/h (2nd Run)

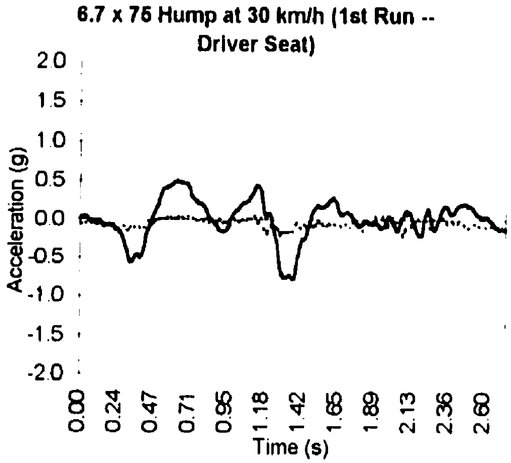


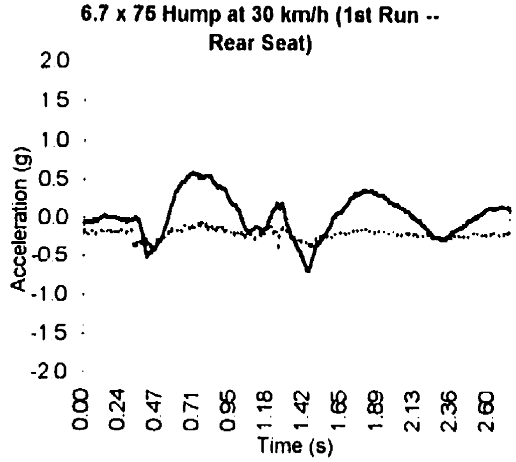
6.7 x 100 Hump at 45 km/h (2nd Run)

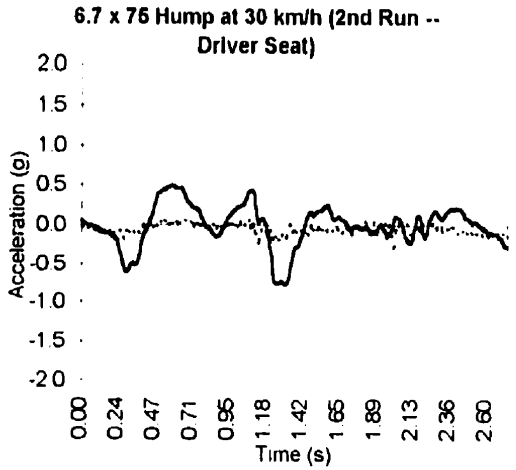


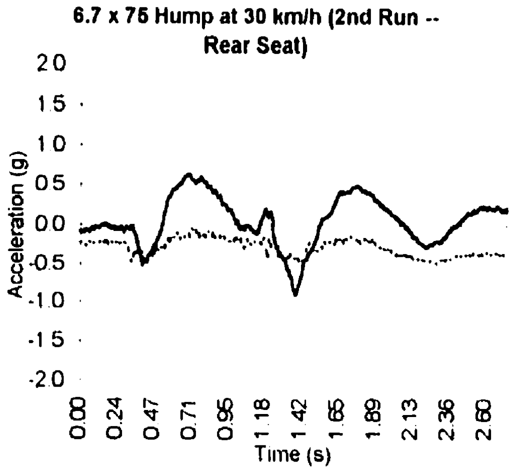
Horizontal Acceleration . . . .
Vertical Acceleration ————

Figures D.98 to D.101
Acceleration Plots for GM Classic (Discomfort Criteria)









Horizontal Acceleration . . . .
Vertical Acceleration ————

APPENDIX E
DISCOMFORT CRITERIA

Table E.1
Comparison of Discomfort Critera for 15th Percentile Speeds

				Peak Accelerations (g)				RMS and RMQ Accelerations (g)						
Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Peak a_x	Peak a_z	(a_x+a_z)	$(a_x^2+a_z^2)^{1/2}$	rms (a_x)	rms (a_z)	rmq (a_x)	rmq (a_z)	RSS	RSQ	3RSS *
37	3.7 x 100	19	Suzuki	0.30	0.50	0.80	0.59	0.08	0.18	0.11	0.24	0.14	0.17	0.16
38	3.7 x 100	19	Suzuki	0.29	0.46	0.75	0.54	0.09	0.17	0.12	0.22	0.13	0.16	0.16
43	3.7 x 100	19	Chevrolet	0.20	0.42	0.62	0.46	0.06	0.18	0.09	0.24	0.13	0.17	0.14
44	3.7 x 100	19	Chevrolet	0.16	0.45	0.61	0.48	0.04	0.18	0.00	0.23	0.13	0.16	0.13
1	3.7 x 75	20	Suzuki	0.19	0.31	0.50	0.36	0.05	0.11	0.00	0.16	0.09	0.11	0.10
2	3.7 x 75	20	Suzuki	0.16	0.33	0.49	0.36	0.05	0.12	0.00	0.16	0.09	0.12	0.10
11	3.7 x 75	20	Chevrolet	0.15	0.37	0.52	0.40	0.04	0.13	0.00	0.17	0.09	0.12	0.10
12	3.7 x 75	20	Chevrolet	0.16	0.36	0.52	0.39	0.04	0.13	0.00	0.18	0.10	0.13	0.10
55	6.7 x 100	24	Suzuki	0.29	0.48	0.77	0.56	0.04	0.15	0.08	0.22	0.11	0.15	0.12
56	6.7 x 100	24	Suzuki	0.26	0.49	0.75	0.56	0.04	0.14	0.08	0.20	0.10	0.14	0.11
61	6.7 x 100	24	Chevrolet	0.14	0.40	0.54	0.42	0.04	0.14	0.00	0.20	0.11	0.14	0.11
62	6.7 x 100	24	Chevrolet	0.16	0.38	0.55	0.42	0.04	0.15	0.00	0.20	0.11	0.14	0.12
19	6.7 x 75	29	Suzuki	0.23	0.37	0.60	0.43	0.04	0.14	0.00	0.19	0.10	0.14	0.11
20	6.7 x 75	29	Suzuki	0.21	0.35	0.56	0.41	0.04	0.13	0.00	0.18	0.09	0.12	0.10
27	6.7 x 75	29	Chevrolet	0.18	0.33	0.50	0.37	0.05	0.12	0.00	0.16	0.09	0.12	0.10
28	6.7 x 75	29	Chevrolet	0.23	0.33	0.56	0.40	0.07	0.13	0.09	0.17	0.10	0.12	0.12
Mean for Automobiles				0.21	0.39	0.60	0.45	0.05	0.14	0.04	0.19	0.11	0.14	0.12
Std. Dev. for Automobiles				0.05	0.06	0.11	0.08	0.01	0.02	0.05	0.03	0.02	0.02	0.02

* $3RSS = (1.5rms(a_x)^2+0.5rms(a_z)^2)^{1/2}$

Table E.2
Comparison of Discomfort Critera for Mean Speeds

Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle or Position	Peak Accelerations (g)				RMS and RMQ Accelerations (g)						
				Peak a_x	Peak a_z	(a_x+a_z)	$(a_x^2+a_z^2)^{1/2}$	rms (a_x)	rms (a_z)	rmq (a_x)	rmq (a_z)	RSS	RSQ	3RSS *
39	3.7 x 100	23	Suzuki	0.33	0.55	0.87	0.64	0.09	0.19	0.13	0.26	0.15	0.19	0.17
40	3.7 x 100	23	Suzuki	0.36	0.48	0.84	0.60	0.11	0.17	0.15	0.24	0.14	0.17	0.18
45	3.7 x 100	23	Chevrolet	0.16	0.57	0.73	0.59	0.04	0.21	0.00	0.29	0.15	0.20	0.16
46	3.7 x 100	23	Chevrolet	0.19	0.52	0.71	0.56	0.05	0.23	0.00	0.29	0.16	0.20	0.17
3	3.7 x 75	24	Suzuki	0.22	0.38	0.60	0.44	0.07	0.14	0.09	0.20	0.11	0.14	0.13
4	3.7 x 75	24	Suzuki	0.22	0.35	0.57	0.41	0.08	0.15	0.09	0.19	0.12	0.14	0.14
13	3.7 x 75	24	Chevrolet	0.16	0.38	0.54	0.41	0.04	0.15	0.00	0.19	0.11	0.13	0.12
14	3.7 x 75	24	Chevrolet	0.17	0.41	0.59	0.45	0.04	0.16	0.00	0.20	0.11	0.14	0.12
57	6.7 x 100	32	Suzuki	0.28	0.62	0.90	0.68	0.07	0.22	0.11	0.30	0.16	0.21	0.17
58	6.7 x 100	32	Suzuki	0.29	0.64	0.93	0.70	0.07	0.22	0.11	0.31	0.16	0.22	0.18
63	6.7 x 100	32	Chevrolet	0.20	0.51	0.72	0.55	0.05	0.20	0.00	0.26	0.15	0.18	0.15
64	6.7 x 100	32	Chevrolet	0.18	0.52	0.70	0.55	0.05	0.20	0.00	0.26	0.14	0.18	0.15
23	6.7 x 75	37	Suzuki	0.32	0.47	0.79	0.57	0.06	0.18	0.11	0.24	0.14	0.17	0.15
24	6.7 x 75	37	Suzuki	0.31	0.48	0.78	0.56	0.07	0.18	0.11	0.24	0.14	0.17	0.15
29	6.7 x 75	37	Chevrolet	0.30	0.35	0.65	0.46	0.09	0.18	0.11	0.22	0.14	0.16	0.16
30	6.7 x 75	37	Chevrolet	0.26	0.35	0.61	0.44	0.07	0.18	0.11	0.22	0.14	0.16	0.16
9	6.7 x 75	30	Driver Seat	0.26	0.78	1.04	0.82	0.07	0.27	0.09	0.38	0.20	0.27	0.20
10	6.7 x 75	30	Driver Seat	0.28	0.76	1.05	0.81	0.06	0.27	0.09	0.38	0.20	0.27	0.21
13	6.7 x 75	30	Rear Seat	0.46	0.69	1.15	0.83	0.16	0.25	0.21	0.34	0.21	0.25	0.26
14	6.7 x 75	30	Rear Seat	0.54	0.91	1.44	1.05	0.20	0.29	0.26	0.39	0.25	0.29	0.32
Mean for Automobiles				0.25	0.47	0.72	0.54	0.07	0.18	0.07	0.24	0.14	0.17	0.15
Std. Dev. for Automobiles				0.07	0.10	0.12	0.09	0.02	0.03	0.06	0.04	0.02	0.03	0.02
Mean for Buses -- Driver Seat				0.27	0.77	1.04	0.63	0.06	0.27	0.09	0.38	0.20	0.27	0.21
Std. Dev. for Buses -- Driver Seat				0.02	0.01	0.01	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean for Buses -- Rear Seat				0.50	0.80	1.30	0.82	0.18	0.27	0.23	0.37	0.23	0.27	0.29
Std. Dev. for Buses -- Rear Seat				0.06	0.15	0.21	0.01	0.03	0.03	0.04	0.04	0.03	0.03	0.04

* $3RSS = (1.5rms(a_x)^2+0.5rms(a_z)^2)^{1/2}$

Table E.3
Comparison of Discomfort Critera for 85th Percentile Speeds

				Peak Accelerations (g)				RMS and RMQ Accelerations (g)						
Run	Hump Shape (m,mm)	Speed (km/h)	Vehicle	Peak a_x	Peak a_z	(a_x+a_z)	$(a_x^2+a_z^2)^{1/2}$	rms (a_x)	rms (a_z)	rmq (a_x)	rmq (a_z)	RSS	RSQ	3RSS *
41	3.7 x 100	25	Suzuki	0.42	0.69	1.11	0.81	0.10	0.23	0.15	0.32	0.18	0.23	0.20
42	3.7 x 100	25	Suzuki	0.39	0.65	1.04	0.76	0.11	0.22	0.16	0.30	0.18	0.22	0.21
47	3.7 x 100	25	Chevrolet	0.16	0.58	0.74	0.60	0.05	0.25	0.00	0.32	0.18	0.23	0.19
48	3.7 x 100	25	Chevrolet	0.17	0.56	0.73	0.59	0.05	0.25	0.00	0.32	0.18	0.23	0.19
7	3.7 x 75	29	Suzuki	0.24	0.52	0.77	0.58	0.07	0.19	0.09	0.26	0.14	0.18	0.16
8	3.7 x 75	29	Suzuki	0.26	0.59	0.86	0.65	0.08	0.20	0.11	0.27	0.15	0.20	0.17
15	3.7 x 75	29	Chevrolet	0.16	0.32	0.48	0.36	0.05	0.15	0.00	0.19	0.11	0.13	0.12
16	3.7 x 75	29	Chevrolet	0.15	0.35	0.50	0.38	0.05	0.17	0.00	0.20	0.12	0.14	0.13
59	6.7 x 100	40	Suzuki	0.35	0.68	1.02	0.76	0.09	0.26	0.14	0.35	0.20	0.25	0.22
60	6.7 x 100	40	Suzuki	0.33	0.72	1.05	0.79	0.08	0.28	0.12	0.38	0.21	0.27	0.22
67	6.7 x 100	40	Chevrolet	0.24	0.63	0.87	0.68	0.06	0.25	0.09	0.32	0.18	0.23	0.19
68	6.7 x 100	40	Chevrolet	0.24	0.61	0.85	0.65	0.06	0.24	0.09	0.32	0.17	0.22	0.18
25	6.7 x 75	44	Suzuki	0.37	0.60	0.97	0.71	0.07	0.23	0.12	0.31	0.17	0.22	0.19
26	6.7 x 75	44	Suzuki	0.38	0.66	1.05	0.76	0.08	0.27	0.13	0.35	0.20	0.25	0.21
31	6.7 x 75	44	Chevrolet	0.26	0.53	0.80	0.59	0.07	0.19	0.09	0.26	0.14	0.19	0.16
32	6.7 x 75	44	Chevrolet	0.29	0.50	0.80	0.58	0.07	0.19	0.11	0.25	0.14	0.18	0.16
Mean for Automobiles				0.28	0.57	0.85	0.64	0.07	0.22	0.09	0.29	0.17	0.21	0.18
Std. Dev. for Automobiles				0.09	0.11	0.19	0.13	0.02	0.04	0.06	0.05	0.03	0.04	0.03

