TRANSPORT RESEARCH LABORATORY

# Safety aspects of road edge drainage features

## Prepared for Traffic, Safety and Environment, Highways Agency

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# Executive Summary

Effective drainage of rain water from road surfaces plays a major part in road safety. The efficient removal of this drainage water from the edge of the carriageway prevents surface flooding and minimises the damage to the structural foundations of the roadway. However, drainage features can, in themselves, present a potential hazard to errant vehicles leaving the carriageway. Therefore, drainage features should be designed to provide the required hydraulic capacity, whilst minimising, as far as practicable, the de-stabilising effects on the handling of vehicles which encroach into them.

The research described in this report has attempted to assess the relative effects of commonly employed drainage features on vehicle handling and safety. This was achieved by physically testing three widely used road edge drainage features and the use of a computer model to investigate alternative drainage features. Two of the drainage features under investigation (1:5 symmetrical triangular and 1:4.5 symmetrical trapezoidal surface drainage channel), were the subject of an earlier research project managed by TRL for which MIRA undertook the testing and reporting of the results (TRL Report TRL230, Robinson 1996). The handling tests on these two channel profiles have been repeated by TRL, because it was deemed necessary to employ alternative vehicles to those used by MIRA, in order that the test vehicles were more representative of modern cars and to provide results against which to validate the computer model. The computer simulations were performed to assess whether the modelling predictions correlated well enough with the results from physical testing to provide the confidence to dispense with expensive physical testing, when assessing the effects of alternative drainage features.

For the track tests, the vehicles were instrumented to record data on steering, vehicle body accelerations and angular velocities. The drainage features were tested at vehicle speeds of between 30 and 120 km/h and at approach angles ranging from 5 degrees to 20 degrees to the longitudinal axis of the features. Three types of handling test were performed: ‘fixed’ steering, where the vehicles were driven straight across the drainage feature and two forms of ‘corrective’ steering where the driver attempted to exit the feature on the same side that the vehicle entered from. The data from these tests were processed and analysed to assess the relative effects of the features. The test results clearly indicated a difference in the effects on the two vehicles, but the difference between the two surface water channels was not so clearly defined. The vehicle transducer data correlated reasonably well with that reported by MIRA. However, the overall assessment of the channel effects determined by TRL suggests a reversal of the severity ranking of the two channel profiles to that suggested by MIRA. It should be stated that the assessment conducted by MIRA was based mainly on the driver’s subjective assessment of the vehicle handling and ‘safe’ maximum speed for each vehicle/test configuration; only the transducer data from the ‘fixed’ steering tests having been analysed. The vehicles used by TRL (Ford Granada and Fiesta) were not the same as those employed by MIRA (British Leyland Rover SD1 and Mini) and it is possible that this may have had some bearing on the results. These vehicles were chosen, as they meet the test vehicle specifications in the current draft standard for road restraint systems (prEN1317). All things considered, these two channels have very similar effects on vehicle handling and are regarded as producing acceptable levels of vehicle disturbance. It was considered that the concrete surface channels should be used as a ‘benchmark’ for safety when assessing alternative drainage features.

Limited vehicle handling tests were also conducted on two forms of French Drain, one finished with the standard aggregate infill, the other capped with a bitumen bound, shredded tyre material. The chosen installation for the French Drain, adjacent to an embankment, was representative of a typical highway installation. However, this meant that only the corrective steering tests could be performed. This was not considered a problem, as ‘fixed’ steering handling tests, straight through the channel, was likely to produce little vehicle disturbance. Some additional testing was also performed on the French Drain and the triangular surface water channel using a pedal cycle and a light-weight motorcycle. The test procedure was similar to that used for the cars, with corrective steering and fixed steering manoeuvres being performed at a range of speeds and approach angles. However, the assessment of two-wheeler handling was purely subjective as no instrumentation was fitted to the vehicles.

The vehicle body accelerations and angular velocities predicted by the computer simulations agree, generally, with those obtained from the track tests. The predictions exhibit some differences to the track test data and these are believed to be a result of simplifications in the vehicle dynamics algorithms. Further refinement of the model would improve the correlation between the model predictions and the ‘real world’, but the model outputs will not be able to predict the handling difficulties that the driver may experience. However, there appears to be a relationship between the vehicle disturbance, measured during the ‘fixed’ steering tests, and the driver’s ability to maintain effective control of the vehicle. Given the observed agreement between the track test results and the computer model predictions, it was concluded that the comparison of the effects on vehicle handling safety of alternative road edge drainage features could be performed via computer modelling. The model was used to rank various drainage features in order of their effects on vehicle handling safety.

Surface drainage channels present a distinctly different problem to that posed by the French Drain, in that the surface drainage channels induce a much larger degree of physical vehicle disturbance. However, the loose surface presented by the conventional French Drain can pose significant handling problems for the average driver.

Single track vehicles, which have an inherent primary instability, are effected to a greater degree than twin track vehicles and are particularly sensitive to abrupt surface transitions of a longitudinal nature. However, it was considered that, at the relatively low speeds a pedal cycle can normally attain, the concrete surface water channels posed no significant risk to cyclists, whereas the conventional French Drain is likely to present distinct problems. Recommendations have been proposed to minimise the risk to errant vehicles posed by road edge drainage features, including the provision of safety fencing, hard strips and raised rib road edge markings under certain circumstances.

# 1 Introduction

The removal of surface water from the carriageway surface plays a vital role in road safety. Invariably, some provision needs to be made to handle this run-off water to prevent ponding at the side of the road and damage to the foundations of the carriageway. Suitable drainage installations can take many forms, some of which may present a hazard to errant vehicles leaving the carriageway. The Highways Agency have formulated an Advice Note, HA83 Safety Aspects of Road-Edge Drainage Features, to provide guidance to highway engineers. The work described in the report was conducted to assist the Highways Agency to formulate the Advice Note.

The Transport Research Laboratory (TRL) were contracted by the Highways Agency to investigate the effects on vehicle handling and safety of a range of road-edge drainage features. Three drainage features were tested and the results reported in TRL Report TRL230 (Robinson 1996). The results from this research were insufficient to formulate the necessary advice note for highway engineers and further investigation was warranted. A second contract was awarded to TRL to perform further handling tests and investigate the potential for simulating such tests via computer modelling. This report presents the results of the second stage of testing and modelling.

# 2 Track tests

## 2.1 Test vehicles

Under the previous project, reported in TRL230, the vehicles used to perform the handling tests were a large saloon car (Rover SD1), a small saloon car (BL Mini) and a light-weight motorcycle (Yamaha DT175). The cars were chosen because, at the time, they were the ‘standard’ vehicles used for barrier impact testing. The two cars represented different chassis layouts: the Rover a large, fairly heavy car with rear wheel drive, the Mini, a small, light-weight car with front wheel drive. The basic handling characteristic for these two chassis layouts, when the drive wheels are being powered, is for the rear wheel drive vehicle to oversteer and the front wheel drive vehicle to understeer. Front wheel drive is almost universal on small cars and is becoming increasingly popular on larger vehicles; it is, by far, the most common chassis layout within the UK vehicle population. The motorcycle, a ‘trials’ or on/off road type, was chosen because it had fairly compliant long-travel suspension and wide handlebars, for greater leverage, which afforded the rider increased control than would a purely road-going motorcycle under the same test conditions.

The two test cars used for the previous contract were in need of significant repair or replacement and it was considered that a move to more modern vehicles would be appropriate. Replacement of the vehicles was therefore deemed the most suitable option. In light of a recent change to the specification for the standard test vehicles for barrier impact testing (prEN1317 ‘Road Restraint Systems’ Parts 1 and 2), a 1990 Ford Granada 2.9i and a 1987 Ford Fiesta 1.4s were purchased. Both vehicles were fitted with a full roll cage and a 3-point safety harness to protect the driver in the event of loss of control of the vehicle during testing.

During testing with a motorcycle under the previous contract, safety problems were encountered and further testing with the motorcycle was abandoned. In view of the problems encountered and the subjective nature of the testing (no vehicle instrumentation), a decision was taken not to pursue testing with a motorcycle under this contract. However, a request from the Highways Agency to perform some handling tests with a pedal cycle resulted in a reconsideration of this decision and limited testing with a light-weight motorcycle was subsequently undertaken.

## 2.2 Vehicle instrumentation and data-logging

Initially, it was considered that in-house data-logging equipment might be used to record test data. However, the need to record steering rate and torque would have necessitated the design and construction of a suitable steering wheel transducer. This would have been time consuming, relatively expensive and there were likely to have been ‘teething’ problems with its function. A portable data-logging system with a suitable steering wheel transducer was therefore hired in. The system chosen was the Datron AEP-2 with a 16 channel analogue input option, L-sensor (for recording vehicle velocity), head-up speed display and steering wheel transducer. Although the software provided with the data logger was quite basic in that it offered limited data-analysis functions, it was the only known system of its type and previous experience had demonstrated its reliability. Besides, the data files were readily convertible to a form suitable for use with comprehensive data-analysis software in routine use at TRL. Other vehicle instrumentation consisted of a tri-axial angular rate sensor (manufactured by Watson Industries) and three uni-axial 5g accelerometers (manufactured by IC Sensors). The data-logging program was run on a Toshiba 486 lap-top computer, using a 350Mb hard disk to store data from successive test runs.

The convention adopted for the vehicle transducers was:

| | |
|---|---|
| Steering wheel angle | positive = clockwise |
| Steering wheel rate | positive = clockwise |
| Steering wheel torque | positive = clockwise |
| Longitudinal accel. (x) | positive = front |
| Lateral accel. (y) | positive = right |
| Vertical accel. (z) | positive = down |
| Roll rate (about x) | positive = clockwise |
| Pitch rate (about y) | positive = anti-clockwise |
| Yaw rate (about z) | positive = clockwise |

## 2.3 Drainage features tested

In view of the fact that different vehicles to those employed for previous testing were to be used, it was considered desirable to conduct tests with the Granada and

Fiesta on a concrete channel profile identical to one of those tested using the Rover and Mini. This would provide information on the vehicles response to similar handling tests and it was anticipated that the results from tests with the Granada and Fiesta would be broadly comparable to those obtained with the Rover and Mini, respectively. Fortunately, the last channel tested under the previous contract (1:4.5 trapezoidal denoted as channel 'C' in TRL230), was still in situ on the research track and hence the expense and delay involved in channel construction were avoided. It was also decided to re-test one of the other profiles previously tested with the Rover and Mini as modification of the existing channel to form another profile (1:5 symmetrical triangular denoted as channel 'B' in TRL230) was reasonably straight forward. These two channel profiles have been tested and the results are reported in chapter 2.6. *For brevity within the report, the two concrete surface drainage features are referred to simply as triangular and trapezoidal, but in all cases reference is to the symmetrical forms of both features.*

It had been considered that any correlation, if such existed, between vehicle disturbance and handling safety would be the best indicator of the potential hazard presented by any particular channel profile. The level of vehicle disturbance could then be used to rank the severity of the drainage profiles. The 'standard' test condition adopted for this purpose was that of running a vehicle, in a straight line, through the test channel at an oblique angle to the channel. However, if this test was performed on a French Drain, no, or very little, disturbance would be recorded. It was therefore deemed necessary to conduct corrective steering tests on a French Drain and compare these results with those recorded for the two surface drainage channels. As the French Drain was not likely to pose any significant handling problems when driving straight through the channel, it was decided to limit the testing to 'corrective' steering tests only. This enabled the feature to be constructed at the side of the research track, adjacent to an embankment, which would be quite a common installation on the highway, where such a feature may be used in a cutting. The French Drain was tested in two forms; one finished with a standard aggregate infill, the other capped with a bitumen bound, shredded tyre material. Again, the results from these tests are reported in chapter 2.6. The profiles and dimensions of the drainage features tested are shown in Figure 1.

## 2.4 Test procedure

Previously, testing had been conducted at four different approach angles and speeds starting at 20km/h up to what the driver considered to be the safe limiting speed, at 10km/h intervals. Two types of test were conducted: the first was 'fixed' steering, where the driver attempted to hold a steady course across the channel and onto the opposite side to that of the approach, the second was termed 'corrective' steering, where the driver drove into the channel and attempted to exit the channel on the same side as that of the approach. In the case of the corrective steering tests, the steering input was varied (fast or slow) and the depth of vehicle entry into the channel was also varied. As the steering rate and depth of entry were controlled by the driver, the path travelled by the car was not distinct and there would inevitably have been overlap between the data recorded for these tests and hence only subjective assessments were made for the corrective steering tests. In an attempt to obtain some meaningful objective measurements for the corrective steering tests conducted under the current contract, it was decided to limit the range of corrective steering manoeuvres.

Corrective steering manoeuvres were of two forms; 'in channel', where the driver attempted to position the off-side

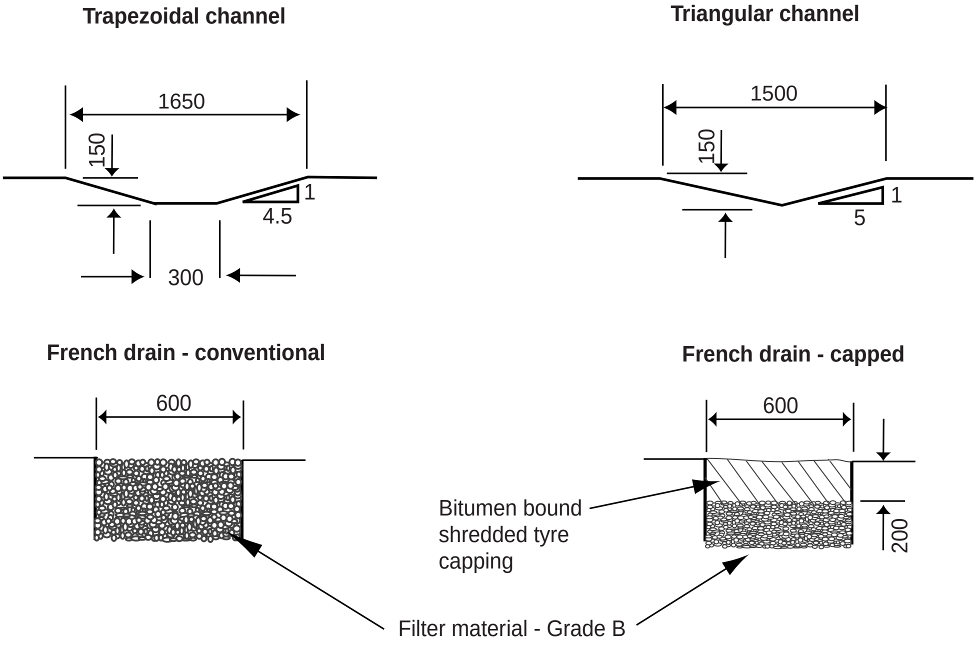


**Figure 1** Drainage features tested

wheels of the vehicle at the lowest point in the channel, and 'straddling channel', where the off-side wheels traversed the full width of the channel without the near-side wheels entering the channel. The 'fixed' steering tests were performed in an identical manner to those conducted under the previous contract. The vehicle approach angles were, again, 5°, 10°, 15° and 20°, and the approach speeds were 30km/h to 120km/h (or safe limiting speed - determined subjectively by the driver) in 10km/h intervals.

Ideally, the test sequence should have been randomised to minimise the learning effect as the tests progressed. However, without prior knowledge of the safe limiting speed for any given test condition, a randomised test sequence would have proved too hazardous. In practice, the test sequence was approached in a logical order, working from the lowest speed up to the safe limiting speed, with all steering manoeuvres being completed at the 5° approach angle before moving on to the 10°, 15° and 20° approach angles.

Before commencing a sequence of tests, all transducer outputs were zeroed within the data-logging program with the vehicle stationary. Just prior to commencing a run, the data-logging system was activated and, on the final approach to the test channel, a switch on the steering wheel was pressed to tell the computer to commence data acquisition. The switch was operated a second time, on completion of the test run, to halt the data acquisition process. Video recordings were made of all test runs to inform the subsequent analysis.

The two-wheeler tests took the same form, with both the pedal-cycle and the motorcycle being ridden at various approach angles and speeds into and across the drainage features, where possible. The driver and the two riders who performed the vehicle handling tests were members of the TRL staff with many years experience in handling such vehicles.

### 2.5 Data analysis

The data-logging software did not permit any data processing, other than graphical and tabular display of the recorded signal and the ability to read values from the signal trace via a cursor. To perform the necessary data analysis, the data files had to be converted to a form suitable to be read into another data processing package.

The raw data from the vehicle transducers, recorded at 500Hz, were converted into DIA_PC format and then filtered within DIA_PC to remove all frequencies above 10Hz. The filtered data were then inspected and the peak values from all transducer channels were tabulated. Graphs were plotted of certain transducer channels against time and vehicle velocity to obtain trends for the two vehicles on both channel profiles.

### 2.6 Results

#### *2.6.1 Fixed steering tests*

For the purposes of comparison, only those transducer channels identified by MIRA as indicating trends in the data were analysed in detail. Peak recorded transducer values, for the 'fixed' steering tests are given in the tables at Appendix A; where negative values are reported (longitudinal [X] acceleration), the sign indicates the direction of transducer sensitivity, not a minimum value. The transducer channels reported in the tables are steering torque, filtered linear accelerations (X,Y and Z) and filtered angular velocities (roll, pitch and yaw).