* 3RSS = $(1.5\text{rms}(a_x)^2+0.5\text{rms}(a_z)^2)^{1/2}$

Table E.4

Peak Acceleration Data for Discomfort Comparison

				Acceleration Readings				Calibrated Accelerations (g)				Peak Accelerations (g)		
Run	**Undulation**	**Speed (km/h)**	**Vehicle or Position**	**Min. a_x**	**Max. a_x**	**Min. a_z**	**Max. a_z**	**Max. a_x**	**Min. a_x**	**Max. a_z**	**Min. a_z**	**Peak a_x**	**Peak a_z**	**Comments**
1	Deceleration	50	Rear Seat	59	370	603	770	-0.063	-0.441	0.218	0.015	0.441	0.218	
2	Collector	45	Rear Seat	-196	342	476	1024	0.246	-0.407	0.373	-0.294	0.407	0.373	
3	Level Crossing	65	Rear Seat	-110	274	412	1212	0.142	-0.324	0.451	-0.523	0.324	0.523	
4	Level Crossing	65	Suzuki	-192	257	358	1256	0.241	-0.304	0.517	-0.577	0.304	0.577	

Date: Oct. 26, 1997 Road Surface: Dry Weather: +6 °C, Overcast

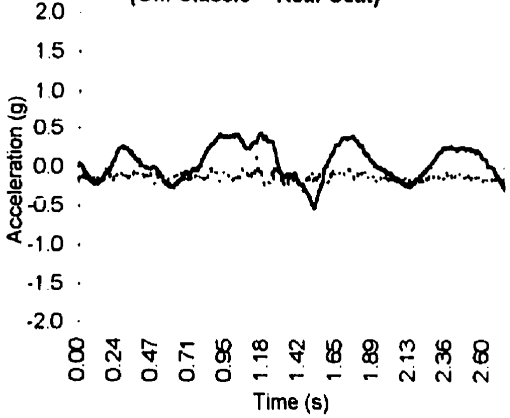
Table E.5
RMS and RMQ Acceleration Data for Discomfort Comparison

Run	Undulation	Speed (km/h)	Vehicle or Position	Time (s)	RMS Accelerations (g)				RMQ Accelerations (g)				Root Sums (g)	
					Avg. a_x^2	Avg. a_z^2	rms (a_x)	rms (a_z)	Avg. a_x^4	Avg. a_z^4	rmq (a_x)	rmq (a_z)	RSS	RSQ
1	Deceleration	50	Rear Seat	2.73	0.128	0.017	0.217	0.078	0.017	0.000	0.280	0.102	0.163	0.199
2	Collector	45	Rear Seat	0.86	0.003	0.033	0.058	0.195	0.001	0.002	0.197	0.222	0.144	0.177
3	Level Crossing	65	Rear Seat	2.63	0.019	0.054	0.085	0.143	0.001	0.006	0.123	0.218	0.118	0.158
4	Level Crossing	65	Suzuki	2.38	0.004	0.049	0.043	0.144	0.000	0.006	0.081	0.224	0.106	0.159

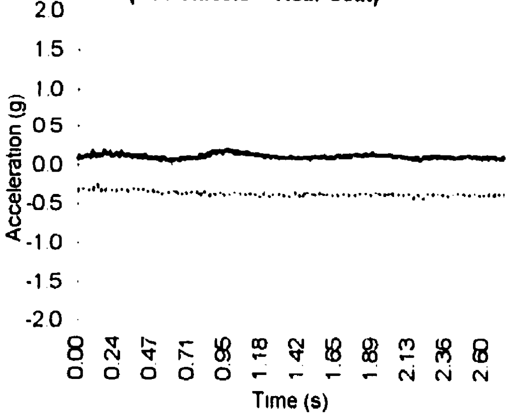
Date: Oct. 26, 1997 Road Surface: Dry Weather: +6 °C, Overcast

Figures E.1 to E.4
Acceleration Plots for Discomfort Comparison

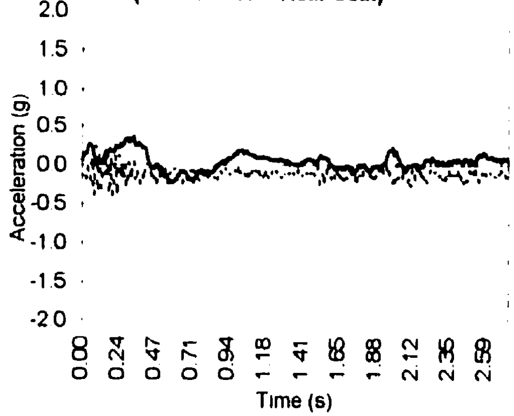
Railway Level Crossing at 65 km/h (GM Classic -- Rear Seat)



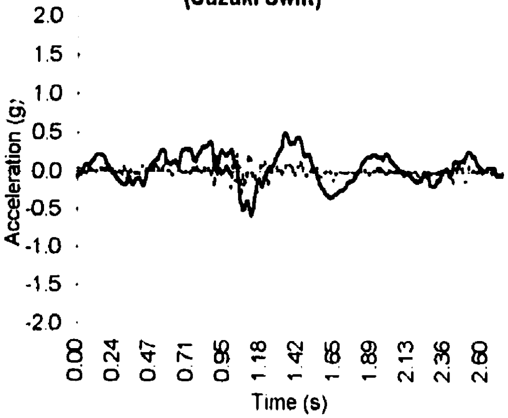
Deceleration from 60 km/h (GM Classic -- Rear Seat)



"Average" Collector Road at 45 km/h (GM Classic -- Rear Seat)



Railway Level Crossing at 65 km/h (Suzuki Swift)



Horizontal Acceleration . . . .
Vertical Acceleration ———

APPENDIX F
REGRESSION MODELLING

Table F.1
Data Analysis Input Variables

		Main Effects				Dummy Variables			Linear Interactions					
No.	**ACC (RSS Accel.)**	**L**	**H**	**S**	**V**	**D1**	**D2**	**D3**	**LH**	**LS**	**LD1**	**LD2**	**LD3**	**HS**
1	0.12	3.7	75	25	*Suz*	1	0	0	277.5	92.5	3.7	0	0	1875
2	0.13	3.7	75	25	*Suz*	1	0	0	277.5	92.5	3.7	0	0	1875
3	0.20	3.7	75	35	*Driver*	0	1	0	277.5	129.5	0	3.7	0	2625
4	0.20	3.7	75	35	*Driver*	0	1	0	277.5	129.5	0	3.7	0	2625
5	0.27	3.7	75	45	*Suz*	1	0	0	277.5	166.5	3.7	0	0	3375
6	0.25	3.7	75	45	*Suz*	1	0	0	277.5	166.5	3.7	0	0	3375
7	0.19	4.9	75	25	*Rear*	0	0	1	367.5	122.5	0	0	4.9	1875
8	0.22	4.9	75	25	*Rear*	0	0	1	367.5	122.5	0	0	4.9	1875
9	0.13	4.9	75	35	*Chev*	0	0	0	367.5	171.5	0	0	0	2625
10	0.12	4.9	75	35	*Chev*	0	0	0	367.5	171.5	0	0	0	2625
11	0.41	4.9	75	45	*Rear*	0	0	1	367.5	220.5	0	0	4.9	3375
12	0.40	4.9	75	45	*Rear*	0	0	1	367.5	220.5	0	0	4.9	3375
13	0.15	6.7	75	25	*Driver*	0	1	0	502.5	167.5	0	6.7	0	1875
14	0.15	6.7	75	25	*Driver*	0	1	0	502.5	167.5	0	6.7	0	1875
15	0.11	6.7	75	35	*Suz*	1	0	0	502.5	234.5	6.7	0	0	2625
16	0.13	6.7	75	35	*Suz*	1	0	0	502.5	234.5	6.7	0	0	2625
17	0.20	6.7	75	45	*Driver*	0	1	0	502.5	301.5	0	6.7	0	3375
18	0.20	6.7	75	45	*Driver*	0	1	0	502.5	301.5	0	6.7	0	3375
19	0.08	9.1	75	25	*Chev*	0	0	0	682.5	227.5	0	0	0	1875
20	0.07	9.1	75	25	*Chev*	0	0	0	682.5	227.5	0	0	0	1875
21	0.18	9.1	75	35	*Rear*	0	0	1	682.5	318.5	0	0	9.1	2625
22	0.20	9.1	75	35	*Rear*	0	0	1	682.5	318.5	0	0	9.1	2625
23	0.14	9.1	75	45	*Chev*	0	0	0	682.5	409.5	0	0	0	3375
24	0.12	9.1	75	45	*Chev*	0	0	0	682.5	409.5	0	0	0	3375
25	0.18	3.7	100	25	*Chev*	0	0	0	370	92.5	0	0	0	2500
26	0.18	3.7	100	25	*Chev*	0	0	0	370	92.5	0	0	0	2500
27	0.40	3.7	100	35	*Rear*	0	0	1	370	129.5	0	0	3.7	3500
28	0.34	3.7	100	35	*Rear*	0	0	1	370	129.5	0	0	3.7	3500
29	0.26	3.7	100	45	*Chev*	0	0	0	370	166.5	0	0	0	4500
30	0.26	3.7	100	45	*Chev*	0	0	0	370	166.5	0	0	0	4500
31	0.14	4.9	100	25	*Suz*	1	0	0	490	122.5	4.9	0	0	2500
32	0.16	4.9	100	25	*Suz*	1	0	0	490	122.5	4.9	0	0	2500
33	0.28	4.9	100	35	*Driver*	0	1	0	490	171.5	0	4.9	0	3500
34	0.27	4.9	100	35	*Driver*	0	1	0	490	171.5	0	4.9	0	3500
35	0.38	4.9	100	45	*Suz*	1	0	0	490	220.5	4.9	0	0	4500
36	0.41	4.9	100	45	*Suz*	1	0	0	490	220.5	4.9	0	0	4500
37	0.23	6.7	100	25	*Rear*	0	0	1	670	167.5	0	0	6.7	2500
38	0.24	6.7	100	25	*Rear*	0	0	1	670	167.5	0	0	6.7	2500
39	0.16	6.7	100	35	*Chev*	0	0	0	670	234.5	0	0	0	3500
40	0.18	6.7	100	35	*Chev*	0	0	0	670	234.5	0	0	0	3500
41	0.51	6.7	100	45	*Rear*	0	0	1	670	301.5	0	0	6.7	4500
42	0.54	6.7	100	45	*Rear*	0	0	1	670	301.5	0	0	6.7	4500
43	0.18	9.1	100	25	*Driver*	0	1	0	910	227.5	0	9.1	0	2500
44	0.19	9.1	100	25	*Driver*	0	1	0	910	227.5	0	9.1	0	2500
45	0.18	9.1	100	35	*Suz*	1	0	0	910	318.5	9.1	0	0	3500
46	0.18	9.1	100	35	*Suz*	1	0	0	910	318.5	9.1	0	0	3500
47	0.25	9.1	100	45	*Driver*	0	1	0	910	409.5	0	9.1	0	4500
48	0.24	9.1	100	45	*Driver*	0	1	0	910	409.5	0	9.1	0	4500