Trends of vehicle roll, yaw and longitudinal acceleration (X) against vehicle speed are shown in Figures 2 to 7. It can be seen from these figures that there is a tendency for these parameters to increase with vehicle speed, but the overall values of roll and yaw are, generally, less for the Granada than for the Fiesta, whereas the longitudinal accelerations are of the same order. The recorded yaw rates, Figures 4 and 5, reveal a tendency to increase to a maximum at around 60-80km/h and then stabilise or recede slightly as the vehicle speed increases beyond this point. This is likely to be an effect of the vehicle tending to 'jump' across the surface drainage channel at the higher speeds and so be less effected by the channel profile; this effect would obviously be associated with channel width.

The transducer outputs from the latest TRL 'fixed' steering tests, correlate reasonably well with those reported by MIRA and the range of values recorded for roll, yaw and longitudinal (X) acceleration are given in Table 1 for the trapezoidal surface drainage channel and Table 2 for the triangular surface drainage channel; for the MIRA tests, the speed range was somewhat more restricted than the TRL tests. This was due mainly to the topography of the earlier MIRA test site where the run-up and run-off areas were insufficient at the higher test speeds. In both the MIRA and TRL tests the smaller vehicle was more severely effected than the larger vehicle. The target maximum vehicle speed of 120km/h was attained in all but one of the 'fixed' steering tests conducted by TRL (Fiesta, 20° approach, trapezoidal channel) and both the Fiesta and Granada remained relatively stable and controllable after traversing the channels. The correlation between the

**Table 1 Approximate range of values recorded for 'fixed' steering tests across trapezoidal channel**

| *Test* | *Vehicle* | *Speed max. [km/h]* | *Roll rate [deg/s]* | *Yaw rate [deg/s]* | *Longitudinal acc. (X) [g]* |
|---|---|---|---|---|---|
| TRL | Fiesta | 120 | 12 - 92 | 3 - 14 | 0.01 - 1.10 |
| | Granada | 120 | 9 - 40 | 2 - 9 | 0.01 - 0.90 |
| MIRA | Mini | 100 | * | 3 - 12 | 0.25 - 0.80 |
| | Rover | 115 | 24 - 58 | 2 - 10 | 0.15 - 0.45 |

** = not reported*

**Table 2 Approximate range of values recorded for 'fixed' steering tests across triangular channel**

| *Test* | *Vehicle* | *Speed max. [km/h]* | *Roll rate [deg/s]* | *Yaw rate [deg/s]* | *Longitudinal acc. (X) [g]* |
|---|---|---|---|---|---|
| TRL | Fiesta | 120 | 9 - 53 | 1 - 8 | 0.03 - 0.60 |
| | Granada | 120 | 10 - 34 | 1 - 7 | 0.04 - 0.75 |
| MIRA | Mini | 80 | 21 - 47 | 2 - 12 | 0.18 - 0.75 |
| | Rover | 100 | 13 - 40 | 2 - 6 | 0.05 - 0.20 |

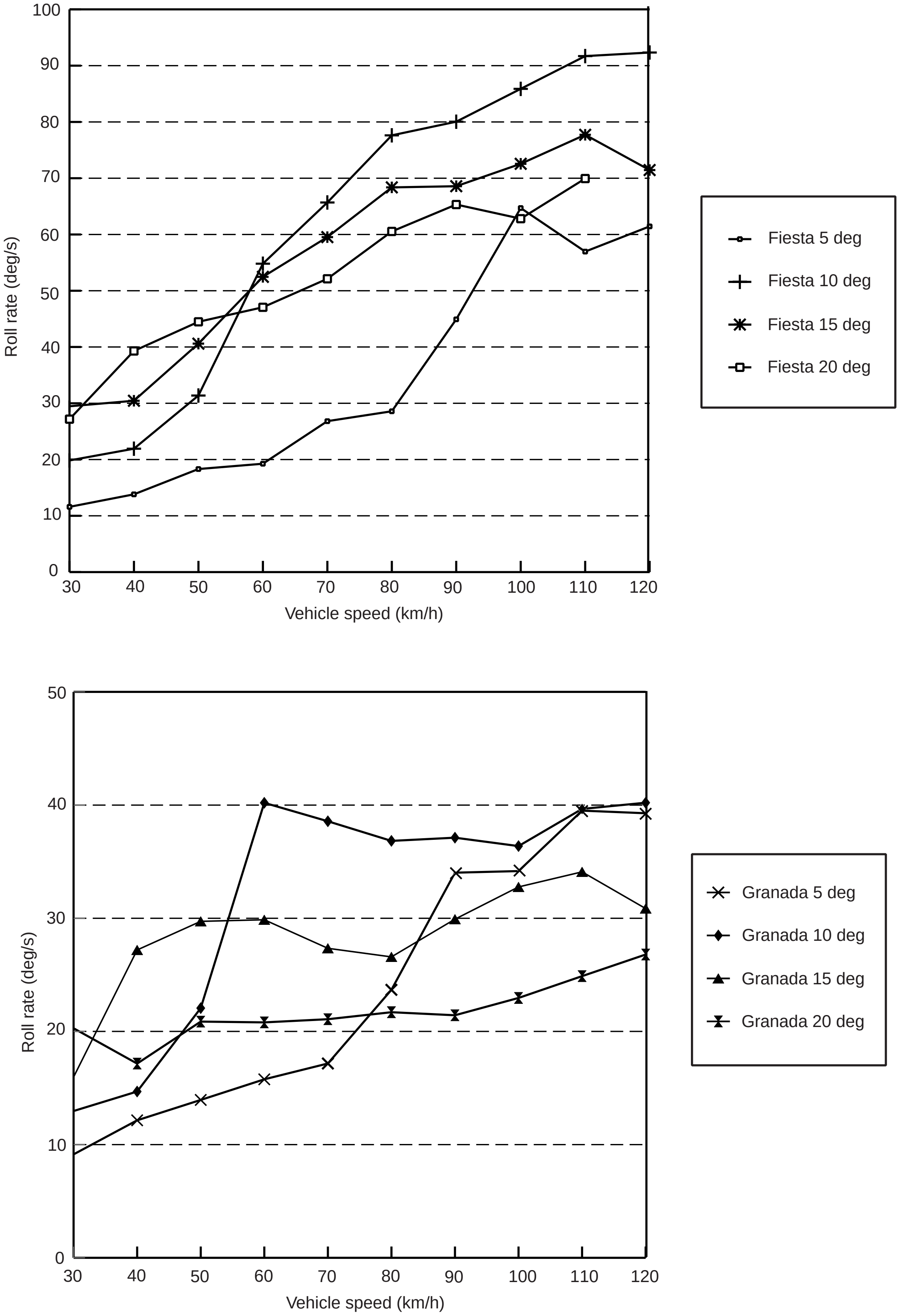


**Figure 2** Peak measured roll rates; fixed steering across trapezoidal channel

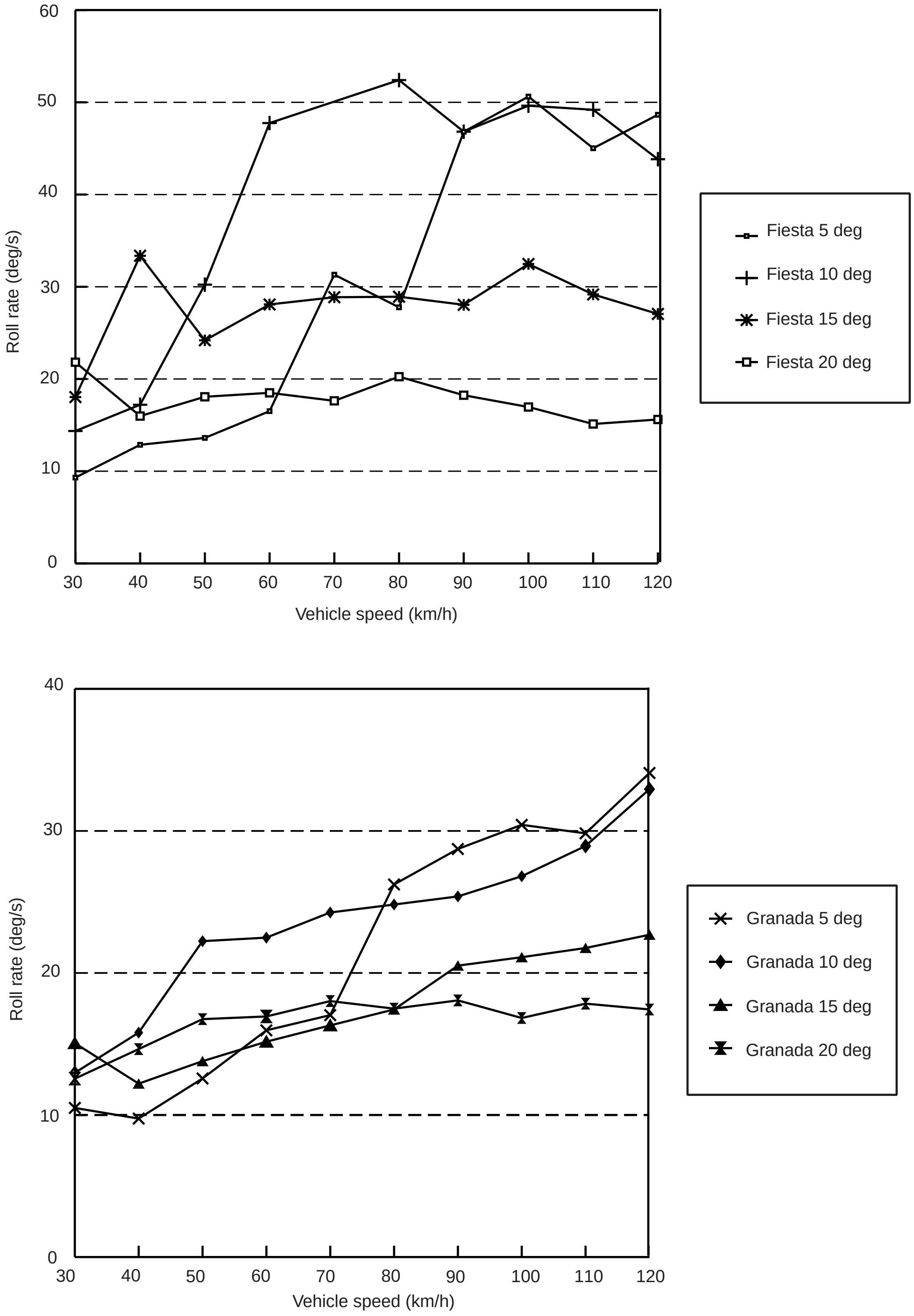
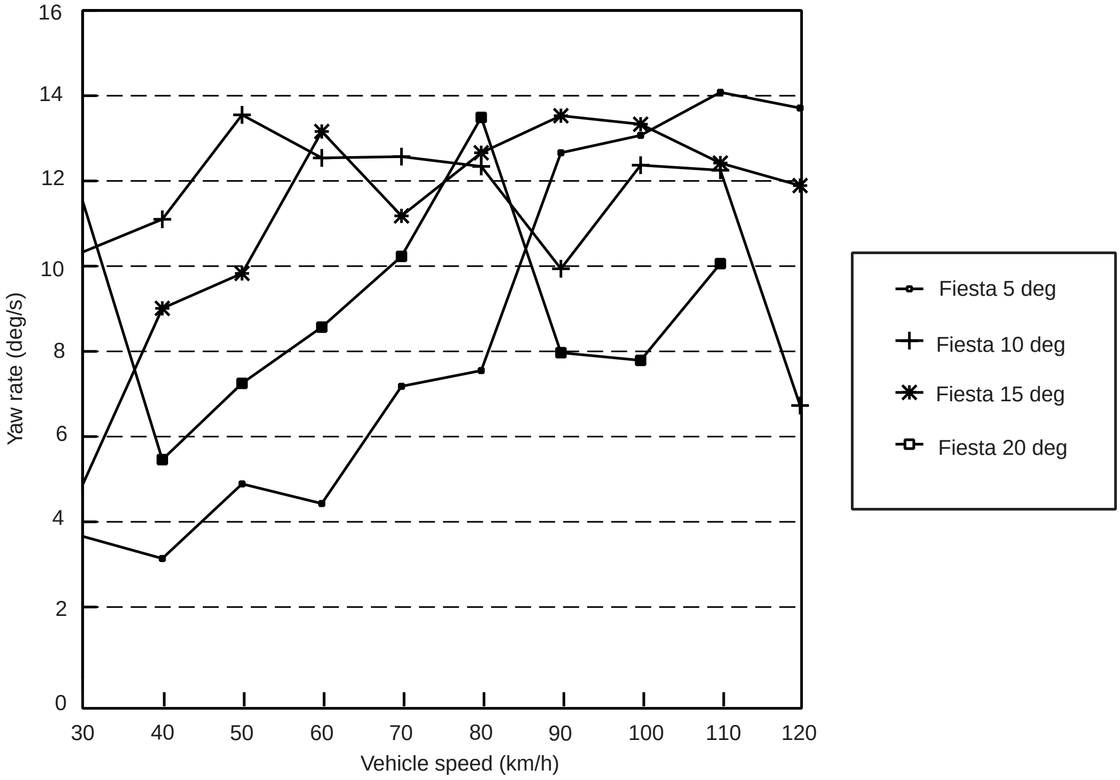