Table F.1
Data Analysis Input Variables

	Linear Interactions						Quadratic Interactions					
No.	HD1	HD2	HD3	SD1	SD2	SD3	LSQ (L^2)	SSQ (S^2)	LSQH (L^2H)	LSQS (L^2S)	LSSQ (LS^2)	HSSQ (HS^2)
1	75	0	0	25	0	0	13.69	625	1026.75	342.25	2312.5	46875
2	75	0	0	25	0	0	13.69	625	1026.75	342.25	2312.5	46875
3	0	75	0	0	35	0	13.69	1225	1026.75	479.15	4532.5	91875
4	0	75	0	0	35	0	13.69	1225	1026.75	479.15	4532.5	91875
5	75	0	0	45	0	0	13.69	2025	1026.75	616.05	7492.5	151875
6	75	0	0	45	0	0	13.69	2025	1026.75	616.05	7492.5	151875
7	0	0	75	0	0	25	24.01	625	1800.75	600.25	3062.5	46875
8	0	0	75	0	0	25	24.01	625	1800.75	600.25	3062.5	46875
9	0	0	0	0	0	0	24.01	1225	1800.75	840.35	6002.5	91875
10	0	0	0	0	0	0	24.01	1225	1800.75	840.35	6002.5	91875
11	0	0	75	0	0	45	24.01	2025	1800.75	1080.45	9922.5	151875
12	0	0	75	0	0	45	24.01	2025	1800.75	1080.45	9922.5	151875
13	0	75	0	0	25	0	44.89	625	3366.75	1122.25	4187.5	46875
14	0	75	0	0	25	0	44.89	625	3366.75	1122.25	4187.5	46875
15	75	0	0	35	0	0	44.89	1225	3366.75	1571.15	8207.5	91875
16	75	0	0	35	0	0	44.89	1225	3366.75	1571.15	8207.5	91875
17	0	75	0	0	45	0	44.89	2025	3366.75	2020.05	13567.5	151875
18	0	75	0	0	45	0	44.89	2025	3366.75	2020.05	13567.5	151875
19	0	0	0	0	0	0	82.81	625	6210.75	2070.25	5687.5	46875
20	0	0	0	0	0	0	82.81	625	6210.75	2070.25	5687.5	46875
21	0	0	75	0	0	35	82.81	1225	6210.75	2898.35	11147.5	91875
22	0	0	75	0	0	35	82.81	1225	6210.75	2898.35	11147.5	91875
23	0	0	0	0	0	0	82.81	2025	6210.75	3726.45	18427.5	151875
24	0	0	0	0	0	0	82.81	2025	6210.75	3726.45	18427.5	151875
25	0	0	0	0	0	0	13.69	625	1369	342.25	2312.5	62500
26	0	0	0	0	0	0	13.69	625	1369	342.25	2312.5	62500
27	0	0	100	0	0	35	13.69	1225	1369	479.15	4532.5	122500
28	0	0	100	0	0	35	13.69	1225	1369	479.15	4532.5	122500
29	0	0	0	0	0	0	13.69	2025	1369	616.05	7492.5	202500
30	0	0	0	0	0	0	13.69	2025	1369	616.05	7492.5	202500
31	100	0	0	25	0	0	24.01	625	2401	600.25	3062.5	62500
32	100	0	0	25	0	0	24.01	625	2401	600.25	3062.5	62500
33	0	100	0	0	35	0	24.01	1225	2401	840.35	6002.5	122500
34	0	100	0	0	35	0	24.01	1225	2401	840.35	6002.5	122500
35	100	0	0	45	0	0	24.01	2025	2401	1080.45	9922.5	202500
36	100	0	0	45	0	0	24.01	2025	2401	1080.45	9922.5	202500
37	0	0	100	0	0	25	44.89	625	4489	1122.25	4187.5	62500
38	0	0	100	0	0	25	44.89	625	4489	1122.25	4187.5	62500
39	0	0	0	0	0	0	44.89	1225	4489	1571.15	8207.5	122500
40	0	0	0	0	0	0	44.89	1225	4489	1571.15	8207.5	122500
41	0	0	100	0	0	45	44.89	2025	4489	2020.05	13567.5	202500
42	0	0	100	0	0	45	44.89	2025	4489	2020.05	13567.5	202500
43	0	100	0	0	25	0	82.81	625	8281	2070.25	5687.5	62500
44	0	100	0	0	25	0	82.81	625	8281	2070.25	5687.5	62500
45	100	0	0	35	0	0	82.81	1225	8281	2898.35	11147.5	122500
46	100	0	0	35	0	0	82.81	1225	8281	2898.35	11147.5	122500
47	0	100	0	0	45	0	82.81	2025	8281	3726.45	18427.5	202500
48	0	100	0	0	45	0	82.81	2025	8281	3726.45	18427.5	202500

Table F.1
Data Analysis Input Variables

	Quadratic Interactions (Centred)					
No.	LSQC (L_c^2)	SSQC (S_c^2)	LSQCH (L_c^2H)	LSQCS (L_c^2S)	LSSQC (LS_c^2)	HSSQC (HS_c^2)
1	5.76	100	432	144	370	7500
2	5.76	100	432	144	370	7500
3	5.76	0	432	201.6	0	0
4	5.76	0	432	201.6	0	0
5	5.76	100	432	259.2	370	7500
6	5.76	100	432	259.2	370	7500
7	1.44	100	108	36	490	7500
8	1.44	100	108	36	490	7500
9	1.44	0	108	50.4	0	0
10	1.44	0	108	50.4	0	0
11	1.44	100	108	64.8	490	7500
12	1.44	100	108	64.8	490	7500
13	0.36	100	27	9	670	7500
14	0.36	100	27	9	670	7500
15	0.36	0	27	12.6	0	0
16	0.36	0	27	12.6	0	0
17	0.36	100	27	16.2	670	7500
18	0.36	100	27	16.2	670	7500
19	9	100	675	225	910	7500
20	9	100	675	225	910	7500
21	9	0	675	315	0	0
22	9	0	675	315	0	0
23	9	100	675	405	910	7500
24	9	100	675	405	910	7500
25	5.76	100	576	144	370	10000
26	5.76	100	576	144	370	10000
27	5.76	0	576	201.6	0	0
28	5.76	0	576	201.6	0	0
29	5.76	100	576	259.2	370	10000
30	5.76	100	576	259.2	370	10000
31	1.44	100	144	36	490	10000
32	1.44	100	144	36	490	10000
33	1.44	0	144	50.4	0	0
34	1.44	0	144	50.4	0	0
35	1.44	100	144	64.8	490	10000
36	1.44	100	144	64.8	490	10000
37	0.36	100	36	9	670	10000
38	0.36	100	36	9	670	10000
39	0.36	0	36	12.6	0	0
40	0.36	0	36	12.6	0	0
41	0.36	100	36	16.2	670	10000
42	0.36	100	36	16.2	670	10000
43	9	100	900	225	910	10000
44	9	100	900	225	910	10000
45	9	0	900	315	0	0
46	9	0	900	315	0	0
47	9	100	900	405	910	10000
48	9	100	900	405	910	10000

Exhibit F.1
Descriptive Statistics for Input Variables

Number of valid observations (listwise) = 48.00

Variable	Mean	Std Dev	Sum	Valid N	Label
ACC	.22	.11	10.71	48	Dependent Variable
D1	.25	.44	12.00	48	
D2	.25	.44	12.00	48	
D3	.25	.44	12.00	48	
H	87.50	12.63	4200.00	48	Height (mm)
HD1	21.88	38.81	1050.00	48	
HD2	21.87	38.81	1050.00	48	
HD3	21.87	38.81	1050.00	48	
HS	3062.50	852.87	147000.00	48	
HSSQ	113020.83	53761.96	5425000.00	48	
HSSQC	5833.33	4294.15	280000.00	48	
L	6.10	2.06	292.80	48	Length (m)
LD1	1.38	2.59	66.00	48	
LD2	1.67	3.10	80.40	48	
LD3	1.50	2.77	72.00	48	
LH	533.75	197.41	25620.00	48	
LS	213.50	89.41	10248.00	48	
LSQ	41.35	26.72	1984.80	48	
LSQC	4.14	3.49	198.72	48	
LSQCH	362.25	313.25	17388.00	48	
LSQCS	144.90	130.15	6955.20	48	
LSQH	3618.12	2419.17	173670.00	48	
LSQS	1447.25	1019.26	69468.00	48	
LSSQ	7879.17	4576.36	378200.00	48	
LSSQC	406.67	335.61	19520.00	48	
S	35.00	8.25	1680.00	48	Speed (km/h)
SD1	8.75	15.86	420.00	48	
SD2	8.75	15.86	420.00	48	
SD3	8.75	15.86	420.00	48	
SSQ	1291.67	579.56	62000.00	48	
SSQC	66.67	47.64	3200.00	48	

SPSS 6.1 for Windows

Exhibit F.2
Pearson Correlation Coefficients

- - Correlation Coefficients - -

	D1	D2	D3	H	HD1	HD2
D1	1.0000	-.3333*	-.3333*	.0000	.9867**	-.3289*
D2	-.3333*	1.0000	-.3333*	.0000	-.3289*	.9867**
D3	-.3333*	-.3333*	1.0000	.0000	-.3289*	-.3289*
H	.0000	.0000	.0000	1.0000	.0814	.0814
HD1	.9867**	-.3289*	-.3289*	.0814	1.0000	-.3245*
HD2	-.3289*	.9867**	-.3289*	.0814	-.3245*	1.0000
HD3	-.3289*	-.3289*	.9867**	.0814	-.3245*	-.3245*
HS	.0000	.0000	.0000	.5184**	.0422	.0422
HSSQ	.0000	.0000	.0000	.3035*	.0247	.0247
HSSQC	.0000	.0000	.0000	.1961	.0160	.0160
L	-.1703	.1703	-.0284	.0000	-.1360	.2080
LD1	.9290**	-.3097*	-.3097*	.0780	.9420**	-.3055*
LD2	-.3153*	.9459**	-.3153*	.0815	-.3111*	.9598**
LD3	-.3160*	-.3160*	.9479**	-.0274	-.3118*	-.3118*
LH	-.1256	.1921	-.0369	.3903**	-.0661	.2609*
LS	-.1370	.1370	-.0228	.0000	-.1095	.1674
LSQ	-.1637	.1637	-.0502	.0000	-.1315	.2058
LSQC	-.0301	.0301	-.1803	.0000	-.0297	.0805
LSQCH	-.0293	.0796	-.1970	.1670	-.0159	.1424
LSQCS	-.0282	.0282	-.1695	.0000	-.0279	.0756
LSQH	-.1289	.2016	-.0623	.2159	-.0837	.2624*
LSQS	-.1503	.1503	-.0461	.0000	-.1207	.1888
LSSQ	-.1090	.1090	-.0182	.0000	-.0892	.1310
LSSQC	-.2086	.2086	-.0348	.0000	-.1960	.2254
S	.0000	.0000	.0000	.0000	.0000	.0000
SD1	.9656**	-.3219*	-.3219*	.0000	.9527**	-.3176*
SD2	-.3219*	.9656**	-.3219*	.0000	-.3176*	.9527**
SD3	-.3219*	-.3219*	.9656**	.0000	-.3176*	-.3176*
SSQ	.0000	.0000	.0000	.0000	.0000	.0000
SSQC	.0000	.0000	.0000	.0000	.0000	.0000

* - Signif. LE .05   ** - Signif. LE .01   (1-tailed)

" . " is printed if a coefficient cannot be computed

Exhibit F.2
Pearson Correlation Coefficients

- - Correlation Coefficients - -

	HD3	HS	HSSQ	HSSQC	L	LD1
D1	-.3289*	.0000	.0000	.0000	-.1703	.9290**
D2	-.3289*	.0000	.0000	.0000	.1703	-.3097*
D3	.9867**	.0000	.0000	.0000	-.0284	-.3097*
H	.0814	.5184**	.3035*	.1961	.0000	.0780
HD1	-.3245*	.0422	.0247	.0160	-.1360	.9420**
HD2	-.3245*	.0422	.0247	.0160	.2080	-.3055*
HD3	1.0000	.0422	.0247	.0160	-.0400	-.3055*
HS	.0422	1.0000	.9694**	.1017	.0000	.0404
HSSQ	.0247	.9694**	1.0000	.1363	.0000	.0105
HSSQC	.0160	.1017	.1363	1.0000	.0000	-.1492
L	-.0400	.0000	.0000	.0000	1.0000	.0144
LD1	-.3055*	.0404	.0105	-.1492	.0144	1.0000
LD2	-.3111*	.0423	.0357	.1535	.3197*	-.2929*
LD3	.9263**	-.0142	-.0086	-.0089	.1098	-.2935*
LH	-.0161	.2024	.1185	.0766	.9114**	.0740
LS	-.0322	.4765**	.5292**	.0000	.8049**	.0116
LSQ	-.0636	.0000	.0000	.0000	.9929**	.0162
LSQC	-.1991	.0000	.0000	.0000	.4145**	.0208
LSQCH	-.2050	.0865	.0507	.0327	.4046**	.0537
LSQCS	-.1871	.2222	.2467*	.0000	.3895**	.0196
LSQH	-.0584	.1119	.0655	.0423	.9597**	.0655
LSQS	-.0583	.2834*	.3147*	.0000	.9111**	.0149
LSSQ	-.0235	.6518**	.7287**	.0616	.5804**	-.0132
LSSQC	-.0196	.0000	.0671	.8405**	.4085**	-.2878*
S	.0000	.8465**	.9401**	.0000	.0000	.0000
SD1	-.3176*	.1101	.1223	.0000	-.1644	.8970**
SD2	-.3176*	.1101	.1223	.0000	.1644	-.2990*
SD3	.9527**	.1101	.1223	.0000	-.0274	-.2990*
SSQ	.0000	.8437**	.9433**	.0798	.0000	-.0136
SSQC	.0000	.0000	.0775	.9707**	.0000	-.1655

* - Signif. LE .05   ** - Signif. LE .01   (1-tailed)

" . " is printed if a coefficient cannot be computed

Exhibit F.2
Pearson Correlation Coefficients

- - Correlation Coefficients - -

	LD2	LD3	LH	LS	LSQ	LSQC
D1	-.3153*	-.3160*	-.1256	-.1370	-.1637	-.0301
D2	.9459**	-.3160*	.1921	.1370	.1637	.0301
D3	-.3153*	.9479**	-.0369	-.0228	-.0502	-.1803
H	.0815	-.0274	.3903**	.0000	.0000	.0000
HD1	-.3111*	-.3118*	-.0661	-.1095	-.1315	-.0297
HD2	.9598**	-.3118*	.2609*	.1674	.2058	.0805
HD3	-.3111*	.9263**	-.0161	-.0322	-.0636	-.1991
HS	.0423	-.0142	.2024	.4765**	.0000	.0000
HSSQ	.0357	-.0086	.1185	.5292**	.0000	.0000
HSSQC	.1535	-.0089	.0766	.0000	.0000	.0000
L	.3197*	.1098	.9114**	.8049**	.9929**	.4145**
LD1	-.2929*	-.2935*	.0740	.0116	.0162	.0208
LD2	1.0000	-.2989*	.3663**	.2573*	.3158*	.1201
LD3	-.2989*	1.0000	.0735	.0884	.0876	-.1182
LH	.3663**	.0735	1.0000	.7336**	.9049**	.3778**
LS	.2573*	.0884	.7336**	1.0000	.7992**	.3336*
LSQ	.3158*	.0876	.9049**	.7992**	1.0000	.5198**
LSQC	.1201	-.1182	.3778**	.3336*	.5198**	1.0000
LSQCH	.1965	-.1582	.4414**	.3256*	.5074**	.9761**
LSQCS	.1128	-.1111	.3550**	.4783**	.4885**	.9397**
LSQH	.3742**	.0580	.9768**	.7725**	.9666**	.5025**
LSQS	.2898*	.0804	.8304**	.9617**	.9177**	.4770**
LSSQ	.2035	.0576	.5290**	.9488**	.5762**	.2405*
LSSQC	.3760**	-.0394	.3723**	.3288*	.4056**	.1693
S	.0000	.0000	.0000	.5629**	.0000	.0000
SD1	-.3045*	-.3051*	-.1213	-.0807	-.1581	-.0290
SD2	.9134**	-.3051*	.1855	.2271	.1581	.0290
SD3	-.3045*	.9153**	-.0357	.0476	-.0485	-.1741
SSQ	.0114	-.0021	.0000	.5610**	.0000	.0000
SSQC	.1383	-.0258	.0000	.0000	.0000	.0000