**Figure 3** Peak measured roll rates; fixed steering across triangular channel



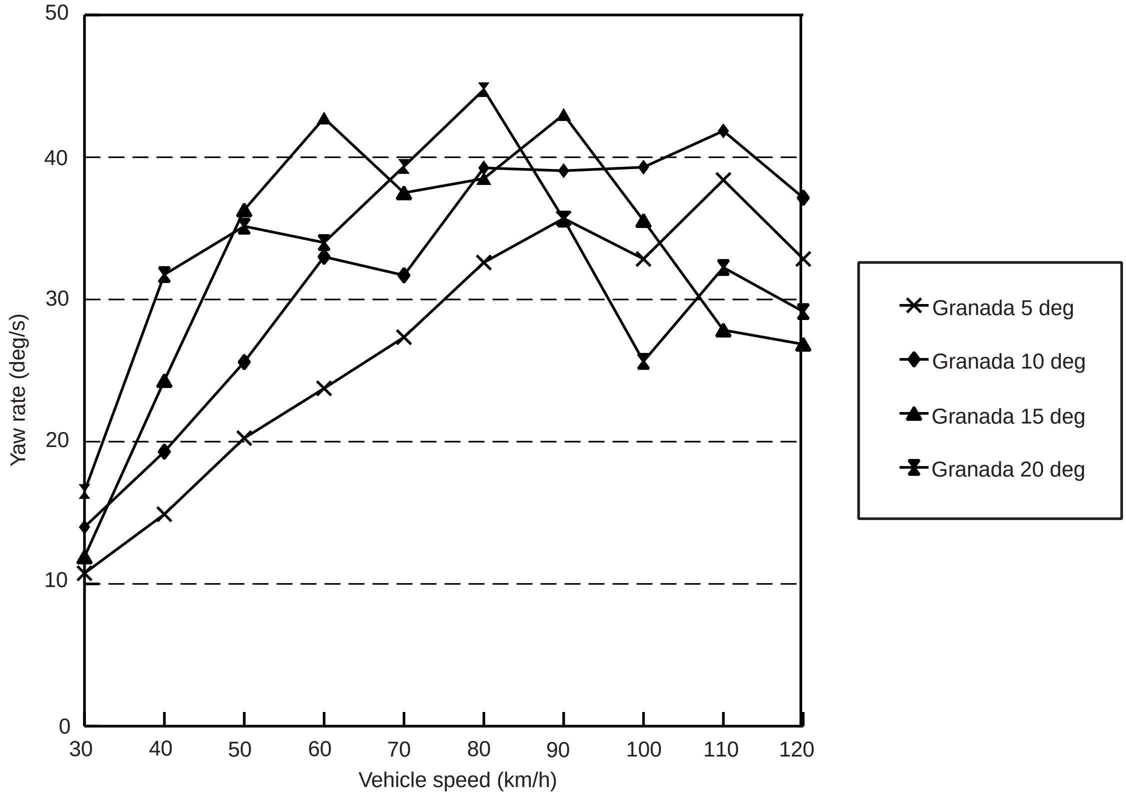


**Figure 4** Peak measured yaw rates; fixed steering across trapezoidal channel

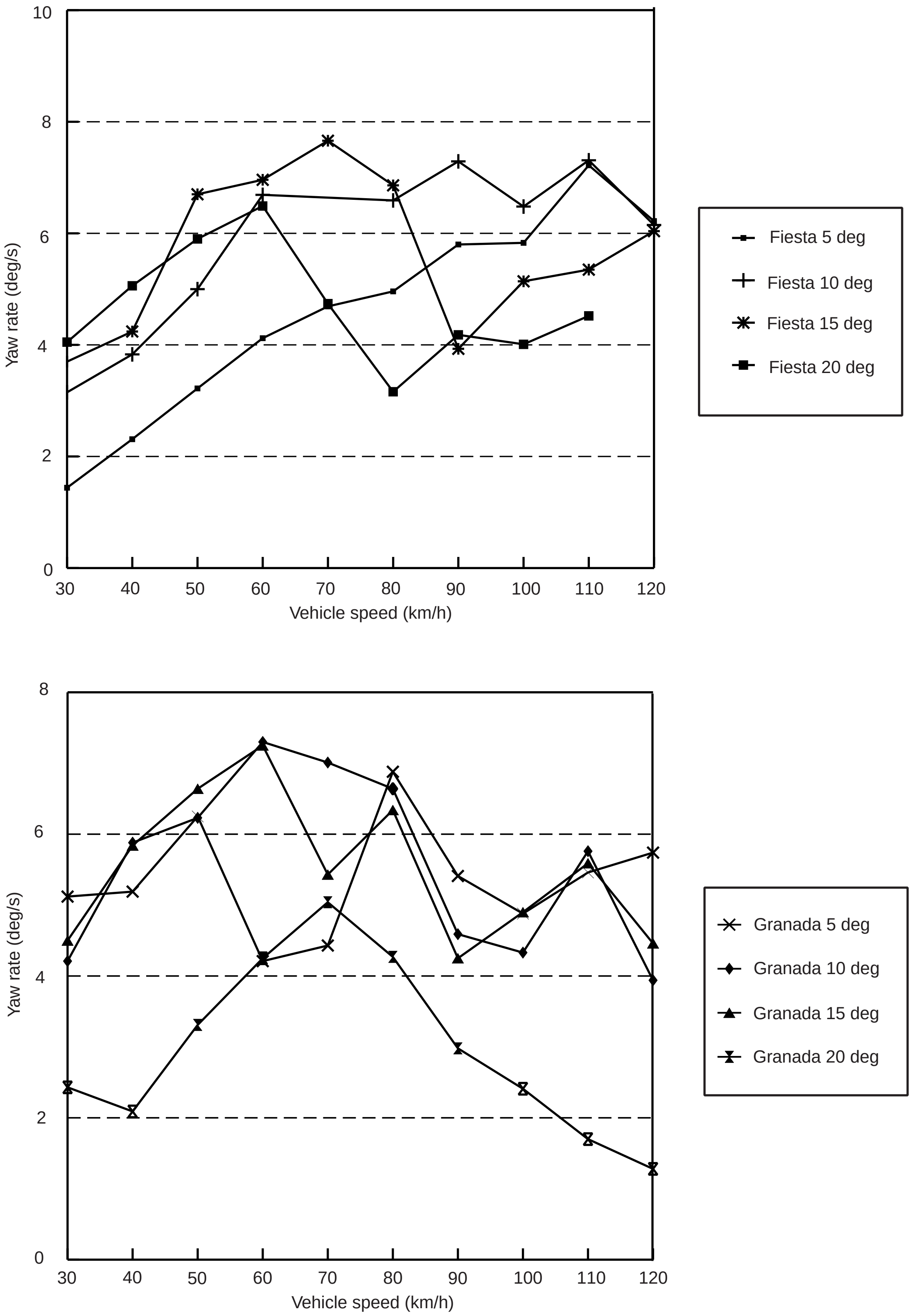


**Figure 5** Peak measured yaw rates; fixed steering across triangular channel

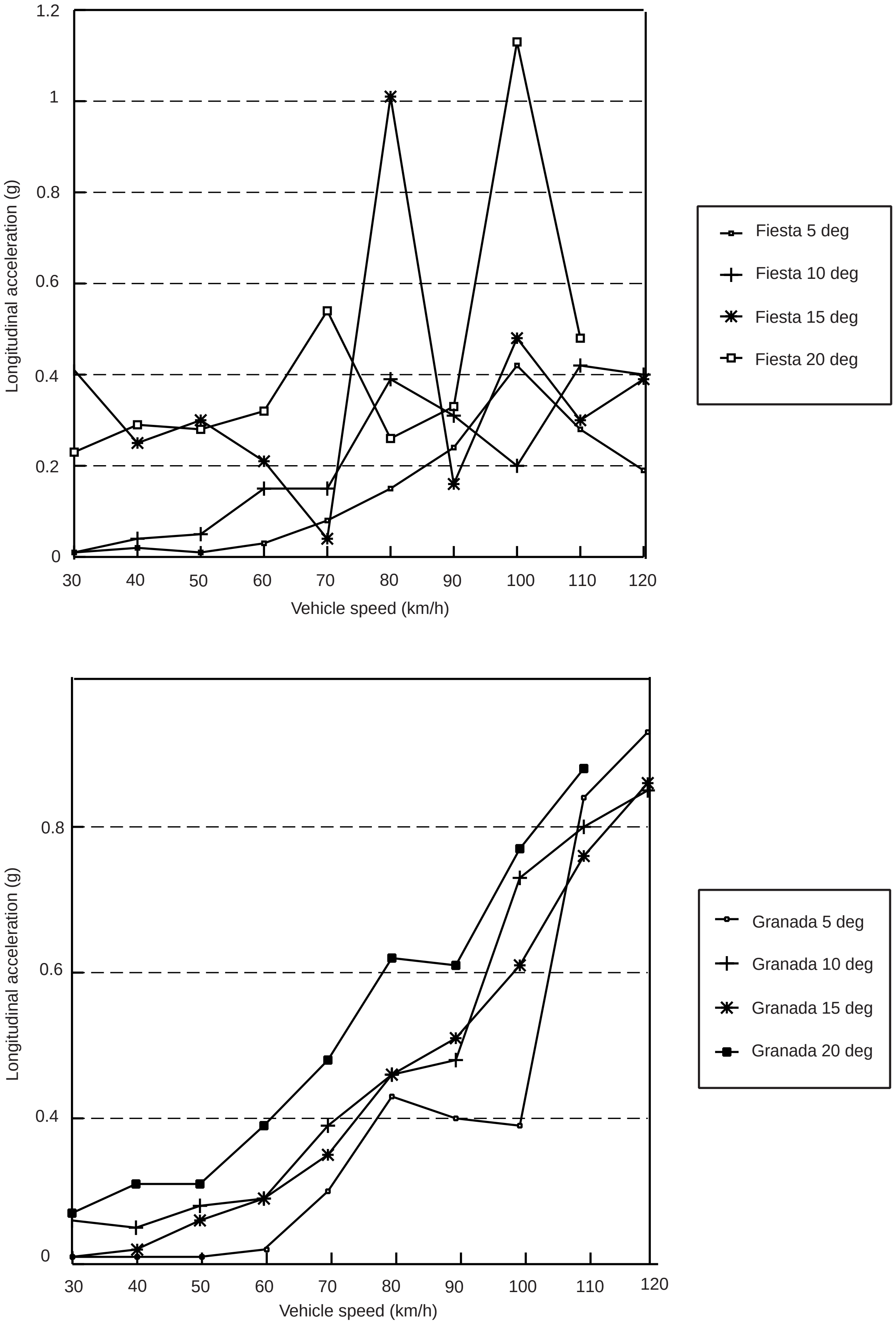


**Figure 6** Peak measured longitudinal acceleration; fixed steering across trapezoidal channel

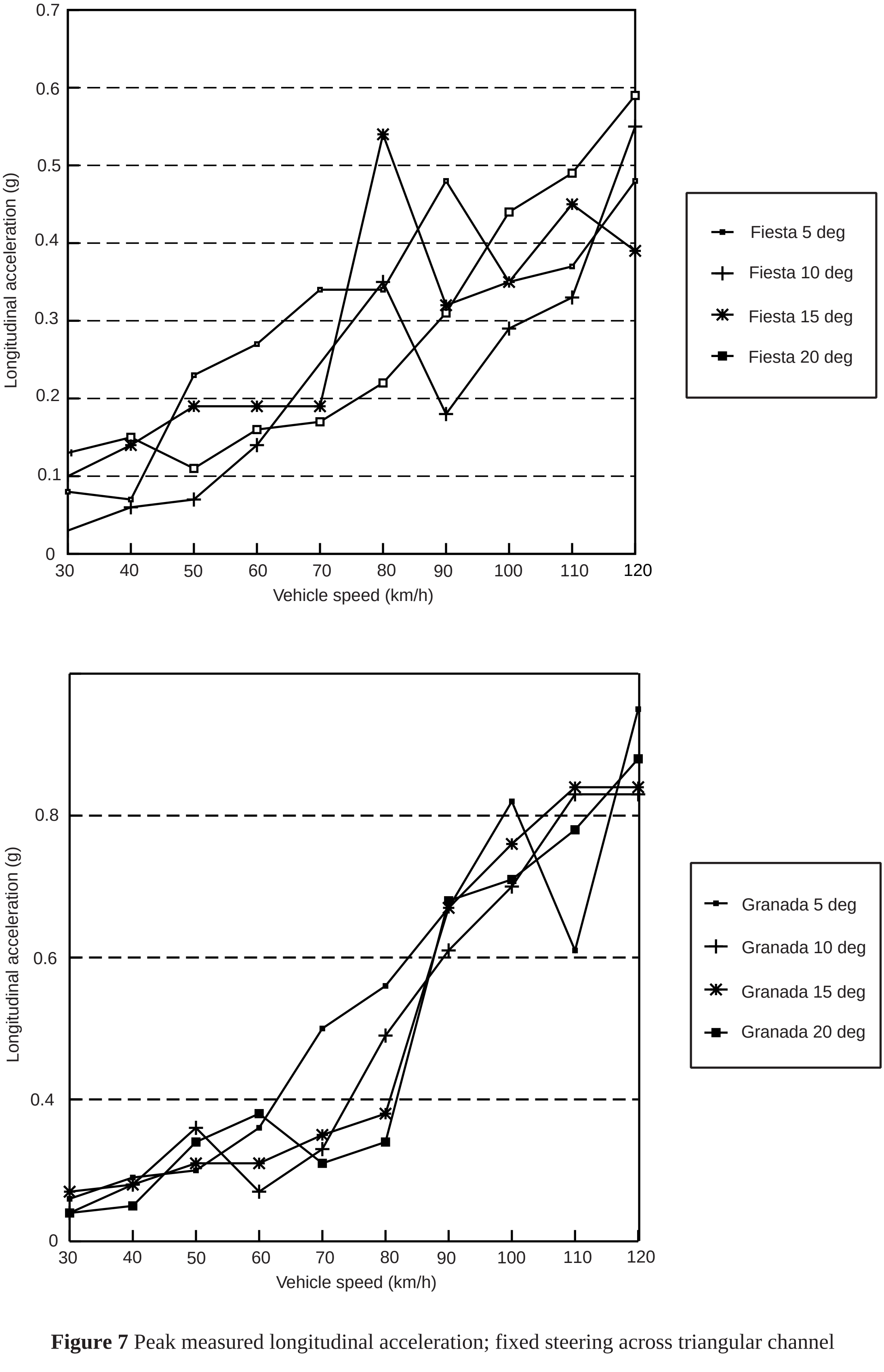


**Figure 7** Peak measured longitudinal acceleration; fixed steering across triangular channel

recorded transducer outputs from the MIRA and TRL tests indicates that the change in vehicle type and transducer specification should not adversely effect the overall assessment of channel profile effect. The results also indicate that the Fiesta and Granada are broadly comparable to the Mini and Rover, although the chassis dynamics of the more modern vehicles appear to be superior, in that the maximum speeds attained in the TRL tests were generally higher than in the MIRA tests. However, this may have been due, in part, to the relative tolerance levels of the two drivers who conducted the tests.

Although in some instances the differences are not great, the range of recorded transducer outputs given in Tables 1 and 2, would suggest that the trapezoidal channel had a slightly greater disturbing effect on the passage of the vehicles than did the triangular channel. This finding is counter to the conclusion arrived at in the MIRA report, which ranked the trapezoidal profile as less severe than the triangular profile. Re-examination of the available data from the MIRA tests indicates that, principally, the basis for ranking the channel profiles was that of maximum speed achieved for each test configuration, as determined by driver comfort and ability to retain control of the vehicle. Where the TRL fixed steering tests are concerned, the tests were terminated at 120km/h, hence the ‘limiting’ speed for this particular manoeuvre was not encountered with either vehicle and, therefore, the relative merits of the channels can only be assessed on the basis of the transducer outputs. In this respect, the MIRA and TRL test results are generally in agreement, with the range of values recorded for roll, yaw and longitudinal (X) acceleration being slightly greater for the trapezoidal channel than for the triangular channel. However, given the TRL test driver’s subjective assessment on handling and the recorded transducer responses, these two channels should be regarded as producing comparable vehicle disturbance at an acceptable level and it was decided that these be adopted as a ‘benchmark’ against which to assess alternative drainage features. It should be restated that the triangular channel has a side slope of 1:5 compared to the 1:4.5 of the trapezoidal channel. This probably results in the trapezoidal channel being slightly more ‘abrupt’ in terms of vehicle disturbance and it is quite likely that a trapezoidal channel with a 1:5 side slope would produce less vehicle disturbance than the triangular channel.

### *2.6.2 Corrective steering tests*

Both the Granada and Fiesta were used for the corrective steering tests on the two surface drainage features (triangular and trapezoidal channel). The results of these indicated, clearly, that the Fiesta was effected to a greater degree than the Granada at any given speed or approach angle. Therefore, when tests on the French Drain were performed, only the Fiesta was used for the vehicle handling assessment. For brevity, only the transducer values recorded from the tests with the Fiesta on the triangular and trapezoidal channel are presented in Appendix B. Table 3 gives the maximum vehicle speeds achieved during the ‘in channel’ corrective steering tests.

**Table 3 Limiting vehicle speeds for ‘in channel’ corrective steering tests on the drainage features tested**

| *Approach angle [deg]* | *Maximum speed achieved [km/h]* | | | | | |
|---|---|---|---|---|---|---|
| | *Fiesta* | | | | *Granada* | |
| | | | *French Drain* | | | |
| | *Trapez.* | *Triang.* | *Capped* | *Conven.* | *Trapez.* | *Triang.* |
| 5 | 80 | 120 | 90 | 90 | 120 | 110 |
| 10 | 90 | 120 | 70 | 80 | 120* | 80+ |
| 15 | 90 | 90 | 60 | 70 | 110 | 110 |
| 20 | 80 | 80 | 50 | 60 | 80 | 90 |

** Complete loss of vehicle control on exiting channel*
*+ Unable to complete test sequence due to transmission fluid loss*

For completeness, the maximum vehicle speeds achieved during the ‘straddling channel’ corrective steering tests are given in Table 4. The vehicle transducer results in Appendix B indicate that, generally, the trapezoidal channel produced greater vehicle disturbance than the triangular channel, over the range of tests conducted. It is also evident that the French Drain, either of the capped or conventional form, produced the least amount of vehicle disturbance at comparable speeds and approach angles. However, the lower limiting speeds achieved whilst testing the two forms of French Drain indicate that the French Drain, in both forms, has a greater effect on vehicle handling and safety than the concrete surface channels. At the higher approach angles, the speeds were limited as much by the problem of physically performing the required manoeuvre as that of maintaining control of the vehicle.

**Table 4 Limiting vehicle speeds for ‘straddling channel’ corrective steering tests on the drainage features tested**

| *Approach angle [deg]* | *Maximum speed achieved [km/h]* | | | |
|---|---|---|---|---|
| | *Fiesta* | | *Granada* | |
| | *Trapez.* | *Triang.* | *Trapez.* | *Triang.* |
| 5 | 80 | 90 | 120 | 120 |
| 10 | 80 | 100 | 120 | 120 |
| 15 | 90 | 80 | 100 | 100 |
| 20 | 80 | 80 | 80 | 90 |

There is a distinct difference in the character of the French Drain compared to that of the two concrete surface channels tested, in that the surface of the French Drain is, nominally, level with the surface on which the vehicle will be travelling before encountering the drain. This implies that there would be very little vehicle disturbance due to surface discontinuity. The problem associated with the French Drain is largely that produced by the change in tyre adhesion due to the variation in surface friction characteristics. This change in friction coefficient appears to be the main cause of adverse handling effects observed by the driver during the tests on the French Drain. With the offside wheels on the French Drain, in either capped or standard form, understeer was experienced, which turned to oversteer as the vehicle's offside front wheel returned to the road surface. This effect was more pronounced on the capped than the standard section of drain. It was considered that, at the higher speeds and steeper entrance/exit angles, that the vehicle's attitude could be effected enough to result in the vehicle re-entering the carriageway almost perpendicular to the direction of traffic flow, resulting in potentially serious conflict with other vehicles. It was also considered that the friction coefficient of the capping material could be significantly reduced when wet, amplifying the adverse vehicle handling effects described above. Unfortunately, due to the coarse and relatively uneven surface of the bituminised capping material, it was not possible to measure the friction coefficient of this surface. The driver reported that the ride quality of the two surfaces differed in that the capped drain felt like riding on underinflated tyres with a 'choppy' ride, an occasional knock through the suspension and a slightly vague feel to the steering. Whereas the aggregate surface gave a smoother, but slightly harsh ride with the steering feeling a little more positive. The driver stated that he felt in greater control of the vehicle whilst on the uncapped section than on the capped section of drain. However, this may have been due, in part, to fact that the driver had previous experience of driving on loose surfaces, but this was his first encounter with the bitumen bound rubberised capping material.

After performing the corrective steering tests on the trapezoidal surface drainage channel, the driver reported that the Fiesta, being front wheel drive, showed a preference for understeer when driving in a regular circle on a flat track. Taking the ground from beneath one front wheel, by driving into the channel, accentuated this basic characteristic. Understeer was also the general behaviour when exiting the channel though less severe than during the entry. Increasing the angle of entry and speed emphasised this basic characteristic. It was difficult to determine whether the speed or the increased angle of turn required was the more important factor in this respect. The Granada conformed initially to the same behaviour as the Fiesta on the trapezoidal surface drainage channel, understeering as the front went 'light'. However, being rear wheel drive, when the rear entered the channel, the initial understeer was followed by oversteer. Once again, increasing speed and angle increased the effect.