* - Signif. LE .05   ** - Signif. LE .01   (1-tailed)

" . " is printed if a coefficient cannot be computed

Exhibit F.2
Pearson Correlation Coefficients

- - Correlation Coefficients - -

	LSQCH	LSQCS	LSQH	LSQS	LSSQ	LSSQC
D1	-.0293	-.0282	-.1289	-.1503	-.1090	-.2086
D2	.0796	.0282	.2016	.1503	.1090	.2086
D3	-.1970	-.1695	-.0623	-.0461	-.0182	-.0348
H	.1670	.0000	.2159	.0000	.0000	.0000
HD1	-.0159	-.0279	-.0837	-.1207	-.0892	-.1960
HD2	.1424	.0756	.2624*	.1888	.1310	.2254
HD3	-.2050	-.1871	-.0584	-.0583	-.0235	-.0196
HS	.0865	.2222	.1119	.2834*	.6518**	.0000
HSSQ	.0507	.2467*	.0655	.3147*	.7287**	.0671
HSSQC	.0327	.0000	.0423	.0000	.0616	.8405**
L	.4046**	.3895**	.9597**	.9111**	.5804**	.4085**
LD1	.0537	.0196	.0655	.0149	-.0132	-.2878*
LD2	.1965	.1128	.3742**	.2898*	.2035	.3760**
LD3	-.1582	-.1111	.0580	.0804	.0576	-.0394
LH	.4414**	.3550**	.9768**	.8304**	.5290**	.3723**
LS	.3256*	.4783**	.7725**	.9617**	.9488**	.3288*
LSQ	.5074**	.4885**	.9666**	.9177**	.5762**	.4056**
LSQC	.9761**	.9397**	.5025**	.4770**	.2405*	.1693
LSQCH	1.0000	.9172**	.5365**	.4656**	.2348	.1652
LSQCS	.9172**	1.0000	.4722**	.5605**	.4515**	.1591
LSQH	.5365**	.4722**	1.0000	.8870**	.5570**	.3920**
LSQS	.4656**	.5605**	.8870**	1.0000	.8411**	.3722**
LSSQ	.2348	.4515**	.5570**	.8411**	1.0000	.2982*
LSSQC	.1652	.1591	.3920**	.3722**	.2982*	1.0000
S	.0000	.2625*	.0000	.3347*	.7699**	.0000
SD1	-.0283	.0024	-.1244	-.1252	-.0347	-.2014
SD2	.0769	.0659	.1946	.2123	.2349	.2014
SD3	-.1902	-.1562	-.0601	-.0082	.0777	-.0336
SSQ	.0000	.2616*	.0000	.3336*	.7725**	.0712
SSQC	.0000	.0000	.0000	.0000	.0635	.8659**

* - Signif. LE .05   ** - Signif. LE .01   (1-tailed)

" . " is printed if a coefficient cannot be computed

Exhibit F.2

Pearson Correlation Coefficients

\- - Correlation Coefficients - -

	S	SD1	SD2	SD3	SSQ	SSQC
D1	.0000	.9656**	-.3219*	-.3219*	.0000	.0000
D2	.0000	-.3219*	.9656**	-.3219*	.0000	.0000
D3	.0000	-.3219*	-.3219*	.9656**	.0000	.0000
H	.0000	.0000	.0000	.0000	.0000	.0000
HD1	.0000	.9527**	-.3176*	-.3176*	.0000	.0000
HD2	.0000	-.3176*	.9527**	-.3176*	.0000	.0000
HD3	.0000	-.3176*	-.3176*	.9527**	.0000	.0000
HS	.8465**	.1101	.1101	.1101	.8437**	.0000
HSSQ	.9401**	.1223	.1223	.1223	.9433**	.0775
HSSQC	.0000	.0000	.0000	.0000	.0798	.9707**
L	.0000	-.1644	.1644	-.0274	.0000	.0000
LD1	.0000	.8970**	-.2990*	-.2990*	-.0136	-.1655
LD2	.0000	-.3045*	.9134**	-.3045*	.0114	.1383
LD3	.0000	-.3051*	-.3051*	.9153**	-.0021	-.0258
LH	.0000	-.1213	.1855	-.0357	.0000	.0000
LS	.5629**	-.0807	.2271	.0476	.5610**	.0000
LSQ	.0000	-.1581	.1581	-.0485	.0000	.0000
LSQC	.0000	-.0290	.0290	-.1741	.0000	.0000
LSQCH	.0000	-.0283	.0769	-.1902	.0000	.0000
LSQCS	.2625*	.0024	.0659	-.1562	.2616*	.0000
LSQH	.0000	-.1244	.1946	-.0601	.0000	.0000
LSQS	.3347*	-.1252	.2123	-.0082	.3336*	.0000
LSSQ	.7699**	-.0347	.2349	.0777	.7725**	.0635
LSSQC	.0000	-.2014	.2014	-.0336	.0712	.8659**
S	1.0000	.1301	.1301	.1301	.9966**	.0000
SD1	.1301	1.0000	-.3108*	-.3108*	.1296	.0000
SD2	.1301	-.3108*	1.0000	-.3108*	.1296	.0000
SD3	.1301	-.3108*	-.3108*	1.0000	.1296	.0000
SSQ	.9966**	.1296	.1296	.1296	1.0000	.0822
SSQC	.0000	.0000	.0000	.0000	.0822	1.0000

* - Signif. LE .05 ** - Signif. LE .01 (1-tailed)

" . " is printed if a coefficient cannot be computed

SPSS 6.1 for Windows

Exhibit F.3
Multiple Regression Analysis for Enter Uncentred Model

```
           * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Listwise Deletion of Missing Data

Equation Number 1    Dependent Variable..   ACC

Block Number  1.  Method:  Enter
   D1        D2        D3        H         HD1       HD2       HD3       HS
   HSSQ      L         LD1       LD2       LD3       LH        LS        LSQ
   LSQH      LSQS      LSSQ      S         SD1       SD2       SD3       SSQ


Variable(s) Entered on Step Number
   1..     SSQ
   2..     LSQH
   3..     LD3
   4..     H
   5..     LD1
   6..     SD2
   7..     SD1
   8..     SD3
   9..     LD2
  10..     LSSQ
  11..     HD3
  12..     HD1
  13..     HD2
  14..     L
  15..     HSSQ
  16..     D1
  17..     D2
  18..     LSQ
  19..     D3
  20..     S
  21..     LSQS


Multiple R           .99502
R Square             .99007
Adjusted R Square    .98206
Standard Error       .01424

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression          21              .52556           .02503
Residual            26              .00527           .00020

F =      123.49825       Signif F =  .0000
```

Exhibit F.3
Multiple Regression Analysis for Enter Uncentred Model

```
        * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   ACC


------------------------ Variables in the Equation -------------------------
```

Variable	B	SE B	Beta	Tolerance	VIF	T
D1	-.225714	.065636	-.929398	.005227	191.327	-3.439
D2	.131367	.069070	.540913	.004720	211.875	1.902
D3	-.118648	.074891	-.488542	.004015	249.087	-1.584
H	2.71165E-04	6.4623E-04	.032232	.064700	15.456	.420
HD1	8.46374E-04	5.8691E-04	.309060	.008312	120.312	1.442
HD2	9.91224E-04	6.3067E-04	.361953	.007198	138.924	1.572
HD3	6.33220E-04	5.9195E-04	.231225	.008171	122.388	1.070
HSSQ	1.65285E-06	2.8715E-07	.836138	.018092	55.274	5.756
L	-.087429	.027763	-1.691604	.001323	755.861	-3.149
LD1	-.001380	.004146	-.033651	.037377	26.755	-.333
LD2	-.012866	.003853	-.375226	.030228	33.082	-3.339
LD3	-.001726	.003581	-.044997	.043814	22.824	-.482
LSQ	.010981	.003906	2.761424	3.957E-04	2527.034	2.811
LSQH	1.27830E-05	8.2788E-06	.290984	.010749	93.031	1.544
LSQS	-3.91772E-04	1.0782E-04	-3.757427	3.570E-04	2800.833	-3.634
LSSQ	7.58665E-05	2.0111E-05	3.266936	5.090E-04	1964.484	3.772
S	-.006713	.006166	-.521235	.001666	600.283	-1.089
SD1	.005759	8.2065E-04	.859588	.025447	39.298	7.018
SD2	-.002479	8.5862E-04	-.370048	.023246	43.019	-2.888
SD3	.006655	9.6778E-04	.993268	.018298	54.652	6.877
SSQ	-2.16008E-04	1.3409E-04	-1.177977	7.140E-04	1400.632	-1.611
(Constant)	.467089	.105346				4.434

Exhibit F.3
Multiple Regression Analysis for Enter Uncentred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

------ in -------

Variable	Sig T
D1	.0020
D2	.0683
D3	.1252
H	.6782
HD1	.1612
HD2	.1281
HD3	.2946
HSSQ	.0000
L	.0041
LD1	.7418
LD2	.0025
LD3	.6338
LSQ	.0093
LSQH	.1347
LSQS	.0012
LSSQ	.0008
S	.2862
SD1	.0000
SD2	.0077
SD3	.0000
SSQ	.1193
(Constant)	.0001

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
HS	4.618272	.313593	4.577E-05	21850.654	4.577E-05	1.651	.1112
LH	.	.	.000000	.	.000000	.	.
LS	7.108822	.313593	1.932E-05	51772.694	1.932E-05	1.651	.1112

Exhibit F.3
Multiple Regression Analysis for Enter Uncentred Model

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D1	D2	D3	H	HD1
1	12.11155	1.000	.00000	.00001	.00001	.00001	.00001	.00001
2	3.92026	1.758	.00000	.00007	.00014	.00003	.00000	.00011
3	3.88090	1.767	.00000	.00011	.00000	.00011	.00000	.00018
4	.90498	3.658	.00000	.00021	.00032	.00017	.00000	.00029
5	.60396	4.478	.00001	.00005	.00002	.00005	.00004	.00014
6	.25133	6.942	.00035	.00000	.00001	.00000	.00130	.00001
7	.08090	12.236	.00002	.00164	.00000	.00013	.00024	.00001
8	.07701	12.541	.00011	.00001	.00129	.00001	.00004	.00000
9	.04124	17.137	.00044	.00397	.00163	.00000	.00206	.00000
10	.03654	18.206	.00009	.00690	.00424	.00348	.00000	.00491
11	.03405	18.859	.00004	.00512	.00230	.00350	.00189	.04187
12	.01905	25.217	.00038	.00046	.00415	.00165	.00007	.01600
13	.01128	32.773	.00014	.01596	.00310	.00116	.00032	.01085
14	.00882	37.067	.00022	.04928	.12976	.00069	.00211	.15617
15	.00778	39.456	.00004	.06828	.01526	.17025	.00000	.09119
16	.00487	49.856	.00070	.10035	.00152	.02308	.04771	.00065
17	.00202	77.374	.00057	.00011	.05017	.00012	.00034	.00702
18	.00166	85.315	.00552	.08718	.21990	.07261	.00190	.09657
19	.00119	100.729	.00020	.19884	.20998	.20416	.02049	.17978
20	.00045	164.680	.22205	.34977	.20688	.25483	.85789	.36152
21	.00014	295.926	.69774	.04337	.01484	.02167	.02667	.00029
22	.00002	749.972	.07136	.06830	.13447	.24228	.03693	.03243

Number	HD2	HD3	HSSQ	L	LD1	LD2	LD3	LSQ
1	.00001	.00001	.00002	.00000	.00005	.00005	.00006	.00000
2	.00021	.00005	.00000	.00000	.00048	.00087	.00026	.00000
3	.00000	.00022	.00000	.00000	.00079	.00001	.00118	.00000
4	.00042	.00038	.00000	.00000	.00044	.00095	.00080	.00001
5	.00008	.00008	.00099	.00000	.00299	.00128	.00258	.00002
6	.00001	.00002	.00034	.00003	.00135	.00048	.00149	.00000
7	.00000	.00281	.00061	.00001	.13163	.00137	.10635	.00001
8	.00035	.00141	.00184	.00001	.02378	.09566	.05006	.00000
9	.00033	.01444	.01147	.00010	.00390	.00182	.05315	.00005
10	.01274	.02530	.00380	.00000	.07087	.01444	.11517	.00001
11	.00005	.01231	.00296	.00005	.02580	.01114	.07650	.00007
12	.04222	.01069	.00045	.00001	.22213	.44377	.12952	.00008
13	.09176	.01319	.00404	.00011	.02468	.00080	.00653	.00051
14	.06403	.02824	.00103	.00023	.00461	.00611	.00005	.00009
15	.03479	.14323	.00068	.00003	.00311	.00206	.05600	.00000
16	.02751	.00888	.01662	.00001	.00022	.01311	.00411	.00168
17	.03728	.00038	.34196	.00954	.03855	.02205	.00407	.00628
18	.25352	.08703	.18110	.01768	.03141	.00495	.05781	.00079
19	.10891	.23365	.16097	.01373	.08676	.23581	.08766	.00997
20	.15976	.26419	.26888	.00008	.00498	.06667	.08937	.01380
21	.08364	.01665	.00213	.08996	.31584	.04817	.09991	.05676
22	.08236	.13685	.00011	.86839	.00565	.02842	.05736	.90985