When the corrective steering tests on the triangular surface drainage channel were performed with the Fiesta, the entry phase of the manoeuvre did not cause as much understeer as the trapezoidal channel. However, at higher angles of approach the front dropping into the channel seemed to take the weight off the rear of the car causing the back to break away. The exit phase was characterised by understeer, as with the trapezoidal channel. The Granada exhibited the same behaviour in the triangular channel as the Fiesta, though generally less violent with the exception that, being rear wheel drive, the rear end break away was more noticeable. During runs at the higher speeds, the steering input needed to correct the oversteer was still being applied during and after the exit from the channel.

### *2.6.3 Single track vehicle tests*

A great deal of concern had been expressed regarding the potential for injury to cyclists and motorcyclists who come into conflict with road-edge drainage features, specifically surface drainage channels. At the request of the Highways Agency, limited testing was conducted with a pedal-cycle on the triangular surface drainage channel and the French Drain. Subsequently the author decided to extend this phase of the testing to include a light-weight motorcycle.

On the French Drain, the pedal cycle was tested at speeds up to approximately 30 km/h and the motorcycle 55 km/h. On the conventional form of French Drain, both vehicles were controllable providing the aggregate surface was level. It was found that both vehicles would tend to follow any ruts or ridging in the aggregate surface and it was thought that this could destabilise the vehicles to a point where loss of vehicle control would occur. This effect worsened with increasing speed. When the surface was loose, this tended to arrest the progress of both vehicles, making the steering feel heavy. Where the pedal cycle was concerned, when insufficient momentum was carried into the drain, the vehicle came to a complete halt, despite the best efforts of the rider to continue. On the capped section of French Drain, the ride on both vehicles felt 'choppy', but it was never felt that either vehicle was out of control. However, it was again considered that, at higher speeds, the change in friction coefficient when passing from the road surface onto the capping material combined with the rough ride, could cause a rider to lose control of his motorcycle. It was not considered likely that any such problems would be encountered by a cyclist, due to the low speeds involved; the only obvious problem would result from the capping material not being at the same level as the road surface. It is quite possible that the capping material may be slightly lower in places than the adjacent road surface. This would result in a small vertical step at the edge of the carriageway, which has the potential to unseat a rider who strayed onto the drain and tried to rejoin the carriageway. Any gaps left between the capping material and the road surface would have the potential to 'trap' narrow bicycle wheels, which could also unseat the rider.

Two-wheeler tests were also conducted on the triangular surface channel. At no time, during the testing with the pedal-cycle on this channel profile, was it considered that the rider was in any danger of loosing control of the vehicle. Only when attempting to traverse the channel at very steep approach angles (45 degrees or more), was the ride considered to be uncomfortable or at all hazardous. However, such large approach angles to road edge drainage features are unlikely to be experienced by any cyclist in everyday riding conditions. However, for features such as speed humps and cushions placed in the running lane, cyclists (and all other vehicular traffic) encounter relatively steep ramp faces, perpendicular to their direction of travel, as an everyday occurrence. The tests conducted with the motorcycle were more revealing. Runs straight through the channel did not result in any handling problems. However, the ride became uncomfortable at relatively low speeds, because there was a tendency for the rider to be 'bucked' from the seat of the motorcycle as it exited the far side of the channel. This was very noticeable at around 65 km/h for the 5° angle of approach and 40 km/h for the 20° angle of approach. For safety reasons, it was decided not to pursue testing at higher speeds. It is possible that, at higher speeds, this effect may reduce again as the vehicle tends to 'leap' across the channel, rather than following its full contour, as was indicated by the data recorded from the car tests. Some corrective steering tests were conducted and it was found that this manoeuvre was safe up to 65 km/h at the 5° approach angle and 40 km/h at the 20° approach angle. Again, for safety reasons limiting speeds were not established, but it was considered that speeds above these could give rise to problems. It is thought that, at higher speeds, the motorcycle's tyres would tend to lose adhesion on leaving the road surface and entering the channel, caused by the vehicles suspension unloading and the change in tyre/surface contact patch due to the abrupt change in camber angle. This could result in the tyres sliding down the leading face of the channel, unseating the rider.

MIRA's opinions, reported in TRL230, suggest that the 1:5 symmetrical triangular channel would pose similar handling problems to those experienced on the 1:4.5 asymmetrical triangular channel with the motorcycle. MIRA also believe that the trapezoidal channel, with its shallow side slopes and flat bottom, would be the least severe. However, the author considers that, in keeping with the handling tests and simulation work conducted at TRL, that there would be little to choose between the 1:5 symmetrical and 1:4.5 asymmetrical channels, where single track vehicles are concerned.

No tests were conducted on any form of vertical or near vertical features, such as kerbs or vertical drops, of the types represented by the drainage profiles D, E, F and H shown in Appendix D. It was considered that the unpredictable nature of such testing presented too great a hazard, especially for the single track vehicles. However, testing has previously been conducted on kerbs, primarily in the United States, the results of which are discussed in chapter 5.

### 2.7 Problems encountered during testing

During testing with the Granada on the trapezoidal channel, the driver lost control of the vehicle after attempting to perform an 'in channel' corrective steering run at 120km/h with a $10^{o}$ approach angle. The track surface was wet and there was a high cross wind. As the vehicle started to enter the channel, the rear of the car had already begun to slip sideways. The vehicle continued to slide as it went up the opposite side of the channel and the vehicle was heaved upwards, the two off-side wheels momentarily losing contact with the surface. The vehicle landed heavily and started to cut back across the channel. As the vehicle hit the upward slope on the near-side of the channel, it was again heaved into the air and landed about 1.5m from the channel. At this stage, the vehicle was at an angle of approximately $15^{o}$ to the direction of travel. The rear of the vehicle continued to slide, until it had turned through $180^{o}$, at which point the driver had the presence of mind to lock the brakes, ensuring that the vehicle travelled in a straight line, albeit backwards, and braced his head against the head restraint. The vehicle continued on its course for around 40m before hitting and then travelling along the face of the track-side safety barrier, for a further 15-20m, before coming to a halt. Needless to say, the driver was shaken and testing was halted, whilst the driver regained his composure and the damage to the vehicle was assessed. Besides the cosmetic damage, it was discovered that the steering rack had been damaged and, hence, testing was postponed until the steering rack had been replaced. The vehicle was out of service for approximately 24 hours. As a result of this incident, it was decided that future high-speed testing should not be conducted whilst the track surface was wet.

The wet track surface also caused problems, on at least one occasion, with the vehicle approach to the test site. At the $20^{o}$ approach angle, understeer prevented the driver from exceeding 100km/h in the Fiesta, when attempting the 'fixed steering' manoeuvre, because of a lack of space, which necessitated the use of a dog-legged approach run.

Some of the manoeuvres planned turned out to be impossible to achieve; namely the higher speed runs at steeper approach angles. It is not practical to approach a test drainage feature at, say, 90km/h at an angle of incidence of $20^{o}$ and perform a corrective steering manoeuvre which requires the driver to place the vehicle accurately within a 1.5m wide drainage channel. Under such conditions, the driver was having to anticipate the turning point (before reaching the channel) in the hope that the apex of the vehicle path would coincide with the required position in the channel. Hence, tests under these conditions were not pursued beyond moderate speeds (typically, 90-100km/h for the $15^{o}$ approach angle and 80-90km/h for the $20^{o}$ approach angle).

## 3 Computer modelling

A major objective of this project was to investigate the feasibility of using a computer program to simulate the effects of vehicles encroaching into road edge drainage features. After some initial enquiries and a literature search, it was decided that the Highway Vehicle Object Simulation Model (HVOSM) - a computer simulation program used fairly extensively in the USA - appeared to be able to handle the situations envisaged. The program had been written to model cars encountering road-side objects including ditches, kerbs and barriers. The source code (Fortran) was readily available and relatively easily modified and appeared to be the ideal program for the task envisaged. A copy of the program was therefore acquired from the Texas Transportation Institute (TTI). However, before the program could be used, a number of deficiencies had to be addressed. The default vehicle parameters for the modelling program were based on 1960s American saloon cars and, as such, bear little resemblance to 1990s British traffic. For the simulation run performed as a feasibility study, several of the default vehicle parameters were changed in an attempt to describe a 'Mini' type vehicle. The results from this simulation were encouraging when compared to the test results recorded by MIRA during their track tests of the asymmetrical triangular channel. However, further simulations of other drainage features, would necessitate the measurement or calculation of appropriate vehicle parameters to represent the Granada and Fiesta. To determine which parameters were of greatest importance, a series of sensitivity trials were performed, whereby various input parameters were varied and their effects on the simulation outputs assessed. The findings of this investigation are summarised below. Subsequently, a series of physical measurements were taken from the two vehicles to be used for the track tests and these were later used as input parameters for the simulation runs of track tests.

### 3.1 Program sensitivity tests

In order to determine the sensitivity of the simulation output values to variations in the vehicle parameter inputs, a series of simulation runs were performed in which certain parameters were varied in isolation or as related groups. The input parameters were varied by 20% and/or 50%. A subjective assessment of the variation in outputs was made and the input parameters awarded points and ranked accordingly. The program sensitivity was assessed by analysing six program outputs: the longitudinal, lateral and vertical accelerations about the centre of mass of the sprung mass, and roll, pitch and yaw of the sprung mass.

The conclusions were that the parameters relating to the inertial properties and geometry of the vehicle were of greatest influence. Parameters defining the suspension and damping forces were found to be more important than those relating to the properties of the tyres. Consequently, resources were concentrated on determining the physical and inertial properties of the Granada and Fiesta in anticipation of performing the drainage feature simulations.

### 3.2 Simulation of track tests

A series of simulation runs with the HVOSM program were performed to test the correlation between the program outputs and the results from track testing. Having entered the data for the concrete surface channel profiles and the new vehicle parameters derived for the Fiesta and Granada, ‘fixed’ steering runs were simulated at approach angles from 5$^o$ to 20$^o$ at speeds of 40, 80 and 120km/h. The runs performed at 40km/h appeared to provide sensible results in terms of both the shape of the curves on the graphs representing the vehicle body accelerations, and the predicted peak values. However, on progressing to the runs at 80km/h, a severe oscillation in the yaw rate was produced at all approach angles. On progressing to the 120km/h runs, this oscillation became unstable. This effect indicated a non-convergence in one or more of the calculations performed by HVOSM and needed investigation. The problem was discovered to have been caused by a lack of restraint imposed on the steering system of the vehicle. In initial, low-speed simulations, it was found that the steering angle was effected very little by the channel as the vehicle crossed over and, for this reason, the decision was taken to allow the steering to ‘float’ for subsequent simulations. It was not until the high-speed runs were performed that the unstable oscillations in the vehicle yaw were discovered. The problem was overcome by fixing the steering angle relative to the vehicle body and although not representative of the ‘real world’, it appears to be a necessary compromise to stabilise the model in its present form. The peak accelerations and angular velocities predicted by the model are given in Appendix C.

### 3.3 Comparison of track test and simulation results

The results from the track tests revealed a trend for the vehicle pitching to increase with vehicle speed at the 5° approach angle, but to decrease with increasing vehicle speed at the 10° approach angle and beyond with the effect increasing as the approach angle increased. The simulations predicted the decrease in pitching as the vehicle speed and approach angle increased, but failed to replicate the increase in pitching with increasing vehicle speed at the 5° approach angle as observed in the track tests. The predicted vehicle body roll increased with increasing vehicle speed in a similar manner to that observed during the track tests, although the predicted values were generally higher than the track test results. Lateral (Y) accelerations observed during the track tests were higher than those predicted by the model, but the trends were in agreement, in that lateral acceleration increases with increasing vehicle speed. Vertical accelerations predicted by the model were of the same order as those observed during the track tests and followed the same trend of increasing with increasing vehicle speed. The longitudinal (X) accelerations and yaw rates predicted by the model are somewhat lower than the actual values recorded during track tests. The trend for the longitudinal accelerations to increase with vehicle speed, observed in the track test data, is evident in the simulation results, but the effect is not as distinct.

Generally, the model predictions, in all cases, are in accord with the results of the track tests. In some cases the levels of the predicted accelerations do differ from those observed during the track tests, but this is believed to be a result of simplifications in the vehicle dynamics algorithms used in the program. However, overall, the model predictions of vehicle body accelerations and angular velocities indicate that the trapezoidal channel would have a greater disturbing effect on the passage of the vehicles than would the triangular channel. In this respect, the model predictions support the conclusion drawn from the latest track test results. This, as indicted earlier, is in contrast to the MIRA test results which indicated that the 1:4.5 trapezoidal channel was slightly less severe than the 1:5 triangular channel. However, the differences are marginal and are likely to be accounted for by minor differences in the experimental procedure used for the two sets of track tests.

The French Drain was not modelled, as the fixed steering manoeuvre employed was unlikely to result in any significant vehicle disturbance, due to the flat nature of this particular drainage feature. Handling problems are encountered when vehicles encroach into a French Drain, as witnessed by the track test results, but these would not have been evident from the simulation tests.

### 3.4 Simulation of additional drainage features

A number of additional drainage channel profiles have been modelled and are detailed in Appendix D, along with the vehicle body accelerations and angular velocities predicted by HVOSM (Tables D1 to D8). Simulation of the French Drain (channel profile G) has not been performed, as this was likely to involve an element of skidding, which has not been addressed by TRL in the modelling work conducted. Simulation runs for channel profile D (kerb-stone) were attempted, initially, using the 'ditch' algorithm in HVOSM; the results of these indicated that the algorithm could not cope with this channel profile. The simulation was re-run using the 'kerb' algorithm, but this defaulted to the 'free' steering mode, which resulted in unstable vehicle oscillations. Another 'problem' discovered whilst performing this latest set of simulations, concerns the use of vertical faces in the channel profile, which also cause the program to produce implausible predictions. TRL subsequently learned that this was a recognised 'bug' in the program, but were not in a position to address the problem, as this was outside the remit of the project.

The geometries of the following profiles are shown in Figure 2 and the results of simulations are tabulated in Appendix C:

Channel B - symmetrical triangular channel
Channel C - symmetrical trapezoidal channel

The geometries of the following profiles are shown in Figure D1 and the results of simulations are tabulated in Appendix D:

Channel A - asymmetrical triangular channel
Channel E - asymmetrical trapezoidal channel
Channel F - HCD block
Channel H - trapezoidal channel for porous asphalt

For 5° and 20° approach angles, the results indicate the following rankings of the respective channel profiles in descending order, based on the level of vehicle disturbance:

*5° Approach*

Channel H (most disturbance)
Channel A
Channel C
Channel B
Channel F
Channel E (least disturbance)

*20° Approach*

Channel A (most disturbance)
Channel H
Channel C
Channel B
Channel F
Channel E (least disturbance)

At the 20° approach angle, the ranking of channel H above channel C is influenced by the high level of vehicle disturbance induced at the lower speed. However, as the speed increased, the level of disturbance caused by channel H reduced to the extent that, at 120 km/h, it was producing less disturbance, generally, than channel C. This is probably a result of the vehicle tending to 'jump' across the channel as the speed increases, hence the vehicle being less influenced by the channel profile. As the carriageway plane associated with channel H is higher than that of channel C, the vehicle will 'jump' further before encountering the channel.

The trends in vehicle disturbance with increasing speed vary between the channels and also vary, in some instances, with the change in approach angle. For this reason, it is difficult to draw any general conclusions about the effects on vehicle disturbance of the differing design elements, other than to say that an increase in depth and a steepening of the side walls appear to increase vehicle disturbance, as would be expected. To gain a greater understanding of the effects of individual features (eg. width, depth, side slope), the dimensions of these features would need to be progressively adjusted, independently of other features, and tested accordingly. This process is a task ideally suited to simulation, but was outside the scope of the project.

## 4 Accident statistics

Little or no information has been published on the number of road accidents in which road edge drainage features are implicated. In an attempt to discover the size of the problem, The Department of Transport's Trunk Road accident database (STATS19) was interrogated. However, this proved not to be very informative, as the categories for recording such information are quite limited. Of the categories available, those which come nearest to providing information relevant to drainage features are:

| *Vehicle Record No.* | *Description* |
|---|---|
| 2.12.10 | Hit object in carriageway - kerb |
| 2.13 | Vehicle leaving carriageway |
| 2.14.09 | Hit object off carriageway - entered ditch |

Note that, in STATS19, the kerb is deemed to be part of the carriageway, whereas the ditch is a feature off the carriageway. All vehicles recorded in STATS19 have been involved in an injury accident, either in isolation or involving another vehicle. A vehicle can be coded as doing all, none or a combination of the above. Clearly it is not possible for a vehicle to hit an object off the carriageway without leaving the carriageway (the only possible exception being something overhanging the carriageway), although incorrect coding can occur.

The STATS19 database search was performed on one year's data (1996), using the above vehicle record codes as search parameters. The data were split into two sections; vehicles leaving or not leaving the carriageway. Within these two categories the data were subdivided by vehicle hitting object in carriageway or hitting object off carriageway. The data were also split into three vehicle categories; pedal cycle, powered two-wheeler and all other vehicles. The tabulated results are shown in Appendix E. Of those vehicles involved in injury accidents, which did not leave the carriageway (380 102), 1 472 (approximately

0.4%) were reported as hitting the kerb. Whereas, the number of vehicles reported as leaving the carriageway totalled 46 863; of these 1 422 (approximately 3%) hit the kerb, 2 853 (approximately 6%) entered the ditch and 355 (approximately 0.8%) did both.

It is not possible to draw any conclusions from these figures, other than to say that just over 11% (48 412) of vehicles involved in injury accidents in 1996 either left the carriageway and/or hit the kerb. To get more detailed information on the circumstances and contributory factors involved in these accidents, would necessitate going back to the original accident records. This would be a mammoth task and there would be no guarantee that information on drainage features would have been recorded, even if such features had played a role in the cause or outcome of the accident. A better approach would involve identifying sections of road which incorporated various forms of road edge drainage and then to examine any accidents which had occurred in the vicinity. Again, depending on whether the drainage feature had played a role in the accident and the details recorded, this may not provide the desired information and would still be a very time consuming exercise. A full accident investigation of this type was considered to be outside the scope of this project.

## 5 Discussion

The results from the track tests indicate that the triangular channel, with its shallower side slope (1:5), presents slightly less of a problem than the trapezoidal channel (1:4.5 side slope). The fact that MIRA, employing their own driver and different vehicles, arrived at the converse conclusion raises some concern over the ability of the test method to conclusively distinguish the relative hazard presented by the channels. It is possible that the difference between the symmetrical triangular and trapezoidal channels is too subtle to be conclusively detected via physical testing and indeed, the differences in the results are marginal. However, the vehicle body accelerations recorded by TRL indicate that, for a given set of test conditions, the trapezoidal channel had a slightly higher disturbing effect on the passage of the vehicles than did the triangular channel. This is supported by the TRL test driver's subjective assessment of the ride quality experienced whilst performing the 'fixed' steering runs. The computer simulation runs also indicated that the trapezoidal channel produced slightly greater disturbance to the vehicles than did the triangular channel. The slight variation in vehicle disturbance observed between the triangular and trapezoidal surface drainage channels is almost certainly due to the differences in side slope and it is highly likely that a trapezoidal channel with a 1:5 side slope would fair as well or better than a triangular channel with a 1:5 side slope.

If a driver's subjective assessment can be relied upon to provide a consistent evaluation of the vehicle handling and ride, then it would undoubtedly be more relevant in determining channel severity than relying on the recorded vehicle body accelerations. However, if the drivers assessment is inconsistent, it cannot be used to rank the relative severity of the effects of the channels. Bearing in mind that there could be several weeks, or perhaps even months, between the testing of alternative channels, there would be some grounds for having reservations regarding the reliability of the driver's assessment, especially where subtle differences in the channel profiles are involved. It must, therefore, be concluded that emphasis in ranking the channel severity should be placed on analysis of the recorded transducer data, with the driver's assessment providing a supporting role in the ranking of the channels, rather than a leading role.

Research has been conducted, in the past, on the discomfort rating of vehicle vibrations (Kenneth et al. 1979) and on human tolerance to acceleration (Stapp 1957). However, there appears to be no published information relating measured, low-level, vehicle body accelerations to a driver's ability to maintain control of a vehicle. TRL's test driver reported that, at the higher levels of vehicle body disturbance, loss of vehicle control was caused by the relatively violent vehicle movement unsettling the driver to the extent where he was, momentarily, unable to maintain control to the foot pedals and steering wheel. Where the 'fixed' steering manoeuvre was concerned, it was considered that, where an unprotected central reserve was encountered, the vehicle may have time to cross the reserve and encroach on the opposite carriageway before the driver could regain control of the vehicle. Unfortunately, it was not possible to determine the speed at which this was likely to present a problem, as the magnitude of the effect increased steadily with increasing vehicle speed and approach angle. The problem was also more severe with the Fiesta than with the Granada. It should also be noted, that the test driver was securely retained in the driving seat by a three-point harness and it must, therefore, logically be concluded that the problem would have been worse still for a driver wearing a standard seat belt. In this respect, it would seem likely that the measured vehicle body accelerations and angular velocities could be directly correlated with the severity of the channel effect on vehicle controllability. If one accepts that the magnitude of vehicle disturbance can be directly related to the severity of the channel effect, then it would appear feasible to investigate alternative channel profiles via computer simulation alone. Although the model predictions differ somewhat from the track test results, they are of a comparable level and follow similar trends and are, therefore, considered valid for making comparisons between the effects on vehicle handling of different drainage features. The computer model used for the simulations during this research has some significant drawbacks and any further use of the program would restrict the extent of investigation. If further simulation were considered, it is recommended that, in the absence of a more comprehensive program than HVOSM, a bespoke program should be commissioned. The use of a more general finite element package would be possible, but may not be cost effective for this type of investigation.

It would seem that the amount of control the driver can exercise over the direction of the vehicle, is related, to a large extent, to the level of vehicle disturbance induced by the channel profile. Therefore, the measured or simulated levels of linear acceleration and angular velocity can be used as objective measures by which to assess the relative safety of alternative drainage features and, indeed, the predicted vehicle disturbance has been used to rank various channel profiles in Chapter 3 of this report. However, it is clearly inappropriate to use these measures to determine the handling difficulties associated with loose or other low friction coefficient surfaces. Such problems may be assessed subjectively by physical testing or with a suitable computer model. It would seem difficult to relate the degree of difficulty presented to the driver by a concrete surface channel with that presented by a nominally flat surfaced feature such as a French Drain - they are different in character. The hazard presented by the surface channel is determined more by its topology than by the surface friction characteristics, whereas the inverse is true for the French Drain.

As a result of this research and previous research conducted in the United States, some recommendations can be made regarding channel profile design for high speed roads. There is a tendency for steep faced kerbs to ‘trip’ a sliding vehicle and cause it to overturn at relatively low speeds (Ross et al. 1989). For a given kerb configuration, the propensity for overturn increases as the vehicle size decreases. To minimise the risk of a small car overturning when sliding into a kerb, the slope of the kerb face should be as flat as possible, preferably 30 degrees (1:1.7) or less (Council et al. 1987). It would seem reasonable to apply this ‘rule’ to the side walls of drainage channels, as vehicles are just as likely to slide into channels. Although no direct comparison of potential vehicle disturbance has been possible between that induced by kerbs and the alternative drainage features investigated here, it is the author’s opinion that kerbs present a far greater potential hazard to all vehicular traffic than that posed by concrete surface channels.

Although no published information could be found on the effects on handling safety of single track vehicles when encountering vertical or near vertical longitudinal surface features, it is well known that such vehicles (pedal cycles and motorcycles) encounter significant difficulties when faced with steep transitions in the terrain they are traversing, as witnessed by MIRA’s aborted attempts to test the asymmetrical triangular channel (Appendix D: channel profile A) with a motorcycle. It is recommended that, where possible, even small vertical steps, such as might be encountered at the transition between carriageway surface and drainage channel (eg. Appendix D: channel profile H), should be avoided where possible, as even these could have a severe disturbing effect on single track vehicles. This handling problem is likely to be inversely proportional to the angle of approach, ie. the smaller the angle, the greater the effect. The absence of vertical faces is also likely to reduce the possibility of concussion punctures to tyres, which can adversely effect vehicle handling and, in the case of front tyre punctures on single track vehicles, lead to complete loss of control or capsize. The handling of twin track vehicles can also be adversely effected by abrupt longitudinal steps as reported by a study conducted in America (Glennon 1987). Glennon found that drivers of cars who had their vehicle wheels off the carriageway and scrubbing against the edge, could negotiate a 3 inch (75mm) drop at speeds of up to 30 mile/h (48 km/h), but found it almost impossible to negotiate a 4.5 inch (114mm) drop at almost any speed. It is, therefore, recommended that vertical or near vertical steps, greater in depth than 25mm, should be avoided, where possible - this is particularly important for single track vehicles. Where small vertical steps are unavoidable, as is the case with a porous asphalt surface, provision should be made to warn the drivers/riders whose vehicles stray towards the edge of the carriageway, by use of raised rib road edge markings. These should be positioned such that there is sufficient space between the marking and the edge of the carriageway to allow the rider/driver some chance of correcting the vehicle’s course before encountering the edge of the carriageway, but this area should not be so wide as to encourage its use as a cycle lane; a distance of 300mm would seem to be a sensible compromise. Where larger vertical or near vertical steps are required, consideration should be given to protecting these with safety barriers.

It is also recommended that steep (30 degree) channel side walls should not extend beyond a height of 150mm in order to avoid vehicle ‘ramping’, chassis contact, suspension bottoming and wheel misalignment (Olson et al. 1974). A preferred maximum height for steep side walls would be 75-100mm. The side walls of channels deeper than 100mm should be of a much shallower angle, as per the channels tested on the track (ie. approx. 12 degrees). The advice given in the Departmental Advice Note HA 37/88 suggests that rectangular channels or triangular channels of depth greater than 150mm, should be protected by safety fencing; the importance of this cannot be over stated from a safety point of view. HA 37/88 also suggests that raised rib road edge markings may be considered in the case of triangular channels; the author believes this should be a recommendation of the Advice Note rather than a suggestion.

Specifically with the safety of single track vehicles in mind, the aggregate used in French Drains should be fairly well compacted and the surface should be maintained as level as possible. However, a level uncompacted surface is preferable to a compacted uneven surface!

## 6 Summary and conclusions

Three road edge drainage features have been tested to assess their effects on vehicle handling and safety. Two of the channel profiles had previously been tested by MIRA under sub-contract to TRL, but were re-tested under the current project because of a change in the test vehicle specification and the need to provide data to validate computer simulations. The vehicles were instrumented to record steering inputs and body accelerations and angular velocities. The tests, which consisted of various steering manoeuvres, were performed with the vehicles approaching the channels at various speeds and angles.

The difference in the responses of the two cars used for the handling tests were clearly defined, but the differences between the effects of the two surface drainage channels were not so obvious. On the basis of the vehicle transducer outputs and the TRL test driver's subjective assessment of the vehicle handling, the effects of the trapezoidal channel (1:4.5 side slope) were considered to be slightly more severe than those of the triangular channel (1:5 side slope). The steeper side wall slope of the trapezoidal channel, designed to provide greater hydraulic capacity, may well have induced the slightly higher vehicle disturbance observed during the track tests. However, when MIRA tested the same two channels, they concluded that the triangular channel was slightly more severe than the trapezoidal channel. Given these results, it must ultimately be concluded that the two channels are broadly comparable in terms of their effects on vehicle handling safety. The trapezoidal channel is therefore to be preferred, where its hydraulic properties can be shown to have an advantage over a triangular channel.

A third channel, the French Drain, was also tested. This channel posses a distinctly different problem to the other two channels tested, in that the levels of physical vehicle disturbance are much less, but the friction coefficient of the surface, either capped or uncapped, is much lower than the concrete surface drainage channels. The main feature of this channel was the change from understeer to oversteer as the offside front wheel of the test vehicle rejoined the edge of the carriageway. This was considered to be more pronounced for the capped drain, but this is offset by the absence of stone scatter associated with the uncapped drain. The handling of the single-track vehicles was considered to be better on the capped drain, but it is likely that the friction coefficient of the capping material would drop significantly when wet, heightening the problems for both twin and single track vehicles.

The main conclusions are as follows:

i The Fiesta, with its shorter wheelbase, lighter mass and stiffer suspension, was more severely disturbed by traversing the channels than was the Granada.

ii The Fiesta and Granada were able to traverse both of the surface drainage channels tested, in the 'fixed' steering mode, at the 'target' maximum speed of 120km/h and remained relatively stable in doing so. There was a finite period of time which the driver took to gather his composure before being able to exercise full control over the direction of the vehicle after traversing either channel at the higher speeds, the duration of which was dependent on the disturbance to the vehicle.

iii The recorded transducer outputs from the TRL track tests indicated that the trapezoidal channel had a slightly greater disturbing effect on the vehicles than did the triangular channel. This was also supported by the TRL test driver's subjective assessment of the vehicle ride quality. However, given the findings of the research conducted by MIRA it should be considered that the two forms of surface drainage channel will produce very similar levels of vehicle disturbance. The trapezoidal channel is therefore to be preferred, where its hydraulic properties can be shown to have an advantage over a triangular channel. The French Drain produced the least amount of physical disturbance out of the three channel profiles tested, but introduces other vehicle handling difficulties due to the loose surface presented by the filter material. The asymmetrical concrete surface channel tested by MIRA is no longer endorsed by the Highways Agency as an approved road edge drainage feature.

iv When considering the results from the 'fixed' steering vehicle tests, there appears to be a good correlation between induced vehicle disturbance and the driver's ability to maintain effective control of the vehicle.

v Single track vehicles are inherently unstable and, as such, are effected to a greater degree by both transitions in the surface on which they are travelling as well changes in surface friction coefficient, than are twin track vehicles. They are particularly sensitive to abrupt surface transitions of a longitudinal nature, such as kerbs. However, at the relatively low speeds normally attainable, it was considered that the standard concrete surface drainage channels pose no significant problems for riders of pedal cycles and would be no worse than commonly used features such as speed control humps, which are routinely placed on the carriageway.

vi The predictions of vehicle disturbance produced by the HVOSM program correlated reasonably well with the transducer recordings made during the track tests of the two surface drainage channels. It was, therefore, considered that vehicle disturbance can be correlated to vehicle handling safety and that computer modelling can be used as a tool to investigate additional channel profiles at a reduced cost compared with physical testing. However, the computer model used for this research suffers from some significant problems which were not resolved and, hence, an alternative model should be sought for any future work in this area.

## 7 Recommendations

Common sense tells us that any change in the surface on which a vehicle is travelling has the potential to destabilise the vehicle and, therefore, unprotected road edge drainage features should be designed to present the least disturbance possible to errant vehicles. HD 33/96 states: 'Whilst the behaviour of an errant vehicle and its occupants is unpredictable and deemed to be hazardous, the Designer must consider carefully the safety implications of the design and minimise potential hazards as far as possible'. However, one must not lose sight of the fact that the primary safety consideration where drainage is concerned, is one of removing water from the carriageway surface, as this is where most vehicles will be most of the time. The onus is on the vehicle driver or rider to remain on the carriageway.

Given the fact that drainage is an essential element to road safety, provision must be made for the speedy collection and disposal of runoff water and, for this purpose, some form of road edge drainage feature has to be provided. This fact accepted, some recommendations can be made to enhance the safety of errant vehicles which deviate from the carriageway:

i in locations where the drainage requirements dictate a deep (greater than 150mm) or steep sided (greater than 30 degrees [approximately 1:1.73]) feature, these should be protected by a safety fence;

ii where deep or steeply sided features are not necessary, or where safety fences cannot be justified, the drainage features should be as shallow and 'gentle' as the drainage requirements will allow. The side slope gradient of unprotected channels should not be greater than 12.5 degrees (1:4.5), nor the depth of such channels be greater than 150mm;

iii where porous asphalt is used, the profile of the edge detail is dictated by the minimum size of the aggregate used in its make-up. This can result in a small vertical step of up to 25mm in depth - this is unavoidable. In such cases, raised rib road edge markings should be provided to warn drivers of errant vehicles of the potential hazard;

iv it is also recommended that triangular and trapezoidal surface drainage channels, and the use of French Drains, in either capped or uncapped form, directly adjacent to the running lane, should be accompanied by raised rib road edge markings with a 300mm hard strip.

This is the first study of its kind known to have been undertaken (both in the UK and outside of the UK). The work carried out under this project has provided much useful information with regard to the safety aspects of all manner of road edge drainage features. The findings presented here, together with previously published information, has provided sufficient material to enable the preparation of an Advice Note HA83 to help highway engineers to select the most appropriate form of drainage for any given location. However, HA83 could be developed further by undertaking a more detailed investigation of a wider range of drainage features by the use of a purpose written computer modelling program.