Exhibit F.3
Multiple Regression Analysis for Enter Uncentred Model

	LSQH	LSQS	LSSQ	S	SD1	SD2	SD3	SSQ
1	.00002	.00000	.00000	.00000	.00003	.00004	.00003	.00000
2	.00000	.00000	.00000	.00000	.00033	.00066	.00011	.00000
3	.00000	.00000	.00000	.00000	.00054	.00001	.00049	.00000
4	.00032	.00002	.00001	.00000	.00095	.00136	.00069	.00000
5	.00065	.00001	.00001	.00001	.00000	.00002	.00001	.00004
6	.00003	.00004	.00009	.00000	.00172	.00271	.00175	.00002
7	.00044	.00000	.00000	.00000	.04083	.00088	.01019	.00000
8	.00209	.00002	.00001	.00001	.01376	.04999	.00662	.00000
9	.00571	.00001	.00001	.00004	.00592	.00800	.10934	.00002
10	.00124	.00010	.00015	.00001	.00654	.06101	.02183	.00003
11	.00037	.00000	.00002	.00003	.16412	.00001	.01370	.00004
12	.00431	.00004	.00000	.00005	.01772	.00108	.03070	.00007
13	.01749	.00090	.00115	.00000	.04564	.40763	.08868	.00006
14	.00865	.00002	.00005	.00001	.01833	.16870	.03935	.00008
15	.00066	.00008	.00000	.00000	.01000	.00030	.03032	.00000
16	.00827	.00106	.00247	.00039	.56928	.01354	.18488	.00314
17	.53441	.00002	.00019	.00190	.00113	.01289	.00293	.00575
18	.00091	.01315	.00856	.00001	.00264	.00487	.00207	.00240
19	.25703	.00723	.00884	.00330	.00230	.01537	.01050	.00601
20	.15549	.00257	.00117	.00984	.02234	.00313	.01278	.02663
21	.00022	.04375	.04823	.25531	.00350	.00343	.00436	.04922
22	.00169	.93098	.92903	.72907	.07236	.24435	.42867	.90648

End Block Number 1 Tolerance = 1.00E-04 Limits reached.

SPSS 6.1 for Windows

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
           * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Listwise Deletion of Missing Data

Equation Number 1    Dependent Variable..   ACC

Block Number  1.  Method:  Stepwise     Criteria   PIN  .0500   POUT  .1000
   D1        D2        D3        H         HD1       HD2       HD3       HS
   HSSQC     L         LD1       LD2       LD3       LH        LS        LSQC
   LSQCH     LSQCS     LSSQC     S         SD1       SD2       SD3       SSQC


Variable(s) Entered on Step Number
   1..    HS


Multiple R           .67415
R Square             .45447
Adjusted R Square    .44261
Standard Error       .07934

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           1              .24125           .24125
Residual            46              .28958           .00630

F =      38.32200       Signif F =  .0000

------------------------- Variables in the Equation --------------------------

Variable              B          SE B       Beta  Tolerance        VIF         T

HS          8.40037E-05  1.3570E-05    .674145   1.000000      1.000     6.190
(Constant)     -.034136     .043107                                        -.792


------ in -------

Variable    Sig T

HS          .0000
(Constant)  .4325
```

Exhibit F.4

Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
D1	-.099508	-.134726	1.000000	1.000	1.000000	-.912	.3666
D2	-.076633	-.103754	1.000000	1.000	1.000000	-.700	.4877
D3	.541005	.732476	1.000000	1.000	1.000000	7.217	.0000
H	.055787	.064589	.731261	1.368	.731261	.434	.6662
HD1	-.098422	-.133137	.998220	1.002	.998220	-.901	.3723
HD2	-.084210	-.113912	.998220	1.002	.998220	-.769	.4458
HD3	.548890	.742489	.998220	1.002	.998220	7.436	.0000
HSSQC	.132139	.177978	.989664	1.010	.989664	1.213	.2314
L	-.264637	-.358296	1.000000	1.000	1.000000	-2.574	.0134
LD1	-.155202	-.209958	.998364	1.002	.998364	-1.441	.1566
LD2	-.109308	-.147862	.998214	1.002	.998214	-1.003	.3213
LD3	.464505	.628837	.999799	1.000	.999799	5.425	.0000
LH	-.227512	-.301660	.959053	1.043	.959053	-2.122	.0393
LS	-.326194	-.388268	.772905	1.294	.772905	-2.826	.0070
LSQC	-.268862	-.364016	1.000000	1.000	1.000000	-2.622	.0119
LSQCH	-.266540	-.359518	.992509	1.008	.992509	-2.585	.0131
LSQCS	-.325072	-.429117	.950628	1.052	.950628	-3.187	.0026
LSSQC	.017956	.024310	1.000000	1.000	1.000000	.163	.8711
S	-.104551	-.075351	.283364	3.529	.283364	-.507	.6147
SD1	-.075290	-.101316	.987879	1.012	.987879	-.683	.4980
SD2	-.121925	-.164072	.987879	1.012	.987879	-1.116	.2705
SD3	.578875	.778984	.987879	1.012	.987879	8.334	.0000
SSQC	.130277	.176385	1.000000	1.000	1.000000	1.202	.2356

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	HS
1	1.96406	1.000	.01797	.01797
2	.03594	7.393	.98203	.98203

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
          * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   ACC


Variable(s) Entered on Step Number
   2..    SD3


Multiple R           .88629
R Square             .78551
Adjusted R Square    .77597
Standard Error       .05030

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           2              .41697           .20849
Residual            45              .11386           .00253

F =       82.39853       Signif F =  .0000

------------------------- Variables in the Equation --------------------------

Variable                  B          SE B        Beta  Tolerance          VIF         T

HS            7.60623E-05  8.6555E-06     .610415    .987879        1.012     8.788
SD3               .003878  4.6540E-04     .578875    .987879        1.012     8.334
(Constant)       -.043753     .027353                                        -1.600

------ in -------

Variable     Sig T

HS           .0000
SD3          .0000
(Constant)   .1167
```

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1 Dependent Variable.. ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
D1	.096978	.198112	.895135	1.117	.884285	1.341	.1869
D2	.122534	.250318	.895135	1.117	.884285	1.715	.0934
D3	-.319235	-.163428	.056214	17.789	.055533	-1.099	.2778
H	.101424	.186848	.727964	1.374	.719141	1.262	.2137
HD1	.098837	.201683	.893125	1.120	.883873	1.366	.1789
HD2	.114722	.234097	.893125	1.120	.883873	1.597	.1174
HD3	-.010141	-.006509	.088372	11.316	.087456	-.043	.9658
HSSQC	.138704	.297919	.989537	1.011	.977543	2.070	.0443
L	-.248966	-.537363	.999240	1.001	.987129	-4.227	.0001
LD1	.022891	.047023	.905145	1.105	.895639	.312	.7563
LD2	.077449	.158778	.901496	1.109	.892162	1.067	.2919
LD3	-.445367	-.371083	.148908	6.716	.147133	-2.651	.0111
LH	-.193218	-.407842	.955653	1.046	.945273	-2.963	.0049
LS	-.322528	-.612234	.772881	1.294	.765244	-5.136	.0000
LSQC	-.173386	-.368585	.969308	1.032	.957559	-2.630	.0117
LSQCH	-.156418	-.329556	.952132	1.050	.947691	-2.315	.0253
LSQCS	-.222798	-.460817	.917585	1.090	.917585	-3.444	.0013
LSSQC	.037433	.080779	.998859	1.001	.986752	.538	.5936
S	-.180711	-.207202	.281989	3.546	.281989	-1.405	.1671
SD1	.127552	.258700	.882334	1.133	.882334	1.776	.0826
SD2	.075339	.152801	.882334	1.133	.882334	1.026	.3107
SSQC	.130277	.281295	1.000000	1.000	.987879	1.944	.0583

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	HS	SD3
1	2.32727	1.000	.01185	.01179	.06958
2	.63684	1.912	.01232	.01134	.92909
3	.03589	8.053	.97583	.97687	.00133

Exhibit F.4

Multiple Regression Analysis for Stepwise Centred Model

```
          * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   ACC


Variable(s) Entered on Step Number
   3..    LS


Multiple R           .93054
R Square             .86591
Adjusted R Square    .85676
Standard Error       .04022

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           3              .45965           .15322
Residual            44              .07118           .00162

F =       94.70900       Signif F =  .0000


------------------------ Variables in the Equation --------------------------

Variable              B          SE B       Beta  Tolerance        VIF         T

HS          9.52364E-05  7.8636E-06    .764290    .765244      1.307    12.111
LS         -3.83350E-04  7.4636E-05   -.322528    .772881      1.294    -5.136
SD3             .003868  3.7214E-04    .577273    .987848      1.012    10.393
(Constant)     -.020534     .022334                                       -.919


------ in -------

Variable    Sig T

HS          .0000
LS          .0000
SD3         .0000
(Constant)  .3629
```

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
* * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   ACC
```

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
D1	.048371	.123226	.870268	1.149	.751410	.814	.4200
D2	.175999	.448656	.871402	1.148	.752389	3.292	.0020
D3	-.425939	-.274746	.055793	17.923	.055152	-1.874	.0678
H	-.009149	-.020125	.648820	1.541	.496505	-.132	.8956
HD1	.052788	.134527	.870868	1.148	.748601	.890	.3783
HD2	.172645	.438653	.865661	1.155	.749114	3.201	.0026
HD3	-.190115	-.151756	.085442	11.704	.084855	-1.007	.3197
HSSQC	.123274	.334358	.986493	1.014	.754908	2.326	.0248
L	.066837	.073303	.161292	6.200	.124755	.482	.6323
LD1	.019612	.050951	.905035	1.105	.761130	.335	.7396
LD2	.175760	.437183	.829654	1.205	.711288	3.188	.0027
LD3	-.251081	-.252899	.136043	7.351	.136011	-1.714	.0937
LH	.048184	.086369	.430854	2.321	.348451	.568	.5727
LSQC	-.073535	-.182513	.826052	1.211	.658656	-1.217	.2301
LSQCH	-.067825	-.170584	.848225	1.179	.688536	-1.135	.2626
LSQCS	-.114492	-.268774	.738989	1.353	.622450	-1.830	.0742
LSSQC	.166875	.422398	.859155	1.164	.664783	3.056	.0038
S	.002202	.003001	.248992	4.016	.248992	.020	.9844
SD1	.080427	.203540	.858830	1.164	.731003	1.363	.1799
SD2	.144966	.363601	.843582	1.185	.738937	2.559	.0141
SSQC	.130277	.355765	1.000000	1.000	.765244	2.496	.0165

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	HS	LS	SD3
1	3.20206	1.000	.00617	.00500	.01009	.02964
2	.68308	2.165	.00391	.00293	.00829	.96367
3	.08074	6.298	.24360	.04627	.89692	.00464
4	.03412	9.687	.74632	.94581	.08471	.00204

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
          * * * *  M U L T I P L E   R E G R E S S I O N  * * * *

Equation Number 1    Dependent Variable..   ACC


Variable(s) Entered on Step Number
   4..    D2


Multiple R           .94493
R Square             .89290
Adjusted R Square    .88293
Standard Error       .03636

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           4              .47398           .11849
Residual            43              .05685           .00132

F =      89.62136       Signif F =  .0000

------------------------ Variables in the Equation -------------------------

Variable                 B        SE B        Beta  Tolerance        VIF         T

D2                 .042743     .012984     .175999    .871402      1.148     3.292
HS             9.62832E-05  7.1161E-06     .772691    .763716      1.309    13.530
LS            -4.20007E-04  6.8387E-05    -.353369    .752389      1.329    -6.142
SD3                .004251  3.5600E-04     .634461    .882248      1.133    11.941
(Constant)        -.029952     .020392                                      -1.469

------ in -------

Variable     Sig T

D2           .0020
HS           .0000
LS           .0000
SD3          .0000
(Constant)   .1492
```

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1 Dependent Variable.. ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
D1	.170621	.427915	.673668	1.484	.673668	3.068	.0038
D3	-.378692	-.272640	.055514	18.013	.055143	-1.836	.0734
H	-.015879	-.039061	.648117	1.543	.494977	-.253	.8012
HD1	.174690	.439241	.677126	1.477	.677126	3.169	.0029
HD2	-.050262	-.024032	.024485	40.841	.024485	-.156	.8769
HD3	-.166395	-.148484	.085286	11.725	.084544	-.973	.3361
HSSQC	.122411	.371503	.986466	1.014	.750066	2.593	.0130
L	.044814	.054914	.160819	6.218	.124720	.356	.7233
LD1	.124989	.322945	.715009	1.399	.688438	2.211	.0325
LD2	.049229	.044623	.087999	11.364	.087999	.289	.7736
LD3	-.208274	-.233537	.134659	7.426	.134659	-1.557	.1271
LH	.023243	.046382	.426494	2.345	.347989	.301	.7650
LSQC	-.055990	-.154713	.817764	1.223	.635280	-1.015	.3160
LSQCH	-.060642	-.170518	.846811	1.181	.669329	-1.122	.2684
LSQCS	-.093017	-.242589	.728474	1.373	.598007	-1.621	.1126
LSSQC	.141896	.396585	.836630	1.195	.658992	2.800	.0077
S	.013512	.020590	.248699	4.021	.248699	.133	.8945
SD1	.208439	.522128	.672039	1.488	.672039	3.968	.0003
SD2	-.449659	-.316084	.052922	18.896	.052922	-2.159	.0366
SSQC	.130277	.398079	1.000000	1.000	.752389	2.812	.0074

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D2	HS	LS	SD3
1	3.46750	1.000	.00518	.01851	.00423	.00845	.01802
2	1.00080	1.861	.00000	.31718	.00002	.00005	.34531
3	.41738	2.882	.00925	.65013	.00931	.01611	.63450
4	.08059	6.559	.23862	.00213	.04347	.88144	.00215
5	.03374	10.138	.74695	.01205	.94297	.09395	.00002

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
          * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   ACC


Variable(s) Entered on Step Number
   5..    SD1


Multiple R           .96026
R Square             .92210
Adjusted R Square    .91282
Standard Error       .03138

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           5              .48948           .09790
Residual            42              .04135           .00098

F =       99.42460       Signif F =  .0000


------------------------ Variables in the Equation -------------------------

Variable              B         SE B       Beta  Tolerance        VIF          T

D2              .066180      .012667    .272503    .681877      1.467      5.225
HS          9.09022E-05   6.2889E-06    .729507    .728196      1.373     14.454
LS         -3.96903E-04   5.9302E-05   -.333931    .745135      1.342     -6.693
SD1             .001397   3.5199E-04    .208439    .672039      1.488      3.968
SD3             .004919   3.5030E-04    .734131    .678564      1.474     14.041
(Constant)     -.042328      .017872                                      -2.368


------ in -------

Variable     Sig T

D2           .0000
HS           .0000
LS           .0000
SD1          .0003
SD3          .0000
(Constant)   .0225
```

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1   Dependent Variable..   ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
D1	-.350071	-.295339	.055448	18.035	.055314	-1.979	.0545
D3	-.318705	-.268041	.055104	18.147	.054983	-1.781	.0822
H	.019170	.054556	.630953	1.585	.459457	.350	.7282
HD1	-.148514	-.157143	.087220	11.465	.086565	-1.019	.3142
HD2	-.001417	-.000794	.024436	40.923	.024436	-.005	.9960
HD3	-.104023	-.108195	.084278	11.865	.084171	-.697	.4898
HSSQC	.126947	.451582	.985806	1.014	.671590	3.241	.0024
L	.075803	.108631	.159990	6.250	.124639	.700	.4881
LD1	-.210070	-.313293	.173274	5.771	.162861	-2.112	.0408
LD2	.041767	.044387	.087984	11.366	.087984	.284	.7775
LD3	-.204362	-.268672	.134650	7.427	.130252	-1.786	.0815
LH	.034505	.080659	.425713	2.349	.347544	.518	.6071
LSQC	-.039169	-.126382	.811033	1.233	.633357	-.816	.4193
LSQCH	-.043797	-.143773	.839526	1.191	.642578	-.930	.3577
LSQCS	-.076240	-.232259	.723003	1.383	.596581	-1.529	.1339
LSSQC	.166796	.542628	.824511	1.213	.657329	4.136	.0002
S	-.045932	-.080879	.241542	4.140	.241542	-.520	.6062
SD2	-.396824	-.326168	.052632	19.000	.052632	-2.209	.0328
SSQC	.130277	.466754	1.000000	1.000	.672039	3.379	.0016

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D2	HS	LS	SD1	SD3
1	3.66992	1.000	.00455	.01116	.00367	.00746	.00997	.01069
2	1.00283	1.913	.00001	.25125	.00005	.00021	.25717	.00066
3	1.00006	1.916	.00000	.07781	.00000	.00000	.09354	.34441
4	.21903	4.093	.00992	.63412	.01198	.08229	.53449	.59125
5	.07459	7.015	.29849	.02216	.05372	.80582	.09928	.05109
6	.03358	10.454	.68702	.00349	.93058	.10422	.00554	.00190

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

Variable(s) Entered on Step Number
6..   LSSQC

Multiple R	.97213
R Square	.94503
Adjusted R Square	.93699
Standard Error	.02668

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	6	.50165	.08361
Residual	41	.02918	.00071

F =   117.48649   Signif F = .0000

------------------------- Variables in the Equation -------------------------

Variable	B	SE B	Beta	Tolerance	VIF	T
D2	.062186	.010812	.256057	.676438	1.478	5.752
HS	9.43024E-05	5.4094E-06	.756795	.711379	1.406	17.433
LS	-4.73122E-04	5.3677E-05	-.398057	.657329	1.521	-8.814
LSSQC	5.28173E-05	1.2769E-05	.166796	.824511	1.213	4.136
SD1	.001547	3.0144E-04	.230837	.662305	1.510	5.131
SD3	.004968	2.9804E-04	.741444	.677492	1.476	16.668
(Constant)	-.058691	.015701				-3.738

------ in -------

Variable	Sig T
D2	.0000
HS	.0000
LS	.0000
LSSQC	.0002
SD1	.0000
SD3	.0000
(Constant)	.0006

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

----------------------- Variables not in the Equation -----------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
D1	-.327872	-.329105	.055380	18.057	.055314	-2.204	.0333
D3	-.337104	-.337395	.055061	18.162	.054902	-2.267	.0289
H	-.003296	-.011088	.622229	1.607	.442641	-.070	.9444
HD1	-.147345	-.185608	.087219	11.465	.086417	-1.195	.2393
HD2	-.098837	-.065573	.024194	41.333	.024194	-.416	.6799
HD3	-.168188	-.206793	.083095	12.034	.082860	-1.337	.1889
HSSQC	-.188251	-.247090	.094695	10.560	.079202	-1.613	.1147
L	.014743	.024820	.155777	6.419	.124639	.157	.8760
LD1	-.080104	-.130912	.146806	6.812	.146806	-.835	.4086
LD2	-.292019	-.318495	.065385	15.294	.065385	-2.125	.0398
LD3	-.150970	-.234092	.132154	7.567	.128806	-1.523	.1357
LH	6.088E-04	.001676	.416629	2.400	.340441	.011	.9916
LSQC	-.044675	-.171517	.810178	1.234	.572998	-1.101	.2774
LSQCH	-.050681	-.197900	.838106	1.193	.600293	-1.277	.2090
LSQCS	-.076757	-.278381	.722997	1.383	.539353	-1.833	.0742
S	-.008241	-.017144	.237905	4.203	.237905	-.108	.9142
SD2	-.341058	-.332428	.052219	19.150	.052219	-2.229	.0315
SSQC	-.156023	-.200396	.090676	11.028	.074763	-1.294	.2032

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D2	HS	LS	LSSQC	SD1
1	4.33470	1.000	.00303	.00847	.00251	.00475	.01267	.00608
2	1.03069	2.051	.00020	.23165	.00033	.00000	.00993	.22871
3	1.00009	2.082	.00000	.05150	.00000	.00000	.00000	.12363
4	.33961	3.573	.00137	.32512	.00305	.00048	.61919	.04568
5	.18993	4.777	.01888	.35920	.03286	.08044	.26799	.51773
6	.07358	7.676	.28694	.02272	.03576	.74963	.01654	.07687
7	.03141	11.748	.68958	.00134	.92548	.16470	.07368	.00130

	SD3
1	.00720
2	.01091
3	.33784
4	.12801
5	.47381
6	.04149
7	.00075

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

Variable(s) Entered on Step Number
7..   D3

Multiple R	.97534
R Square	.95129
Adjusted R Square	.94277
Standard Error	.02542

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	7	.50498	.07214
Residual	40	.02586	.00065

F = 111.60119   Signif F = .0000

------------------------ Variables in the Equation ------------------------

Variable	B	SE B	Beta	Tolerance	VIF	T
D2	.059727	.010361	.245933	.669026	1.495	5.765
D3	-.081869	.036117	-.337104	.055061	18.162	-2.267
HS	9.04792E-05	5.4243E-06	.726113	.642600	1.556	16.680
LS	-4.83262E-04	5.1353E-05	-.406589	.652341	1.533	-9.411
LSSQC	5.35929E-05	1.2174E-05	.169245	.823860	1.214	4.402
SD1	.001493	2.8826E-04	.222838	.657849	1.520	5.179
SD3	.007136	9.9783E-04	1.065067	.054902	18.214	7.152
(Constant)	-.042554	.016571				-2.568

------ in -------

Variable	Sig T
D2	.0000
D3	.0289
HS	.0000
LS	.0000
LSSQC	.0001
SD1	.0000
SD3	.0000
(Constant)	.0141

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1 Dependent Variable.. ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
D1	-.434986	-.449970	.052122	19.186	.051822	-3.147	.0032
H	.023815	.082305	.581795	1.719	.050637	.516	.6089
HD1	-.184303	-.244630	.085815	11.653	.054174	-1.576	.1232
HD2	-.036527	-.025546	.023824	41.974	.023824	-.160	.8740
HD3	.246293	.166978	.022388	44.666	.014835	1.058	.2967
HSSQC	-.177386	-.247098	.094516	10.580	.054865	-1.593	.1193
L	.052206	.091860	.150807	6.631	.052964	.576	.5679
LD1	-.090817	-.157462	.146428	6.829	.054866	-.996	.3255
LD2	-.264678	-.305231	.064778	15.437	.054414	-2.002	.0523
LD3	-.023057	-.029497	.079719	12.544	.033214	-.184	.8547
LH	.030058	.085601	.395047	2.531	.051907	.537	.5946
LSQC	-.047099	-.192018	.809579	1.235	.054816	-1.222	.2291
LSQCH	-.049781	-.206483	.838014	1.193	.054579	-1.318	.1952
LSQCS	-.071175	-.273670	.720123	1.389	.053960	-1.777	.0834
S	-.055332	-.117872	.221047	4.524	.050257	-.741	.4630
SD2	-.275670	-.277669	.049418	20.236	.049418	-1.805	.0788
SSQC	-.180845	-.245766	.089957	11.116	.054101	-1.583	.1214

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D2	D3	HS	LS	LSSQC
1	4.65626	1.000	.00210	.00587	.00075	.00192	.00396	.01049
2	1.62491	1.693	.00033	.04304	.00905	.00030	.00084	.00400
3	1.02965	2.127	.00017	.18431	.00000	.00029	.00000	.00940
4	.35147	3.640	.00047	.41970	.00227	.00111	.00207	.54116
5	.20796	4.732	.01447	.31228	.00936	.03316	.07505	.33868
6	.07461	7.900	.24197	.02879	.00543	.02618	.67116	.01038
7	.03816	11.047	.22540	.00113	.16255	.49438	.24628	.08127
8	.01697	16.567	.51509	.00487	.81059	.44266	.00065	.00462

	SD1	SD3
1	.00424	.00076
2	.02858	.00918
3	.28377	.00000
4	.09218	.00304
5	.50290	.00499
6	.08665	.02006
7	.00104	.16538
8	.00064	.79659

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
           * * * *  M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   ACC


Variable(s) Entered on Step Number
   8..    D1


Multiple R           .98038
R Square             .96115
Adjusted R Square    .95318
Standard Error       .02299

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           8              .51021           .06378
Residual            39              .02062           .00053

F =      120.61885       Signif F =  .0000

------------------------ Variables in the Equation --------------------------

Variable                  B         SE B        Beta  Tolerance        VIF         T

D1                -.105641      .033573    -.434986    .052122     19.186    -3.147
D2                 .055784      .009454     .229694    .657267      1.521     5.900
D3                -.107566      .033670    -.442911    .051822     19.297    -3.195
HS             8.37816E-05   5.3477E-06     .672363    .540799      1.849    15.667
LS            -4.88095E-04   4.6470E-05    -.410655    .651628      1.535   -10.503
LSSQC          5.25810E-05   1.1015E-05     .166049    .823158      1.215     4.773
SD1                .004268   9.1960E-04     .636999    .052874     18.913     4.641
SD3                .007750   9.2332E-04    1.156718    .052449     19.066     8.394
(Constant)        -.016432      .017132                                        -.959

------ in -------

Variable     Sig T

D1           .0032
D2           .0000
D3           .0028
HS           .0000
LS           .0000
LSSQC        .0000
SD1          .0000
SD3          .0000
(Constant)   .3434
```

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
H	.082928	.298430	.503072	1.988	.044943	1.927	.0614
HD1	.379826	.295949	.023584	42.402	.014324	1.910	.0637
HD2	.068540	.052980	.023210	43.085	.023156	.327	.7454
HD3	.356273	.267279	.021863	45.739	.013870	1.710	.0955
HSSQC	-.098146	-.147535	.087780	11.392	.048408	-.920	.3636
L	.058065	.114376	.150729	6.634	.050166	.710	.4822
LD1	.112831	.172147	.090426	11.059	.032188	1.077	.2882
LD2	-.216619	-.277242	.063632	15.715	.050996	-1.779	.0833
LD3	-.027269	-.039061	.079707	12.546	.032096	-.241	.8109
LH	.066201	.206395	.377586	2.648	.047952	1.300	.2013
LSQC	-.049331	-.225157	.809254	1.236	.051771	-1.425	.1625
LSQCH	-.045836	-.212745	.836871	1.195	.051803	-1.342	.1875
LSQCS	-.074056	-.318755	.719700	1.389	.051654	-2.073	.0450
S	-.160565	-.353439	.188225	5.313	.044185	-2.329	.0253
SD2	-.161271	-.174324	.045389	22.032	.045389	-1.091	.2820
SSQC	-.151393	-.229384	.089181	11.213	.051607	-1.453	.1545