## 8 Acknowledgements

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# Appendix A: Peak vehicle body accelerations recorded during track testing: fixed steering tests

**Table A1 Peak recorded transducer values: Fiesta, $5^{o}$ approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | n/a | -0.01 | 0.25 | 0.07 | 11.60 | 7.12 | 3.66 |
| 40 | n/a | -0.02 | 0.28 | 0.12 | 13.82 | 6.45 | 3.14 |
| 50 | n/a | -0.01 | 0.34 | 0.22 | 18.32 | 13.50 | 4.89 |
| 60 | n/a | -0.03 | 0.36 | 0.33 | 19.36 | 11.02 | 4.43 |
| 70 | n/a | -0.08 | 0.43 | 0.38 | 26.82 | 12.89 | 7.18 |
| 80 | n/a | -0.15 | 0.51 | 0.44 | 28.58 | 14.25 | 7.55 |
| 90 | n/a | -0.24 | 0.68 | 0.65 | 44.92 | 18.81 | 12.66 |
| 100 | n/a | -0.42 | 0.77 | 0.80 | 64.70 | 15.91 | 13.07 |
| 110 | 8.82 | -0.28 | 0.61 | 0.90 | 56.96 | 13.61 | 14.08 |
| 120 | 7.93 | -0.19 | 0.62 | 0.69 | 61.44 | 11.84 | 13.71 |

**Table A2 Peak recorded transducer values: Fiesta, $10^{o}$ approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 4.21 | -0.01 | 0.32 | 0.27 | 19.84 | 29.35 | 10.33 |
| 40 | 7.29 | -0.04 | 0.45 | 0.35 | 21.93 | 34.73 | 11.10 |
| 50 | 6.96 | -0.05 | 0.39 | 0.56 | 31.38 | 30.01 | 13.55 |
| 60 | 8.42 | -0.15 | 0.40 | 0.65 | 54.81 | 23.28 | 12.54 |
| 70 | 8.99 | -0.15 | 0.40 | 0.69 | 65.69 | 23.94 | 12.57 |
| 80 | 7.37 | -0.39 | 0.49 | 0.60 | 77.62 | 22.74 | 12.34 |
| 90 | 6.23 | -0.31 | 0.39 | 0.79 | 80.04 | 21.47 | 9.94 |
| 100 | 6.88 | -0.20 | 0.33 | 0.56 | 85.88 | 19.06 | 12.37 |
| 110 | n/a | -0.42 | 0.62 | 0.79 | 91.70 | 19.80 | 12.25 |
| 120 | n/a | -0.40 | 0.81 | 0.55 | 92.34 | 17.67 | 6.73 |

**Table A3 Peak recorded transducer values: Fiesta, $15^{o}$ approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 5.75 | -0.41 | 0.39 | 0.35 | 29.47 | 35.36 | 4.87 |
| 40 | 6.31 | -0.25 | 0.44 | 0.42 | 30.45 | 30.59 | 9.01 |
| 50 | 6.88 | -0.30 | 0.45 | 0.59 | 40.60 | 28.54 | 9.83 |
| 60 | 6.64 | -0.21 | 0.51 | 0.45 | 52.47 | 25.21 | 13.16 |
| 70 | 5.82 | 0.04 | 0.46 | 0.31 | 59.53 | 19.24 | 11.18 |
| 80 | 7.20 | -1.01 | 0.79 | 1.46 | 68.37 | 18.04 | 12.66 |
| 90 | 4.86 | -0.16 | 0.50 | 0.38 | 68.58 | 23.86 | 13.53 |
| 100 | 7.45 | -0.48 | 0.67 | 0.52 | 72.56 | 19.03 | 13.33 |
| 110 | 9.88 | -0.30 | 0.69 | 0.42 | 77.72 | 19.92 | 12.42 |
| 120 | 13.11 | -0.39 | 0.72 | 0.61 | 71.45 | 17.59 | 11.89 |

**Table A4 Peak recorded transducer values: Fiesta, $20^{o}$ approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 5.75 | -0.23 | 0.53 | 0.35 | 27.18 | 34.03 | 11.53 |
| 40 | 6.07 | -0.29 | 0.64 | 0.44 | 39.30 | 30.45 | 5.46 |
| 50 | 5.75 | -0.28 | 0.67 | 0.30 | 44.48 | 24.47 | 7.25 |
| 60 | 6.64 | -0.32 | 0.64 | 0.33 | 47.06 | 23.17 | 8.57 |
| 70 | 6.88 | -0.54 | 0.72 | 0.30 | 52.13 | 17.15 | 10.23 |
| 80 | 11.74 | -0.26 | 0.36 | 0.42 | 60.54 | 23.49 | 13.49 |
| 90 | 7.53 | -0.33 | 0.35 | 0.48 | 65.32 | 19.44 | 7.97 |
| 100 | 11.49 | -1.13 | 0.30 | 0.68 | 62.81 | 22.98 | 7.79 |
| 110 | 11.74 | -0.48 | 0.66 | 0.51 | 69.94 | 21.10 | 10.06 |
| 120 | - | - | - | - | - | - | - |

**Table A5 Peak recorded transducer values: Granada, 5º approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 2.51 | -0.01 | 0.12 | 0.10 | 9.14 | 4.06 | 2.15 |
| 40 | 2.27 | -0.01 | 0.11 | 0.18 | 12.15 | 6.88 | 2.98 |
| 50 | 3.08 | -0.01 | 0.11 | 0.27 | 13.95 | 9.03 | 4.05 |
| 60 | 3.24 | -0.02 | 0.12 | 0.35 | 15.77 | 10.74 | 4.75 |
| 70 | 2.51 | -0.10 | 0.11 | 0.41 | 17.17 | 10.65 | 5.47 |
| 80 | 3.16 | -0.23 | 0.08 | 0.43 | 23.68 | 10.39 | 6.52 |
| 90 | 2.91 | -0.20 | 0.14 | 0.61 | 34.03 | 16.67 | 7.14 |
| 100 | 3.08 | -0.19 | 0.18 | 0.54 | 34.17 | 16.91 | 6.57 |
| 110 | 3.32 | -0.64 | 0.28 | 0.59 | 39.51 | 16.92 | 7.68 |
| 120 | 4.70 | -0.73 | 0.31 | 0.61 | 39.28 | 16.25 | 6.57 |

**Table A6 Peak recorded transducer values: Granada, 10º approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 1.78 | -0.06 | 0.09 | 0.16 | 12.97 | 13.80 | 2.80 |
| 40 | 2.51 | -0.05 | 0.10 | 0.27 | 14.69 | 21.69 | 3.86 |
| 50 | 3.08 | -0.08 | 0.12 | 0.38 | 22.06 | 17.80 | 5.12 |
| 60 | 2.75 | -0.09 | 0.42 | 0.63 | 40.20 | 20.55 | 6.60 |
| 70 | 2.59 | -0.19 | 0.41 | 0.42 | 38.57 | 20.19 | 6.34 |
| 80 | 2.67 | -0.26 | 0.38 | 0.38 | 36.84 | 19.16 | 7.85 |
| 90 | 5.94 | -0.28 | 0.46 | 0.35 | 37.12 | 18.54 | 7.81 |
| 100 | 3.24 | -0.53 | 0.41 | 0.28 | 36.38 | 17.29 | 7.86 |
| 110 | 2.75 | -0.60 | 0.43 | 0.32 | 39.66 | 14.72 | 8.37 |
| 120 | 4.13 | -0.65 | 0.45 | 0.31 | 40.21 | 14.54 | 7.43 |

**Table A7 Peak recorded transducer values: Granada, 15º approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 1.86 | -0.01 | 0.16 | 0.24 | 15.97 | 24.13 | 2.38 |
| 40 | 2.67 | -0.02 | 0.29 | 0.34 | 27.20 | 25.42 | 4.86 |
| 50 | 2.43 | -0.06 | 0.30 | 0.33 | 29.73 | 20.74 | 7.26 |
| 60 | 2.27 | -0.09 | 0.34 | 0.30 | 29.87 | 19.79 | 8.55 |
| 70 | 1.21 | -0.15 | 0.34 | 0.28 | 27.35 | 18.06 | 7.50 |
| 80 | 3.80 | -0.26 | 0.42 | 0.32 | 26.59 | 16.05 | 7.70 |
| 90 | 1.70 | -0.31 | 0.45 | 0.37 | 29.92 | 13.65 | 8.60 |
| 100 | 3.00 | -0.41 | 0.41 | 0.34 | 32.77 | 11.65 | 7.11 |
| 110 | 3.40 | -0.56 | 0.34 | 0.35 | 34.10 | 8.85 | 5.57 |
| 120 | 3.56 | -0.66 | 0.25 | 0.36 | 30.86 | 9.37 | 5.37 |

**Table A8 Peak recorded transducer values: Granada, 20º approach angle, fixed steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 1.86 | -0.07 | 0.23 | 0.26 | 20.28 | 26.05 | 3.30 |
| 40 | 2.67 | -0.11 | 0.24 | 0.23 | 17.16 | 21.18 | 6.35 |
| 50 | 3.08 | -0.11 | 0.20 | 0.30 | 20.87 | 20.08 | 7.03 |
| 60 | 2.27 | -0.19 | 0.25 | 0.22 | 20.80 | 16.77 | 6.80 |
| 70 | 3.72 | -0.28 | 0.36 | 0.22 | 21.08 | 14.43 | 7.87 |
| 80 | 3.64 | -0.42 | 0.40 | 0.22 | 21.70 | 10.60 | 8.95 |
| 90 | 3.16 | -0.41 | 0.34 | 0.28 | 21.43 | 8.71 | 7.13 |
| 100 | 3.56 | -0.57 | 0.30 | 0.27 | 22.96 | 10.02 | 5.13 |
| 110 | 3.08 | -0.68 | 0.24 | 0.28 | 24.89 | 8.22 | 6.45 |
| 120 | 4.21 | -0.90 | 0.21 | 0.30 | 26.80 | 8.26 | 5.83 |

**Table A9 Peak recorded transducer values: Fiesta, 5º approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 3.24 | -0.08 | 0.11 | 0.10 | 9.31 | 7.40 | 1.44 |
| 40 | 3.32 | -0.07 | 0.06 | 0.12 | 12.86 | 9.75 | 2.31 |
| 50 | 3.24 | -0.23 | 0.18 | 0.24 | 13.61 | 9.72 | 3.22 |
| 60 | 4.94 | -0.27 | 0.21 | 0.33 | 16.51 | 12.85 | 4.12 |
| 70 | 3.88 | -0.34 | 0.34 | 0.45 | 31.31 | 14.62 | 4.69 |
| 80 | 5.50 | -0.34 | 0.28 | 0.47 | 27.77 | 14.24 | 4.96 |
| 90 | 5.50 | -0.48 | 0.47 | 0.65 | 46.81 | 15.03 | 5.80 |
| 100 | 6.48 | -0.35 | 0.41 | 0.71 | 50.62 | 15.73 | 5.83 |
| 110 | 4.94 | -0.37 | 0.51 | 0.77 | 45.02 | 15.38 | 7.22 |
| 120 | 5.59 | -0.48 | 0.47 | 0.70 | 48.65 | 14.69 | 6.22 |

**Table A10 Peak recorded transducer values: Fiesta, 10º approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 1.62 | -0.03 | 0.09 | 0.20 | 14.36 | 14.79 | 3.15 |
| 40 | 3.00 | -0.06 | 0.12 | 0.36 | 17.21 | 19.64 | 3.83 |
| 50 | 3.56 | -0.07 | 0.24 | 0.52 | 30.23 | 21.31 | 5.00 |
| 60 | 3.72 | -0.14 | 0.40 | 0.59 | 47.75 | 22.40 | 6.69 |
| 70 | - | - | - | - | - | - | - |
| 80 | 6.56 | -0.35 | 0.40 | 0.57 | 52.41 | 19.13 | 6.59 |
| 90 | 3.80 | -0.18 | 0.38 | 0.52 | 46.82 | 17.71 | 7.29 |
| 100 | 6.48 | -0.29 | 0.38 | 0.38 | 49.63 | 13.94 | 6.48 |
| 110 | 8.74 | -0.33 | 0.32 | 0.42 | 49.19 | 13.67 | 7.31 |
| 120 | 9.88 | -0.55 | 0.43 | 0.51 | 43.83 | 6.59 | 6.15 |

**Table A11 Peak recorded transducer values: Fiesta, 15º approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 2.43 | -0.10 | 0.23 | 0.31 | 18.04 | 27.16 | 3.70 |
| 40 | 4.13 | -0.14 | 0.46 | 0.39 | 33.36 | 26.65 | 4.24 |
| 50 | 5.10 | -0.19 | 0.31 | 0.46 | 24.19 | 25.30 | 6.70 |
| 60 | 5.10 | -0.19 | 0.26 | 0.47 | 28.08 | 24.61 | 6.96 |
| 70 | 3.97 | -0.19 | 0.31 | 0.25 | 28.87 | 20.18 | 7.66 |
| 80 | 6.15 | -0.54 | 0.30 | 0.32 | 28.92 | 19.28 | 6.86 |
| 90 | 6.31 | -0.32 | 0.20 | 0.41 | 28.04 | 9.94 | 3.93 |
| 100 | 9.23 | -0.35 | 0.26 | 0.40 | 32.47 | 10.85 | 5.14 |
| 110 | 9.47 | -0.45 | 0.34 | 0.41 | 29.17 | 10.29 | 5.35 |
| 120 | 8.66 | -0.39 | 0.29 | 0.37 | 27.05 | 13.01 | 6.04 |

**Table A12 Peak recorded transducer values: Fiesta, 20º approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 3.97 | -0.13 | 0.31 | 0.27 | 21.82 | 25.54 | 4.05 |
| 40 | 4.13 | -0.15 | 0.24 | 0.31 | 15.98 | 24.74 | 5.06 |
| 50 | 2.35 | -0.11 | 0.22 | 0.34 | 18.07 | 21.83 | 5.90 |
| 60 | 4.05 | -0.16 | 0.23 | 0.27 | 18.50 | 17.30 | 6.49 |
| 70 | 4.05 | -0.17 | 0.23 | 0.34 | 17.63 | 13.69 | 4.74 |
| 80 | 4.37 | -0.22 | 0.22 | 0.42 | 20.25 | 8.83 | 3.16 |
| 90 | 7.37 | -0.31 | 0.26 | 0.46 | 18.24 | 14.73 | 4.18 |
| 100 | 8.42 | -0.44 | 0.25 | 0.90 | 16.96 | 13.13 | 4.01 |
| 110 | 8.26 | -0.49 | 0.21 | 0.67 | 15.12 | 9.71 | 4.52 |
| 120 | 13.68 | -0.59 | 1.09 | 1.18 | 15.61 | 31.90 | 23.51 |

**Table A13 Peak recorded transducer values: Granada, 5° approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 2.51 | -0.06 | 0.16 | 0.15 | 10.50 | 6.18 | 5.12 |
| 40 | 2.27 | -0.09 | 0.15 | 0.15 | 9.75 | 6.49 | 5.19 |
| 50 | 2.59 | -0.10 | 0.19 | 0.21 | 12.57 | 8.16 | 6.25 |
| 60 | 2.91 | -0.16 | 0.14 | 0.27 | 15.96 | 9.62 | 4.21 |
| 70 | 2.75 | -0.30 | 0.17 | 0.33 | 17.03 | 11.04 | 4.43 |
| 80 | 2.91 | -0.36 | 0.19 | 0.45 | 26.23 | 11.56 | 6.88 |
| 90 | 3.24 | -0.47 | 0.22 | 0.53 | 28.73 | 12.08 | 5.41 |
| 100 | 3.97 | -0.62 | 0.24 | 0.53 | 30.43 | 11.40 | 4.88 |
| 110 | 3.40 | -0.41 | 0.23 | 0.53 | 29.83 | 11.42 | 5.46 |
| 120 | 3.80 | -0.75 | 0.29 | 0.47 | 34.08 | 10.69 | 5.74 |

**Table A14 Peak recorded transducer values: Granada, 10° approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 2.43 | -0.04 | 0.13 | 0.19 | 12.97 | 13.63 | 4.21 |
| 40 | 1.70 | -0.08 | 0.13 | 0.34 | 15.80 | 16.36 | 5.88 |
| 50 | 3.40 | -0.16 | 0.23 | 0.40 | 22.24 | 15.86 | 6.23 |
| 60 | 2.59 | -0.07 | 0.26 | 0.37 | 22.49 | 14.79 | 7.30 |
| 70 | 2.19 | -0.13 | 0.27 | 0.34 | 24.26 | 13.43 | 7.01 |
| 80 | 2.67 | -0.29 | 0.28 | 0.34 | 24.82 | 12.23 | 6.64 |
| 90 | 2.19 | -0.41 | 0.22 | 0.34 | 25.39 | 13.27 | 4.59 |
| 100 | 3.48 | -0.50 | 0.27 | 0.31 | 26.81 | 10.74 | 4.33 |
| 110 | 3.97 | -0.63 | 0.29 | 0.29 | 28.94 | 10.28 | 5.76 |
| 120 | 3.08 | -0.63 | 0.27 | 0.35 | 32.94 | 9.19 | 3.94 |

**Table A15 Peak recorded transducer values: Granada, 15° approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 2.83 | -0.07 | 0.17 | 0.22 | 15.06 | 23.85 | 4.50 |
| 40 | 2.51 | -0.08 | 0.25 | 0.32 | 12.21 | 18.57 | 5.84 |
| 50 | 2.51 | -0.11 | 0.28 | 0.35 | 13.79 | 16.63 | 6.64 |
| 60 | 2.67 | -0.11 | 0.30 | 0.32 | 15.16 | 15.07 | 7.25 |
| 70 | 2.02 | -0.15 | 0.31 | 0.19 | 16.31 | 14.24 | 5.43 |
| 80 | 2.59 | -0.18 | 0.38 | 0.22 | 17.43 | 12.68 | 6.34 |
| 90 | 2.10 | -0.47 | 0.27 | 0.24 | 20.52 | 10.95 | 4.25 |
| 100 | 3.08 | -0.56 | 0.25 | 0.27 | 21.11 | 8.04 | 4.90 |
| 110 | 3.40 | -0.64 | 0.23 | 0.33 | 21.76 | 5.67 | 5.59 |
| 120 | 4.61 | -0.64 | 0.19 | 0.37 | 22.69 | 6.36 | 4.46 |

**Table A16 Peak recorded transducer values: Granada, 20° approach angle, fixed steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 1.70 | -0.04 | 0.12 | 0.25 | 12.56 | 17.41 | 2.43 |
| 40 | 1.54 | -0.05 | 0.13 | 0.31 | 14.64 | 15.86 | 2.09 |
| 50 | 3.16 | -0.14 | 0.19 | 0.26 | 16.75 | 12.97 | 3.31 |
| 60 | 2.27 | -0.18 | 0.28 | 0.25 | 16.94 | 11.03 | 4.25 |
| 70 | 2.67 | -0.11 | 0.28 | 0.23 | 18.02 | 10.51 | 5.04 |
| 80 | 1.86 | -0.14 | 0.24 | 0.31 | 17.49 | 8.24 | 4.27 |
| 90 | 2.59 | -0.48 | 0.25 | 0.33 | 18.07 | 7.49 | 2.98 |
| 100 | 3.97 | -0.51 | 0.15 | 0.35 | 16.83 | 7.34 | 2.41 |
| 110 | 5.10 | -0.58 | 0.10 | 0.46 | 17.84 | 4.64 | 1.70 |
| 120 | 5.67 | -0.68 | 0.12 | 0.54 | 17.43 | 6.57 | 1.28 |