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D1	D2	D3	HS	LS
1	4.88674	1.000	.00148	.00047	.00461	.00054	.00148	.00356
2	1.97854	1.572	.00001	.00539	.00002	.00443	.00001	.00000
3	1.38770	1.877	.00013	.00286	.15541	.00379	.00011	.00118
4	.36204	3.674	.00002	.00191	.53043	.00331	.00007	.00481
5	.23023	4.607	.01165	.00891	.26106	.00793	.03154	.06458
6	.07483	8.081	.18900	.00112	.03106	.00488	.01976	.64182
7	.04221	10.760	.12948	.09267	.00181	.05826	.35640	.27389
8	.02600	13.709	.00001	.35208	.00000	.39333	.00261	.00984
9	.01171	20.431	.66823	.53459	.01560	.52353	.58803	.00031

	LSSQC	SD1	SD3
1	.00915	.00049	.00056
2	.00037	.00557	.00456
3	.01480	.00296	.00391
4	.44125	.00236	.00404
5	.43090	.00613	.00436
6	.00808	.01473	.01932
7	.08643	.09518	.06169
8	.00240	.36583	.40358
9	.00663	.50675	.49798

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
* * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Variable(s) Entered on Step Number
   9..    S

Multiple R           .98286
R Square             .96601
Adjusted R Square    .95795
Standard Error       .02179

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           9              .51279           .05698
Residual            38              .01804           .00047

F =      119.98325       Signif F =  .0000

------------------------ Variables in the Equation --------------------------

Variable               B         SE B        Beta  Tolerance        VIF          T

D1              -.136585      .034479   -.562401    .044383      22.531     -3.961
D2               .055384      .008961    .228048    .657026       1.522      6.180
D3              -.136670      .034268   -.562749    .044931      22.256     -3.988
HS           9.50323E-05   7.0013E-06    .762652    .283364       3.529     13.573
LS          -4.45427E-04   4.7697E-05   -.374756    .555499       1.800     -9.339
LSSQC        4.91120E-05   1.0545E-05    .155094    .806735       1.240      4.658
S               -.002068   8.8792E-04   -.160565    .188225       5.313     -2.329
SD1              .005168   9.5334E-04    .771343    .044185      22.632      5.421
SD3              .008586   9.4579E-04   1.281510    .044893      22.275      9.078
(Constant)       .013714      .020764                                          .660

------ in -------

Variable      Sig T

D1            .0003
D2            .0000
D3            .0003
HS            .0000
LS            .0000
LSSQC         .0000
S             .0253
SD1           .0000
SD3           .0000
(Constant)    .5129
```

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1   Dependent Variable..   ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
H	-.098559	-.121443	.051613	19.375	.014625	-.744	.4614
HD1	.225915	.169667	.019174	52.155	.013942	1.047	.3018
HD2	-.170201	-.125765	.018561	53.877	.018561	-.771	.4455
HD3	.228778	.173795	.019617	50.975	.013791	1.073	.2900
HSSQC	-.097821	-.157191	.087779	11.392	.041650	-.968	.3392
L	-.431589	-.436054	.034701	28.818	.023473	-2.947	.0055
LD1	.007535	.010903	.071171	14.051	.032113	.066	.9475
LD2	-.367191	-.467408	.055082	18.155	.044029	-3.216	.0027
LD3	-.062865	-.095325	.078160	12.794	.030557	-.582	.5638
LH	-.300603	-.362988	.049568	20.174	.024709	-2.370	.0231
LSQC	-.063115	-.304091	.789122	1.267	.044030	-1.942	.0598
LSQCH	-.071927	-.343372	.774731	1.291	.044038	-2.224	.0323
LSQCS	-.071405	-.328372	.718905	1.391	.044175	-2.115	.0413
SD2	.006467	.006437	.033681	29.691	.033542	.039	.9690
SSQC	-.056847	-.081947	.070639	14.157	.040848	-.500	.6199

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D1	D2	D3	HS	LS
1	5.83662	1.000	.00064	.00028	.00333	.00031	.00056	.00215
2	1.97906	1.717	.00000	.00453	.00003	.00390	.00000	.00000
3	1.39205	2.048	.00005	.00258	.15072	.00340	.00004	.00082
4	.36227	4.014	.00001	.00145	.51075	.00265	.00004	.00406
5	.26294	4.711	.00300	.00837	.28981	.00735	.00943	.02464
6	.07620	8.752	.08923	.00043	.02384	.00319	.00726	.63507
7	.04608	11.255	.12206	.06881	.00596	.04713	.08942	.22961
8	.02600	14.982	.00000	.30138	.00000	.33982	.00087	.00816
9	.01304	21.157	.19383	.25459	.00954	.26049	.60164	.00178
10	.00573	31.921	.59116	.35760	.00604	.33177	.29074	.09370

	LSSQC	S	SD1	SD3
1	.00619	.00027	.00028	.00032
2	.00042	.00000	.00459	.00396
3	.01287	.00002	.00261	.00346
4	.45116	.00002	.00181	.00327
5	.37126	.00399	.00543	.00405
6	.02007	.00196	.00907	.01309
7	.10971	.01420	.07546	.05391
8	.00231	.00002	.30720	.34431
9	.00176	.08496	.23328	.24208
10	.02424	.89456	.36026	.33156

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Variable(s) Entered on Step Number
10.. LD2

Multiple R	.98663
R Square	.97343
Adjusted R Square	.96625
Standard Error	.01952

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	10	.51673	.05167
Residual	37	.01410	.00038

F = 135.56945 Signif F = .0000

------------------------- Variables in the Equation --------------------------

Variable	B	SE B	Beta	Tolerance	VIF	T
D1	-.138447	.030896	-.570067	.044367	22.539	-4.481
D2	.136971	.026609	.563992	.059814	16.718	5.148
D3	-.138279	.030705	-.569377	.044919	22.262	-4.503
HS	1.01855E-04	6.6216E-06	.817408	.254276	3.933	15.382
LD2	-.012590	.003915	-.367191	.055082	18.155	-3.216
LS	-3.87947E-04	4.6320E-05	-.326396	.472794	2.115	-8.375
LSSQC	6.67093E-05	1.0917E-05	.210666	.604085	1.655	6.110
S	-.003076	8.5501E-04	-.238828	.162932	6.138	-3.598
SD1	.005332	8.5562E-04	.795793	.044029	22.713	6.232
SD3	.008664	8.4769E-04	1.293092	.044857	22.293	10.220
(Constant)	.008117	.018684				.434

------ in -------

Variable	Sig T
D1	.0001
D2	.0000
D3	.0001
HS	.0000
LD2	.0027
LS	.0000
LSSQC	.0000
S	.0009
SD1	.0000
SD3	.0000
(Constant)	.6665

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1 Dependent Variable.. ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
H	-.069058	-.095955	.051292	19.496	.014625	-.578	.5666
HD1	.013689	.010922	.016910	59.137	.012848	.066	.9481
HD2	.105163	.080263	.015476	64.617	.015476	.483	.6319
HD3	.097942	.082093	.018665	53.577	.013364	.494	.6241
HSSQC	-.052760	-.094675	.085545	11.690	.041508	-.571	.5718
L	-.393988	-.448536	.034433	29.042	.023473	-3.011	.0047
LD1	-.045766	-.073925	.069319	14.426	.031958	-.445	.6591
LD3	-.120093	-.202848	.075797	13.193	.030331	-1.243	.2219
LH	-.216193	-.285607	.046366	21.567	.024477	-1.788	.0822
LSQC	-.051589	-.278869	.776305	1.288	.043910	-1.742	.0900
LSQCH	-.052527	-.276352	.735371	1.360	.043938	-1.725	.0930
LSQCS	-.060082	-.310286	.708569	1.411	.044010	-1.958	.0580
SD2	-.006462	-.007274	.033655	29.713	.021969	-.044	.9654
SSQC	-.019247	-.031169	.069676	14.352	.040741	-.187	.8526

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D1	D2	D3	HS	LD2
1	6.11169	1.000	.00058	.00022	.00038	.00025	.00045	.00037
2	2.00699	1.745	.00002	.00394	.00538	.00010	.00002	.00523
3	1.97247	1.760	.00000	.00190	.00127	.00565	.00000	.00121
4	.41381	3.843	.00059	.00566	.02016	.00750	.00063	.01049
5	.29683	4.538	.00336	.00507	.00041	.00376	.00696	.00629
6	.08380	8.540	.07148	.00088	.02321	.00337	.00182	.02981
7	.04619	11.503	.10981	.06758	.00052	.04480	.08655	.00182
8	.02633	15.235	.01038	.08070	.32263	.24727	.03388	.31815
9	.02572	15.414	.00759	.23851	.27775	.10920	.04670	.27518
10	.01101	23.563	.39651	.32565	.23396	.33149	.40023	.21418
11	.00517	34.391	.39969	.26989	.11434	.24661	.42278	.13728

	LS	LSSQC	S	SD1	SD3
1	.00169	.00443	.00021	.00022	.00025
2	.00001	.00220	.00001	.00398	.00011
3	.00000	.00002	.00000	.00192	.00574
4	.00946	.16842	.00031	.00577	.00770
5	.00926	.42807	.00302	.00316	.00183
6	.45377	.05331	.00100	.00622	.00928
7	.22636	.07015	.01238	.07083	.04956
8	.02919	.11315	.00413	.06123	.27280
9	.07268	.06526	.00326	.27830	.09796
10	.02545	.09074	.02926	.27650	.30007
11	.17213	.00426	.94642	.29187	.25469

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Variable(s) Entered on Step Number
11.. L

Multiple R	.98933
R Square	.97878
Adjusted R Square	.97229
Standard Error	.01769

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	11	.51957	.04723
Residual	36	.01127	.00031

F = 150.93910 Signif F = .0000

------------------------ Variables in the Equation --------------------------

Variable	B	SE B	Beta	Tolerance	VIF	T
D1	-.194212	.033566	-.799686	.030861	32.404	-5.786
D2	.131098	.024189	.539806	.059425	16.828	5.420
D3	-.164579	.029161	-.677670	.040889	24.456	-5.644
HS	1.01345E-04	6.0022E-06	.813311	.254073	3.936	16.885
L	-.020363	.006763	-.393988	.034433	29.042	-3.011
LD2	-.011648	.003561	-.339719	.054657	18.296	-3.271
LS	1.64966E-04	1.8836E-04	.138793	.023473	42.602	.876
LSSQC	6.73915E-05	9.8947E-06	.212820	.603768	1.656	6.811
S	-.006985	.001512	-.542304	.042793	23.368	-4.620
SD1	.006908	9.3537E-04	1.030986	.030246	33.062	7.385
SD3	.009410	8.0710E-04	1.404499	.040625	24.615	11.659
(Constant)	.152461	.050839				2.999

------ in -------

Variable	Sig T
D1	.0000
D2	.0000
D3	.0000
HS	.0000
L	.0047
LD2	.0024
LS	.3869
LSSQC	.0000
S	.0000
SD1	.0000
SD3	.0000
(Constant)	.0049

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
H	-.071315	-.110866	.051289	19.497	.014379	-.660	.5136
HD1	.060074	.053445	.016797	59.535	.010871	.317	.7534
HD2	.117100	.099977	.015469	64.644	.015469	.594	.5560
HD3	.092939	.087155	.018663	53.582	.013016	.518	.6080
HSSQC	-.127089	-.246221	.079657	12.554	.023473	-1.503	.1418
LD1	.008557	.015169	.066697	14.993	.021909	.090	.9290
LD3	-.086877	-.162778	.074503	13.422	.023473	-.976	.3358
LH	.109082	.103194	.018993	52.652	.014105	.614	.5433
LSQC	-.045464	-.274151	.771693	1.296	.023473	-1.687	.1006
LSQCH	-.046997	-.276017	.732034	1.366	.023473	-1.699	.0982
LSQCS	-.059029	-.341058	.708463	1.412	.023373	-2.146	.0389
SD2	-.145013	-.173487	.030375	32.922	.021043	-1.042	.3045
SSQC	-.110043	-.190606	.063670	15.706	.023473	-1.149	.2585

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D1	D2	D3	HS	L
1	7.03030	1.000	.00005	.00011	.00028	.00017	.00034	.00006
2	2.00833	1.871	.00000	.00274	.00529	.00011	.00002	.00000
3	1.97250	1.888	.00000	.00134	.00123	.00515	.00000	.00000
4	.43333	4.028	.00004	.00405	.02038	.00699	.00027	.00037
5	.29852	4.853	.00032	.00308	.00065	.00289	.00585	.00006
6	.11072	7.968	.00105	.00175	.00591	.00126	.02427	.01082
7	.07208	9.876	.01301	.01112	.01585	.01972	.01653	.00466
8	.02659	16.259	.00023	.10529	.24110	.20867	.03912	.00043
9	.02575	16.523	.00137	.14916	.35137	.05725	.05084	.00004
10	.01269	23.536	.01191	.28032	.05519	.50313	.04335	.02242
11	.00846	28.821	.01528	.00141	.30239	.01524	.81017	.03696
12	.00072	98.653	.95675	.43962	.00037	.17943	.00925	.92417

	LD2	LS	LSSQC	S	SD1	SD3
1	.00028	.00006	.00338	.00004	.00011	.00017
2	.00514	.00000	.00206	.00000	.00275	.00012
3	.00116	.00000	.00002	.00000	.00134	.00520
4	.01116	.00041	.11748	.00004	.00426	.00744
5	.00546	.00040	.47377	.00067	.00193	.00140
6	.00845	.00713	.14325	.00222	.00001	.00000
7	.02291	.00816	.00260	.00079	.01766	.02826
8	.23768	.00371	.07622	.00060	.08785	.22710
9	.34743	.00309	.09112	.00118	.17621	.04798
10	.04329	.02738	.02480	.00003	.25190	.47661
11	.31683	.01319	.06529	.08028	.00481	.02069
12	.00022	.93647	.00001	.91416	.45118	.18504

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