# Appendix B: Peak vehicle body accelerations recorded during track testing: corrective steering tests

**Table B1 Peak recorded transducer values: Fiesta, 5° approach angle, corrective steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | n/a | 0.03 | 0.48 | 0.16 | 13.85 | 2.76 | 21.84 |
| 40 | n/a | -0.01 | 0.77 | 0.22 | 17.48 | 2.93 | 27.60 |
| 50 | n/a | -0.13 | 0.94 | 0.27 | 21.62 | 3.45 | 32.24 |
| 60 | n/a | -0.44 | 1.17 | 0.31 | 24.21 | 7.72 | 34.49 |
| 70 | n/a | -0.33 | 1.19 | 0.37 | 19.43 | 8.81 | 38.94 |
| 80 | n/a | -0.23 | 1.23 | 0.34 | 41.31 | 5.57 | 69.08 |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B2 Peak recorded transducer values: Fiesta, 10° approach angle, corrective steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 6.54 | -0.03 | 0.58 | 0.11 | 1.77 | 0.47 | 21.90 |
| 40 | 11.42 | -0.13 | 1.01 | 0.36 | 23.45 | 8.33 | 31.13 |
| 50 | 11.92 | -0.10 | 1.22 | 0.41 | 28.67 | 7.99 | 37.30 |
| 60 | 14.99 | -0.21 | 1.11 | 0.43 | 43.04 | 18.07 | 35.76 |
| 70 | 20.63 | -0.28 | 1.31 | 0.48 | 48.60 | 23.00 | 37.80 |
| 80 | 19.65 | -1.14 | 1.22 | 0.72 | 51.15 | 30.03 | 39.21 |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B3 Peak recorded transducer values: Fiesta, 15° approach angle, corrective steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 11.47 | -0.11 | 0.80 | 0.25 | 28.67 | 10.16 | 31.96 |
| 40 | n/a | -0.34 | 0.54 | 0.07 | n/a | n/a | n/a |
| 50 | 10.69 | -0.17 | 1.22 | 0.40 | 27.37 | 5.20 | 44.82 |
| 60 | 6.33 | -0.21 | 1.15 | 0.40 | 24.43 | 3.18 | 45.13 |
| 70 | 8.65 | -0.41 | 1.27 | 0.45 | 38.01 | 17.66 | 42.00 |
| 80 | 14.38 | -0.39 | 1.69 | 0.45 | 44.75 | 26.08 | 40.63 |
| 90 | 9.74 | -0.44 | 1.62 | 0.54 | 38.64 | 20.99 | 39.00 |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B4 Peak recorded transducer values: Fiesta, 20° approach angle, corrective steering across trapezoidal channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 7.24 | -0.12 | 0.75 | 0.14 | 14.92 | 7.26 | 39.42 |
| 40 | 9.69 | -0.19 | 1.13 | 0.26 | 24.06 | 7.52 | 46.53 |
| 50 | 10.22 | -0.23 | 1.17 | 0.41 | 20.49 | 8.74 | 44.96 |
| 60 | 10.55 | -0.28 | 1.30 | 0.48 | 41.11 | 22.33 | 44.04 |
| 70 | 17.77 | -0.36 | 1.63 | 0.48 | 43.65 | 32.38 | 44.96 |
| 80 | n/a | -0.39 | 1.21 | 0.51 | 26.72 | 11.67 | 42.18 |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B5 Peak recorded transducer values: Fiesta, 5º approach angle, corrective steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 5.73 | -0.09 | 0.29 | 0.09 | 8.53 | 4.73 | 8.71 |
| 40 | 6.19 | -0.10 | 0.37 | 0.21 | 13.93 | 5.14 | 10.80 |
| 50 | 6.70 | -0.11 | 0.48 | 0.22 | 13.70 | 4.23 | 13.04 |
| 60 | 6.79 | -0.15 | 0.57 | 0.26 | 16.43 | 7.94 | 13.21 |
| 70 | 8.85 | -0.18 | 0.78 | 0.35 | 21.60 | 10.50 | 16.74 |
| 80 | 8.10 | -0.49 | 0.79 | 0.24 | 21.52 | 7.11 | 19.06 |
| 90 | 8.28 | -0.56 | 1.00 | 0.41 | 25.36 | 12.54 | 19.64 |
| 100 | 9.50 | -0.24 | 0.86 | 0.36 | 28.23 | 12.99 | 15.83 |
| 110 | 6.44 | -0.20 | 0.87 | 0.37 | 21.60 | 6.06 | 15.53 |
| 120 | 10.31 | -0.32 | 1.07 | 0.56 | 35.25 | 19.63 | 16.80 |

**Table B6 Peak recorded transducer values: Fiesta, 10º approach angle, corrective steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 5.27 | -0.01 | 0.38 | 0.11 | 12.25 | 3.70 | 14.04 |
| 40 | 8.16 | -0.03 | 0.56 | 0.18 | 16.63 | 7.63 | 17.51 |
| 50 | 7.95 | -0.10 | 0.64 | 0.22 | 19.05 | 7.20 | 18.93 |
| 60 | 7.85 | -0.13 | 0.74 | 0.23 | 19.72 | 5.48 | 17.64 |
| 70 | 10.04 | -0.28 | 0.94 | 0.38 | 29.28 | 12.43 | 20.26 |
| 80 | 12.70 | -0.27 | 1.17 | 0.45 | 35.94 | 17.57 | 23.55 |
| 90 | 7.59 | -0.18 | 0.90 | 0.34 | 20.99 | 8.80 | 20.78 |
| 100 | 11.10 | -0.24 | 1.17 | 0.44 | 34.00 | 16.77 | 22.79 |
| 110 | 9.76 | -0.25 | 1.10 | 0.54 | 27.92 | 9.34 | 18.55 |
| 120 | 9.25 | -0.30 | 1.18 | 0.54 | 27.39 | 11.10 | 19.35 |

**Table B7 Peak recorded transducer values: Fiesta, 15º approach angle, corrective steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 4.79 | -0.04 | 0.38 | 0.11 | 10.83 | 4.78 | 17.48 |
| 40 | 7.57 | -0.05 | 0.67 | 0.23 | 16.28 | 13.11 | 20.18 |
| 50 | 6.88 | -0.10 | 0.75 | 0.26 | 17.63 | 7.46 | 23.85 |
| 60 | 7.59 | -0.07 | 0.45 | 0.14 | 20.25 | 6.00 | 25.60 |
| 70 | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| 80 | 8.80 | -0.25 | 1.09 | 0.39 | 19.68 | 9.58 | 22.77 |
| 90 | 7.83 | -0.19 | 1.13 | 0.44 | 23.35 | 12.41 | 28.21 |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B8 Peak recorded transducer values: Fiesta, 20º approach angle, corrective steering across triangular channel**

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 5.87 | 0.00 | 0.48 | 0.17 | 13.86 | 6.39 | 21.46 |
| 40 | 6.43 | -0.01 | 0.58 | 0.17 | 12.75 | 5.56 | 20.32 |
| 50 | 8.18 | -0.05 | 0.92 | 0.26 | 16.39 | 6.55 | 32.24 |
| 60 | 11.11 | -0.01 | 1.07 | 0.38 | 21.04 | 9.36 | 32.41 |
| 70 | 13.68 | -0.17 | 1.20 | 0.34 | 25.96 | 10.37 | 26.62 |
| 80 | 14.30 | -0.18 | 1.37 | 0.53 | 40.16 | 14.54 | 26.15 |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

### Table B9 Peak recorded transducer values: Fiesta, 5º approach angle, corrective steering across capped French Drain

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 2.50 | -0.07 | 0.08 | 0.13 | 3.14 | 2.29 | 1.51 |
| 40 | 3.46 | -0.11 | 0.16 | 0.13 | 3.75 | 3.06 | 5.73 |
| 50 | 2.08 | -0.10 | 0.11 | 0.19 | 3.89 | 3.16 | 4.00 |
| 60 | 2.93 | -0.10 | 0.12 | 0.18 | 5.84 | 3.43 | 3.61 |
| 70 | 2.81 | -0.13 | 0.13 | 0.18 | 4.57 | 3.89 | 4.57 |
| 80 | 3.32 | -0.16 | 0.20 | 0.24 | 6.07 | 3.83 | 4.49 |
| 90 | 2.92 | -0.18 | 0.14 | 0.21 | 5.68 | 3.48 | 4.75 |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

### Table B10 Peak recorded transducer values: Fiesta, 10º approach angle, corrective steering across capped French Drain

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 2.16 | -0.16 | 0.07 | 0.14 | 4.62 | 3.85 | 4.68 |
| 40 | 2.78 | -0.19 | 0.12 | 0.17 | 5.10 | 4.46 | 4.80 |
| 50 | 3.94 | -0.19 | 0.16 | 0.18 | 5.12 | 4.27 | 5.14 |
| 60 | 3.26 | -0.23 | 0.23 | 0.24 | 4.43 | 4.08 | 4.61 |
| 70 | 4.87 | -0.17 | 0.34 | 0.20 | 4.74 | 3.79 | 5.73 |
| 80 | - | - | - | - | - | - | - |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

### Table B11 Peak recorded transducer values: Fiesta, 15º approach angle, corrective steering across capped French Drain

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 3.17 | -0.14 | 0.14 | 0.12 | 7.09 | 4.15 | 4.92 |
| 40 | 4.48 | -0.16 | 0.23 | 0.14 | 5.15 | 4.33 | 6.16 |
| 50 | 5.44 | -0.16 | 0.35 | 0.16 | 5.39 | 4.27 | 7.90 |
| 60 | 8.22 | -0.23 | 0.49 | 0.20 | 5.52 | 5.08 | 12.71 |
| 70 | - | - | - | - | - | - | - |
| 80 | - | - | - | - | - | - | - |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

### Table B12 Peak recorded transducer values: Fiesta, 20º approach angle, corrective steering across capped French Drain

| *Speed km/h* | *Steer torque [Nm]* | *Acc. X filtered [g]* | *Acc. Y filtered [g]* | *Acc. Z filtered [g]* | *Roll filtered [deg/s]* | *Pitch filtered [deg/s]* | *Yaw filtered [deg/s]* |
|---|---|---|---|---|---|---|---|
| 30 | 6.18 | -0.15 | 0.25 | 0.14 | 5.76 | 3.80 | 10.84 |
| 40 | 6.39 | -0.16 | 0.29 | 0.14 | 6.19 | 3.97 | 10.75 |
| 50 | 7.67 | -0.20 | 0.47 | 0.17 | 6.15 | 3.39 | 13.16 |
| 60 | - | - | - | - | - | - | - |
| 70 | - | - | - | - | - | - | - |
| 80 | - | - | - | - | - | - | - |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B13 Peak recorded transducer values: Fiesta, 5º approach angle, corrective steering across standard French Drain**

| Speed km/h | Steer torque [Nm] | Acc. X filtered [g] | Acc. Y filtered [g] | Acc. Z filtered [g] | Roll filtered [deg/s] | Pitch filtered [deg/s] | Yaw filtered [deg/s] |
|---|---|---|---|---|---|---|---|
| 30 | 5.02 | -0.15 | 0.22 | 0.16 | 12.63 | 7.18 | 12.79 |
| 40 | 4.40 | -0.12 | 0.28 | 0.16 | 9.10 | 5.08 | 11.73 |
| 50 | 5.12 | -0.13 | 0.34 | 0.18 | 8.83 | 4.99 | 11.44 |
| 60 | 6.71 | -0.13 | 0.50 | 0.29 | 8.72 | 7.46 | 14.27 |
| 70 | 7.81 | -0.24 | 0.72 | 0.41 | 13.93 | 11.63 | 20.56 |
| 80 | 7.78 | -0.16 | 0.54 | 0.21 | 11.47 | 6.04 | 18.17 |
| 90 | 8.39 | -0.33 | 0.66 | 0.75 | 12.01 | 6.34 | 18.75 |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B14 Peak recorded transducer values: Fiesta, 10º approach angle, corrective steering across standard French Drain**

| Speed km/h | Steer torque [Nm] | Acc. X filtered [g] | Acc. Y filtered [g] | Acc. Z filtered [g] | Roll filtered [deg/s] | Pitch filtered [deg/s] | Yaw filtered [deg/s] |
|---|---|---|---|---|---|---|---|
| 30 | 2.49 | -0.14 | 0.07 | 0.12 | 4.69 | 4.57 | 4.53 |
| 40 | 2.57 | -0.14 | 0.08 | 0.13 | 5.90 | 4.38 | 5.38 |
| 50 | 2.99 | -0.17 | 0.20 | 0.21 | 6.90 | 4.78 | 6.05 |
| 60 | 4.33 | -0.20 | 0.30 | 0.19 | 7.63 | 5.52 | 5.60 |
| 70 | 5.22 | -0.10 | 0.30 | 0.18 | 6.84 | 5.38 | 7.17 |
| 80 | 5.26 | -0.20 | 0.50 | 0.20 | 6.31 | 5.13 | 8.90 |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B15 Peak recorded transducer values: Fiesta, 15º approach angle, corrective steering across standard French Drain**

| Speed km/h | Steer torque [Nm] | Acc. X filtered [g] | Acc. Y filtered [g] | Acc. Z filtered [g] | Roll filtered [deg/s] | Pitch filtered [deg/s] | Yaw filtered [deg/s] |
|---|---|---|---|---|---|---|---|
| 30 | 3.93 | -0.20 | 0.16 | 0.12 | 6.69 | 4.94 | 5.34 |
| 40 | 4.85 | -0.15 | 0.22 | 0.12 | 7.02 | 4.97 | 5.87 |
| 50 | 5.64 | -0.16 | 0.35 | 0.13 | 5.70 | 4.41 | 8.39 |
| 60 | 5.63 | -0.19 | 0.37 | 0.17 | 5.28 | 4.37 | 5.85 |
| 70 | 7.56 | -0.18 | 0.51 | 0.17 | 7.04 | 3.99 | 10.22 |
| 80 | - | - | - | - | - | - | - |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

**Table B16 Peak recorded rransducer values: Fiesta, 20º approach angle, corrective steering across standard French Drain**

| Speed km/h | Steer torque [Nm] | Acc. X filtered [g] | Acc. Y filtered [g] | Acc. Z filtered [g] | Roll filtered [deg/s] | Pitch filtered [deg/s] | Yaw filtered [deg/s] |
|---|---|---|---|---|---|---|---|
| 30 | 4.80 | -0.15 | 0.17 | 0.16 | 4.48 | 4.37 | 6.31 |
| 40 | 5.07 | -0.15 | 0.23 | 0.15 | 5.82 | 4.18 | 7.46 |
| 50 | 7.42 | -0.19 | 0.44 | 0.18 | 5.09 | 4.56 | 12.05 |
| 60 | 8.06 | -0.17 | 0.54 | 0.18 | 5.76 | 4.38 | 13.46 |
| 70 | - | - | - | - | - | - | - |
| 80 | - | - | - | - | - | - | - |
| 90 | - | - | - | - | - | - | - |
| 100 | - | - | - | - | - | - | - |
| 110 | - | - | - | - | - | - | - |
| 120 | - | - | - | - | - | - | - |

# Appendix C: Peak vehicle body accelerations predicted by HVOSM

**Table C1** Peak accelerations and angular velocities predicted by simulation: Fiesta, fixed steering across trapezoidal channel

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.02 | 0.14 | 0.17 | 25.08 | 5.24 | 2.08 |
| | 80 | -0.03 | 0.23 | 0.51 | 50.05 | 6.33 | 2.48 |
| | 120 | -0.03 | 0.21 | 0.77 | 74.64 | 7.95 | 2.21 |
| 10 | 40 | -0.03 | 0.22 | 0.41 | 38.60 | 12.09 | 2.61 |
| | 80 | -0.07 | 0.40 | 0.91 | 73.20 | 16.89 | 2.95 |
| | 120 | -0.07 | 0.44 | 1.04 | 105.89 | 17.03 | 3.99 |
| 15 | 40 | -0.06 | 0.30 | 0.55 | 48.45 | 21.41 | 3.83 |
| | 80 | -0.10 | 0.42 | 0.68 | 86.62 | 23.30 | 4.09 |
| | 120 | -0.11 | 0.37 | 0.63 | 95.60 | 22.26 | 3.50 |
| 20 | 40 | -0.09 | 0.31 | 0.49 | 47.58 | 25.14 | 3.06 |
| | 80 | -0.12 | 0.44 | 0.56 | 75.40 | 24.14 | 3.39 |
| | 120 | -0.14 | 0.49 | 0.58 | 73.97 | 21.47 | 2.75 |

**Table C2** Peak accelerations and angular velocities predicted by simulation: Granada, fixed steering across trapezoidal channel

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.01 | 0.09 | 0.12 | 16.22 | 3.48 | 1.55 |
| | 80 | -0.01 | 0.16 | 0.37 | 30.22 | 4.81 | 1.56 |
| | 120 | -0.01 | 0.18 | 0.54 | 46.07 | 6.18 | 1.20 |
| 10 | 40 | -0.02 | 0.16 | 0.22 | 25.39 | 9.08 | 1.71 |
| | 80 | -0.03 | 0.24 | 0.36 | 52.19 | 11.90 | 1.62 |
| | 120 | -0.04 | 0.23 | 0.43 | 70.52 | 12.69 | 2.03 |
| 15 | 40 | -0.03 | 0.18 | 0.21 | 27.83 | 15.45 | 2.03 |
| | 80 | -0.05 | 0.25 | 0.26 | 52.59 | 15.87 | 1.99 |
| | 120 | -0.08 | 0.21 | 0.50 | 62.75 | 15.57 | 2.09 |
| 20 | 40 | -0.05 | 0.21 | 0.19 | 24.70 | 16.02 | 2.41 |
| | 80 | -0.08 | 0.28 | 0.25 | 42.59 | 15.18 | 1.87 |
| | 120 | -0.11 | 0.29 | 0.45 | 45.12 | 14.01 | 1.63 |

**Table C3** Peak accelerations and angular velocities predicted by simulation: Fiesta, fixed steering across triangular channel

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.02 | 0.11 | 0.19 | 18.31 | 9.07 | 2.87 |
| | 80 | -0.02 | 0.18 | 0.50 | 34.26 | 10.96 | 2.94 |
| | 120 | -0.02 | 0.19 | 0.78 | 53.06 | 11.81 | 2.43 |
| 10 | 40 | -0.03 | 0.18 | 0.32 | 31.21 | 15.26 | 3.81 |
| | 80 | -0.06 | 0.29 | 0.91 | 61.92 | 20.57 | 3.22 |
| | 120 | -0.08 | 0.32 | 0.96 | 86.64 | 20.40 | 3.53 |
| 15 | 40 | -0.06 | 0.31 | 0.53 | 45.42 | 22.51 | 4.62 |
| | 80 | -0.09 | 0.37 | 0.68 | 72.28 | 26.06 | 3.42 |
| | 120 | -0.09 | 0.29 | 0.62 | 75.01 | 21.53 | 3.11 |
| 20 | 40 | -0.07 | 0.27 | 0.44 | 41.03 | 24.94 | 3.98 |
| | 80 | -0.11 | 0.35 | 0.44 | 57.73 | 21.84 | 2.76 |
| | 120 | -0.13 | 0.38 | 0.50 | 59.68 | 18.05 | 2.43 |

**Table C4** Peak accelerations and angular velocities predicted by simulation: Granada, fixed steering across triangular channel

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.01 | 0.08 | 0.13 | 11.13 | 5.97 | 1.76 |
| | 80 | -0.01 | 0.11 | 0.38 | 21.67 | 7.03 | 1.59 |
| | 120 | -0.01 | 0.14 | 0.51 | 32.04 | 8.19 | 1.51 |
| 10 | 40 | -0.02 | 0.11 | 0.24 | 19.62 | 10.70 | 2.38 |
| | 80 | -0.03 | 0.18 | 0.53 | 39.59 | 13.04 | 1.57 |
| | 120 | -0.04 | 0.17 | 0.47 | 55.63 | 13.02 | 1.62 |
| 15 | 40 | -0.03 | 0.17 | 0.18 | 28.02 | 16.06 | 2.68 |
| | 80 | -0.05 | 0.20 | 0.24 | 46.26 | 16.31 | 1.68 |
| | 120 | -0.06 | 0.18 | 0.39 | 49.12 | 15.25 | 1.79 |
| 20 | 40 | -0.04 | 0.19 | 0.29 | 41.03 | 14.83 | 2.69 |
| | 80 | -0.07 | 0.21 | 0.43 | 57.73 | 13.83 | 1.48 |
| | 120 | -0.08 | 0.22 | 0.50 | 35.20 | 11.20 | 1.36 |

# Appendix D: Additional drainage profiles: peak vehicle body accelerations predicted by HVOSM

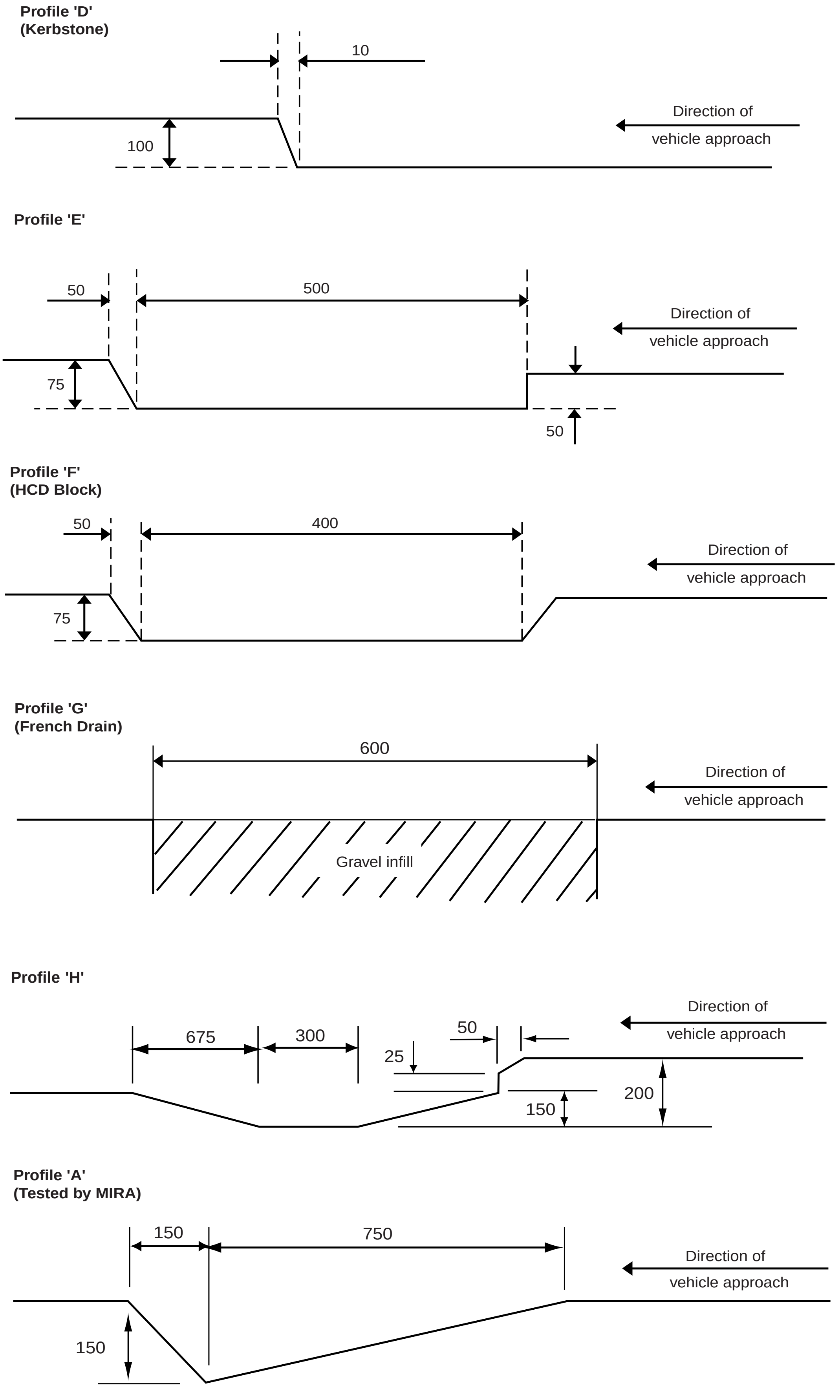

**Figure D1** Geometry of additional simulated profiles

**Table D1 Peak accelerations and angular velocities predicted by simulation: Fiesta, fixed steering across channel profile 'A'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.08 | 0.68 | 0.20 | 25.21 | 17.81 | 4.53 |
| | 80 | -0.11 | 1.23 | 0.63 | 43.79 | 25.86 | 10.87 |
| | 120 | -0.15 | 1.72 | 0.75 | 51.09 | 29.57 | 9.89 |
| 20 | 40 | -0.63 | 1.69 | 0.56 | 57.21 | 24.46 | 26.65 |
| | 80 | -1.25 | 3.57 | 0.61 | 35.67 | 15.25 | 17.34 |
| | 120 | -0.78 | 2.14 | 0.59 | 28.56 | 10.41 | 3.49 |

**Table D2 Peak accelerations and angular velocities predicted by simulation: Granada, fixed steering across channel profile 'A'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.05 | 0.56 | 0.24 | 19.38 | 12.22 | 7.19 |
| | 80 | -0.07 | 0.95 | 0.29 | 28.97 | 14.70 | 8.46 |
| | 120 | -0.11 | 1.98 | 0.35 | 30.74 | 16.04 | 6.40 |
| 20 | 40 | -0.62 | 2.38 | 0.43 | 37.85 | 14.31 | 16.27 |
| | 80 | -1.50 | 4.97 | 0.76 | 37.54 | 11.00 | 11.49 |
| | 120 | -0.24 | 0.58 | 0.73 | 15.98 | 7.25 | 5.15 |

**Table D3 Peak accelerations and angular velocities predicted by simulation: Fiesta, fixed steering across channel profile 'E'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.01 | 0.35 | 0.17 | 13.92 | 8.36 | 1.85 |
| | 80 | -0.02 | 0.28 | 0.23 | 13.75 | 8.22 | 1.74 |
| | 120 | -0.01 | 0.24 | 0.21 | 15.09 | 9.05 | 1.62 |
| 20 | 40 | -0.02 | 0.43 | 0.22 | 13.13 | 6.21 | 1.79 |
| | 80 | -0.02 | 0.30 | 0.35 | 16.18 | 7.98 | 1.65 |
| | 120 | -0.03 | 0.19 | 0.38 | 15.64 | 6.31 | 0.84 |

**Table D4 Peak accelerations and angular velocities predicted by simulation: Granada, fixed steering across channel profile 'E'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.01 | 0.20 | 0.11 | 9.50 | 5.11 | 1.12 |
| | 80 | -0.01 | 0.15 | 0.12 | 9.72 | 5.31 | 1.26 |
| | 120 | -0.01 | 0.12 | 0.13 | 10.31 | 5.67 | 1.23 |
| 20 | 40 | -0.01 | 0.24 | 0.13 | 8.81 | 3.94 | 1.47 |
| | 80 | -0.01 | 0.17 | 0.24 | 11.73 | 4.12 | 1.03 |
| | 120 | -0.02 | 0.13 | 0.35 | 12.37 | 3.84 | 0.65 |

**Table D5 Peak accelerations and angular velocities predicted by simulation: Fiesta, fixed steering across channel profile 'F'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.03 | 0.21 | 0.31 | 12.63 | 12.93 | 1.08 |
| | 80 | -0.03 | 0.22 | 0.38 | 15.85 | 8.67 | 1.62 |
| | 120 | -0.03 | 0.20 | 0.66 | 26.61 | 7.07 | 2.99 |
| 20 | 40 | -0.05 | 0.20 | 0.38 | 13.23 | 17.90 | 3.08 |
| | 80 | -0.08 | 0.14 | 0.63 | 19.71 | 9.84 | 3.70 |
| | 120 | -0.09 | 0.20 | 0.76 | 28.85 | 10.60 | 6.06 |

**Table D6 Peak accelerations and angular velocities predicted by simulation: Granada, fixed steering across channel profile 'F'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.02 | 0.17 | 0.31 | 9.10 | 6.72 | 0.76 |
| | 80 | -0.02 | 0.14 | 0.38 | 14.05 | 4.05 | 0.99 |
| | 120 | -0.02 | 0.11 | 0.37 | 18.88 | 3.98 | 1.24 |
| 20 | 40 | -0.04 | 0.15 | 0.34 | 9.73 | 8.00 | 1.59 |
| | 80 | -0.05 | 0.11 | 0.39 | 13.77 | 5.70 | 1.53 |
| | 120 | -0.06 | 0.12 | 0.43 | 17.16 | 5.37 | 2.37 |

**Table D7 Peak accelerations and angular velocities predicted by simulation: Fiesta, fixed steering across channel profile 'H'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.28 | 1.07 | 1.22 | 147.10 | 66.91 | 10.03 |
| | 80 | -0.51 | 1.97 | 1.21 | 153.3 | 70.77 | 32.96 |
| | 120 | -0.29 | 2.72 | 1.09 | 170.29 | 68.48 | 19.57 |
| 20 | 40 | -0.35 | 1.78 | 0.70 | 134.96 | 51.99 | 3.17 |
| | 80 | -0.06 | 0.61 | 0.47 | 26.35 | 12.08 | 1.99 |
| | 120 | -0.04 | 0.28 | 0.54 | 22.55 | 8.62 | 1.06 |

**Table D8 Peak accelerations and angular velocities predicted by simulation: Granada, fixed steering across channel profile 'H'**

| *Approach angle [deg]* | *Speed km/h* | *Acc. X [g]* | *Acc. Y [g]* | *Acc. Z [g]* | *Roll [deg/s]* | *Pitch [deg/s]* | *Yaw [deg/s]* |
|---|---|---|---|---|---|---|---|
| 5 | 40 | -0.08 | 1.19 | 0.78 | 119.77 | 47.41 | 12.01 |
| | 80 | -0.06 | 1.40 | 0.93 | 110.92 | 46.86 | 18.03 |
| | 120 | -0.07 | 1.94 | 1.07 | 127.66 | 49.95 | 11.21 |
| 20 | 40 | -0.15 | 1.36 | 0.96 | 102.54 | 34.21 | 5.41 |
| | 80 | -0.06 | 1.54 | 0.76 | 35.11 | 12.13 | 1.65 |
| | 120 | -0.03 | 0.33 | 0.61 | 20.06 | 5.96 | 0.76 |

# Appendix E: STATS19 accidents statistics — 1996

## Table E1 STATS19 accident data 1996 — vehicles not leaving carriageway

***Pedal cycles***

| *Hit object off carriageway* | *Hit object in carriageway*<br>*Did not* | *Kerb* | *Other object* |
|---|---|---|---|
| Did not | 22,801 | 153 | 1,179 |
| Entered ditch | 1 | 0 | 0 |
| Other object | 64 | 1 | 6 |

***Powered two-wheelers***

| *Hit object off carriageway* | *Hit object in carriageway*<br>*Did not* | *Kerb* | *Other object* |
|---|---|---|---|
| Did not | 19,848 | 234 | 655 |
| Entered ditch | 2 | 0 | 1 |
| Other object | 85 | 9 | 5 |

***All other vehicles***

| *Hit object off carriageway* | *Hit object in carriageway*<br>*Did not* | *Kerb* | *Other object* |
|---|---|---|---|
| Did not | 324,422 | 1,085 | 7,379 |
| Entered ditch | 31 | 4 | 3 |
| Other object | 1,878 | 63 | 193 |

## Table E2 STATS19 accident data 1996 — vehicles leaving carriageway

***Pedal cycles***

| *Hit object off carriageway* | *Hit object in carriageway*<br>*Did not* | *Kerb* | *Other object* |
|---|---|---|---|
| Did not | 557 | 72 | 20 |
| Entered ditch | 22 | 0 | 0 |
| Other object | 120 | 34 | 4 |

***Powered two-wheelers***

| *Hit object off carriageway* | *Hit object in carriageway*<br>*Did not* | *Kerb* | *Other object* |
|---|---|---|---|
| Did not | 1,131 | 196 | 58 |
| Entered ditch | 166 | 19 | 5 |
| Other object | 956 | 268 | 50 |

***All other vehicles***

| *Hit object off carriageway* | *Hit object in carriageway*<br>*Did not* | *Kerb* | *Other object* |
|---|---|---|---|
| Did not | 11,460 | 1,154 | 669 |
| Entered ditch | 2,665 | 336 | 58 |
| Other object | 21,105 | 4,579 | 1,159 |

## Abstract

Three roadside drainage features have been assessed for their effects on the handling and safety of two saloon cars. The features tested were a triangular and trapezoidal surface drainage channel, and a French Drain in an ‘open’ and ‘capped’ form. The vehicles, suitably instrumented, were driven into and across the features at a range of speeds and approach angles and a subjective assessment of the vehicle handling made by the driver. Computer simulations of the track test configurations were also performed. It was the intention to dispense with further expensive physical track tests if the simulation results correlated sufficiently well with the track test data. Limited testing was also conducted with a pedal cycle and a motorcycle (uninstrumented) on the triangular channel and the two forms of French Drain.

The track test results revealed a clear difference in the effects on the two vehicles, but the difference in the effects of the two surface drainage channels was less obvious. However, it was considered that the concrete surface drainage channels represented an acceptable level of risk to vehicle safety and were adopted as the ‘benchmark’ against which alternative features were assessed. The computer simulations agreed generally with the track test results; the observed differences were thought to be a result of simplifications in the vehicle dynamics algorithms. Further refinement of the computer model would have improved the correlation between the track test results and the model predictions, but this was outside of the scope of the project.

It was concluded that the surface drainage channels present a distinctly different problem to that posed by the French Drain, in that the surface drainage channels induce a much larger degree of physical vehicle disturbance. Single track vehicles, which have an inherent primary instability, are affected to a greater degree than twin track vehicles and are particularly sensitive to abrupt surface transitions of a longitudinal nature. However, it was considered that, at the relatively low speeds a pedal cycle can normally attain, the concrete surface water channels posed no significant risk to cyclists. Recommendations have been proposed to minimise the risk to errant vehicles posed by road edge drainage features, including the provision of safety fencing, hard strips and raised rib road edge markings under certain circumstances.

## Related publications

| | |
|---|---|
| TRL230 | *Assessment of vehicle handling safety when driving into roadside water drainage channels* by B J Robinson. 1996 (price £50, code P) |
| TRL200 | *Re-use of scrap tyres in highway drainage* by J Carswell and E J Jenkins. 1996 (price £25, code E) |
| RR368 | *Observations of slope drainage at Colchester, Essex* by D M Farrar. 1992 (price £25, code E) |
| RR302 | *Observations of slope drainage at Romford, Essex* by D M Farrar. 1991 (price £20, code B) |
| RR37 | *Motorway run-off - the effect of drainage systems on water quality* by D M Colwill, C J Peters and R Perry. 1985 (price £20, code AA) |

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