```
           * * * *   M U L T I P L E   R E G R E S S I O N   * * * *


Variable(s) Removed on Step Number
  12..     LS


Multiple R           .98910
R Square             .97833
Adjusted R Square    .97247
Standard Error       .01763

Analysis of Variance
                    DF        Sum of Squares       Mean Square
Regression          10                .51933            .05193
Residual            37                .01151            .00031

F =      167.00788       Signif F =  .0000


------------------------ Variables in the Equation --------------------------

Variable                 B         SE B        Beta  Tolerance        VIF          T

D1               -.177757      .027727    -.731929    .044943     22.250     -6.411
D2                .131098      .024113     .539806    .059425     16.828      5.437
D3               -.156785      .027682    -.645575    .045089     22.178     -5.664
HS             1.01345E-04  5.9833E-06     .813311    .254073      3.936     16.938
L                -.014589      .001502    -.282274    .693554      1.442     -9.713
LD2              -.011648      .003550    -.339719    .054657     18.296     -3.281
LSSQC          6.73915E-05  9.8635E-06     .212820    .603768      1.656      6.832
S                -.005805   6.8443E-04    -.450725    .207443      4.821     -8.482
SD1               .006438   7.6358E-04     .960815    .045102     22.172      8.431
SD3               .009187   7.6358E-04    1.371260    .045102     22.172     12.032
(Constant)        .111178      .018984                                        5.857

------ in -------

Variable      Sig T

D1            .0000
D2            .0000
D3            .0000
HS            .0000
L             .0000
LD2           .0023
LSSQC         .0000
S             .0000
SD1           .0000
SD3           .0000
(Constant)    .0000
```

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1 Dependent Variable.. ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
H	-.071315	-.109703	.051289	19.497	.014625	-.662	.5120
HD1	.060074	.052885	.016797	59.535	.012220	.318	.7525
HD2	.117100	.098929	.015469	64.644	.015469	.596	.5546
HD3	.092939	.086241	.018663	53.582	.013414	.519	.6067
HSSQC	-.127089	-.243639	.079657	12.554	.044560	-1.507	.1405
LD1	.008557	.015010	.066697	14.993	.028177	.090	.9287
LD3	-.086877	-.161071	.074503	13.422	.029071	-.979	.3340
LH	.109082	.102112	.018993	52.652	.018993	.616	.5418
LS	.138793	.144436	.023473	42.602	.023473	.876	.3869
LSQC	-.045464	-.271276	.771693	1.296	.044908	-1.691	.0995
LSQCH	-.046997	-.273123	.732034	1.366	.044910	-1.704	.0971
LSQCS	-.057138	-.327364	.711478	1.406	.044012	-2.079	.0448
SD2	-.093283	-.116535	.033827	29.563	.022527	-.704	.4860
SSQC	-.110043	-.188607	.063670	15.706	.044409	-1.152	.2568

Collinearity Diagnostics

Number	Eigenval	Cond Index	Variance Proportions Constant	D1	D2	D3	HS	L
1	6.11561	1.000	.00046	.00022	.00038	.00025	.00045	.00170
2	2.00773	1.745	.00001	.00396	.00535	.00012	.00002	.00002
3	1.97250	1.761	.00000	.00196	.00122	.00567	.00000	.00000
4	.41272	3.849	.00052	.00495	.02022	.00662	.00036	.00851
5	.28736	4.613	.00438	.00606	.00017	.00449	.00858	.00270
6	.09252	8.130	.00467	.00726	.00191	.00706	.02950	.44075
7	.04673	11.440	.11458	.03077	.15278	.03087	.02638	.15498
8	.02616	15.289	.00035	.34176	.00235	.29994	.00013	.00102
9	.02271	16.412	.05119	.07004	.41795	.13294	.06180	.22035
10	.00988	24.880	.44982	.22516	.37333	.19956	.49337	.16994
11	.00609	31.682	.37403	.30785	.02433	.31247	.37942	.00002

	LD2	LSSQC	S	SD1	SD3
1	.00037	.00446	.00027	.00023	.00025
2	.00519	.00216	.00001	.00406	.00012
3	.00116	.00002	.00000	.00200	.00578
4	.00984	.19617	.00023	.00567	.00767
5	.00827	.37581	.00474	.00435	.00279
6	.00086	.15065	.01138	.00633	.00682
7	.15256	.08894	.00093	.03424	.03421
8	.00228	.00015	.00005	.35289	.30293
9	.42621	.08500	.01469	.09917	.15342
10	.36112	.08979	.06569	.17810	.17254
11	.03214	.00685	.90200	.31298	.31346

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Variable(s) Entered on Step Number
13.. LSQCS

Multiple R	.99028
R Square	.98065
Adjusted R Square	.97474
Standard Error	.01689

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	11	.52056	.04732
Residual	36	.01027	.00029

F = 165.84590   Signif F = .0000

------------------------- Variables in the Equation -------------------------

Variable	B	SE B	Beta	Tolerance	VIF	T
D1	-.175290	.026587	-.721771	.044853	22.295	-6.593
D2	.123595	.023379	.508915	.058009	17.239	5.287
D3	-.151776	.026627	-.624950	.044720	22.361	-5.700
HS	1.00889E-04	5.7358E-06	.809653	.253701	3.942	17.589
L	-.013574	.001520	-.262624	.621856	1.608	-8.932
LD2	-.010807	.003424	-.315189	.053894	18.555	-3.156
LSQCS	-4.66573E-05	2.2445E-05	-.057138	.711478	1.406	-2.079
LSSQC	6.62871E-05	9.4635E-06	.209333	.601865	1.662	7.005
S	-.005484	6.7360E-04	-.425784	.196526	5.088	-8.141
SD1	.006324	7.3348E-04	.943893	.044853	22.295	8.622
SD3	.008948	7.4046E-04	1.335536	.044012	22.721	12.085
(Constant)	.104030	.018507				5.621

------ in -------

Variable	Sig T
D1	.0000
D2	.0000
D3	.0000
HS	.0000
L	.0000
LD2	.0032
LSQCS	.0448
LSSQC	.0000
S	.0000
SD1	.0000
SD3	.0000
(Constant)	.0000

Exhibit F.4
Multiple Regression Analysis for Stepwise Centred Model

* * * * M U L T I P L E   R E G R E S S I O N * * * *

Equation Number 1   Dependent Variable..   ACC

------------------------ Variables not in the Equation ------------------------

Variable	Beta In	Partial	Tolerance	VIF	Min Toler	T	Sig T
H	-.073334	-.119382	.051284	19.499	.014625	-.711	.4816
HD1	.034034	.031629	.016713	59.832	.012135	.187	.8526
HD2	.229751	.198743	.014481	69.057	.014481	1.200	.2383
HD3	.056277	.054957	.018455	54.187	.013160	.326	.7466
HSSQC	-.133033	-.269750	.079565	12.568	.044010	-1.657	.1064
LD1	-.005773	-.010687	.066306	15.082	.027987	-.063	.9499
LD3	-.085953	-.168649	.074501	13.423	.028930	-1.012	.3184
LH	.112946	.111887	.018990	52.658	.018990	.666	.5097
LS	.159947	.175784	.023373	42.784	.023373	1.056	.2980
LSQC	.194934	.252923	.032578	30.696	.028420	1.547	.1310
LSQCH	.139904	.202531	.040555	24.658	.031163	1.224	.2293
SD2	-.112665	-.148573	.033652	29.715	.022492	-.889	.3802
SSQC	-.116019	-.210346	.063610	15.721	.044011	-1.273	.2114

Collinearity Diagnostics

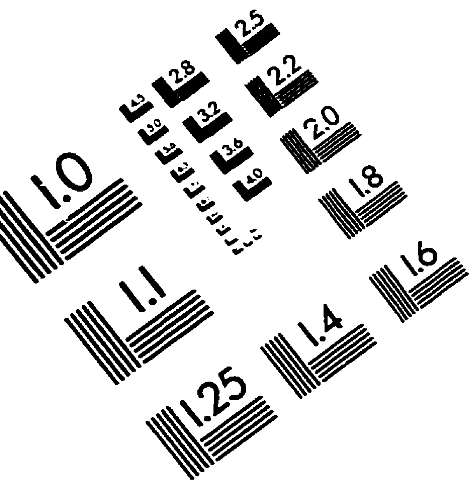
Number	Eigenval	Cond Index	Variance Proportions Constant	D1	D2	D3	HS	L
1	6.72319	1.000	.00036	.00018	.00030	.00019	.00037	.00127
2	2.00786	1.830	.00001	.00379	.00535	.00018	.00002	.00002
3	1.98052	1.842	.00000	.00203	.00093	.00568	.00000	.00000
4	.53268	3.553	.00001	.00488	.01204	.00386	.00006	.00231
5	.32738	4.532	.00010	.00024	.00637	.00007	.00115	.00062
6	.23179	5.386	.00907	.00595	.00041	.00831	.01134	.00327
7	.08977	8.654	.01013	.00820	.00065	.00654	.02826	.39617
8	.04237	12.597	.09692	.02957	.16950	.04447	.03136	.22945
9	.02606	16.061	.00066	.35522	.00086	.28437	.00000	.00404
10	.02271	17.208	.04932	.06928	.40886	.13197	.06192	.19639
11	.00987	26.095	.42962	.21740	.36116	.19290	.50360	.15937
12	.00581	34.030	.40379	.30326	.03358	.32145	.36192	.00708

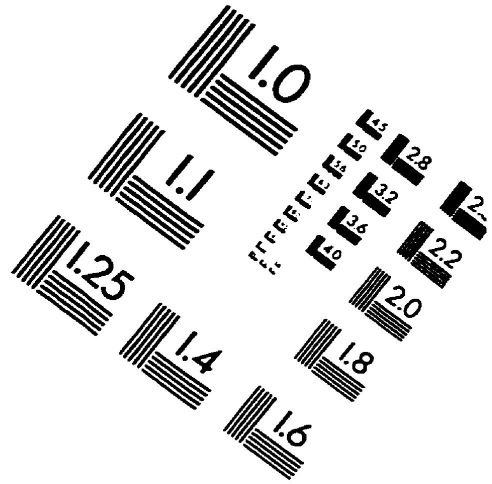
	LD2	LSQCS	LSSQC	S	SD1	SD3
1	.00030	.00449	.00368	.00021	.00019	.00019
2	.00525	.00001	.00212	.00001	.00387	.00018
3	.00090	.00070	.00000	.00000	.00207	.00569
4	.00728	.24785	.01636	.00004	.00475	.00415
5	.00000	.14613	.54987	.00059	.00000	.00041
6	.01468	.40856	.02015	.00586	.00587	.00619
7	.00000	.03352	.12659	.00985	.00939	.00951
8	.15590	.10464	.09853	.00064	.02791	.03710
9	.00103	.00453	.00000	.00004	.36259	.28764
10	.42095	.00001	.08499	.01393	.09793	.15000
11	.35440	.00062	.08881	.06591	.17125	.16514
12	.03931	.04895	.00891	.90293	.31419	.33381

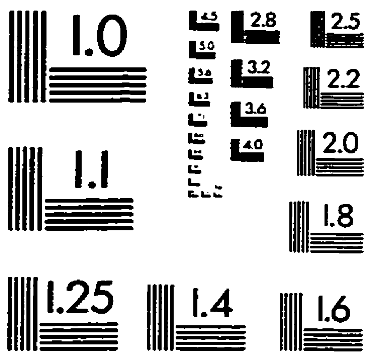
End Block Number   1   PIN =   .050 Limits reached.

SPSS 6.1 for Windows

IMAGE EVALUATION TEST TARGET (QA-3)

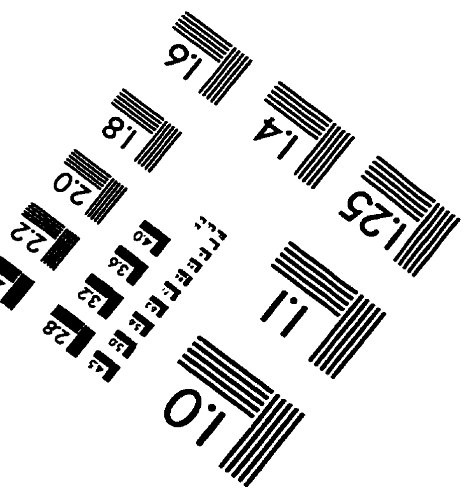


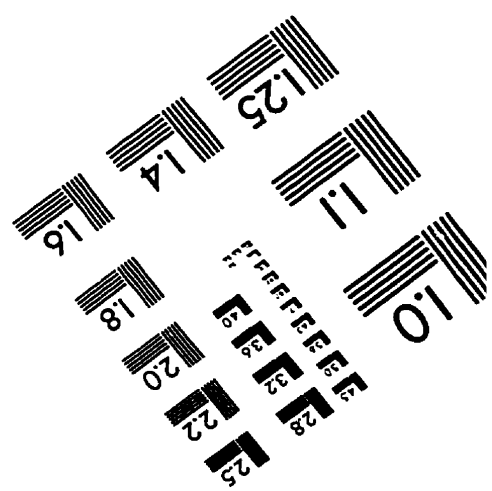




150mm

6″





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