Vehicle Impacts in V-Ditches

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Abstract. V-ditches represent a significant portion of the roadside environment in Sweden and Finland. The consequences of vehicles leaving the road and entering V shaped ditches are not well documented in simulation or experimental studies. A series of tests were conducted to document the behaviour of passenger cars entering V-ditches. Test conditions ranged from 5 to 20 degrees and 80 to 110 km/h. The tests resulted in many vehicles passing over the backslope and rollovers were observed in 4 of the tests. Preliminary simulations of the test conditions were not able to fully reconstruct the vehicle motions. Castor steering of the vehicle and ground contact with the vehicle chassis were the two most important features observed in the tests but not incorporated into the simulation models.

INTRODUCTION

The use of guard-rails as a roadside protection device supposes that the consequences of a run-off-road collision would be worse if the barrier was not present to redirect the vehicle. A weakness in this argument is that little information exists quantifying the risks of vehicles leaving the road and entering hazardous environments. The first step in selecting appropriate safety countermeasures is to quantify the actual risks of the roadside environment so that it can be objectively compared to the different design options.

A significant challenge for the road safety engineers in the Nordic countries is the nature of the terrain. The population density is low, compared to most European countries, and a substantial network of smaller roads (width less than 13 m) exists. These roads represent the bulk of the road network in Sweden and Finland as well as the location for the majority of single vehicle accidents reported annually.

A typical cross-section of rural roads in Sweden and Finland is illustrated in FIGURE 1. This particular profile is problematic in that the inclination of the fore-slope exceeds 1:4 which is the maximum recommended slope in many roadside design guides [1],[2]. The assumption is that a driver cannot safely traverse the slope with control of the vehicle with slopes inclined greater than 1:4.

The safety countermeasures selected for a road segment must be selected according to the risks of the surrounding terrain. The two principal design approaches are the adjustment of sideslopes and safety zone and the installation of longitudinal barriers. Within these two design categories, several design options exist depending on the apparent safety risks and associated design costs. The selection process requires some method to qualitatively assess the risks, as costs are (comparatively) easier to calculate.

The objective of a joint Swedish-Finnish test program was to investigate the dynamics of vehicles entering a V-Ditch. Specific topics to be researched were the influence of impact angle and speed on crash outcome, effects of driver steering on vehicle motion in the ditch, as well as benchmarking the impact conditions used in EN 1317-2 testing of road restraints. The test data was also collected for use as calibration data for computer simulation programs.

METHODS

A series of full-scale crash tests was developed to assess the dynamics of a vehicle entering a V-ditch for various impact conditions. The test matrix selected to represent impact conditions representative of likely real world conditions as well as the worst case conditions represented in the EN 1317 test standard for road restraint barriers. This latter case was used to develop a benchmark for the crash tests used for testing road restraint systems.

The tests were run at the University of Helsinki's crash test facility in Pori, Finland. A ditch was excavated at the site with a 1:3 fore-slope and a 1:2 back-slope. The soil at the test site was a stiff clay. For all but 2 tests, the ditch was 5m wide and the back-slope extended 1 m above level terrain. FIGURE 2 shows the test site.

The last 2 tests had a modified ditch bottoms. In one case a U-shaped ditch bottom (FIGURE 4) was investigated. In the other test a low (approx 40cm high) concrete barrier placed on the backslope about 50 cm from the V-ditch bottom (FIGURE 5).

The test conditions investigated are presented in Table 1. The test vehicles represent the passenger car sizes listed in EN 1317. Not all the tests were run with instrumented vehicles. This practice was chosen to maximise the number of tests. The dynamics of the vehicle in the ditch was the focus of the tests and this information could be adequately observed from the video. The trajectory of each vehicle as well as the occurrence of a rollover was recorded for each vehicle for later comparison to computer simulations. FIGURE 3 shows a vehicle travelling in the ditch during a test.

The steering input for the test with the small car (80 km/h, 10 degrees) was recreated with mechanical actuation of the steering wheel as the vehicle entered the ditch. The steering wheel was rotated a half revolution by a pneumatic actuator. The steering wheel was locked at this position after actuation.

RESULTS

A total of 16 tests were conducted and the results of these tests are listed in TABLE 2. There were 4 rollovers observed for the impact conditions investigated. Two of the rollovers were with a free running vehicle, one resulted from steer input while the vehicle was in the ditch, and the last rollover was a result of a significant impact with the low barrier placed in the bottom of the ditch.

The accelerations experienced by the vehicle as it passed through the ditch varied with type of impact conditions. A moderately severe test (10 degrees and 80 km/h) resulted in peak vehicle accelerations of about 5 g. The more severe tests with an impact angle of 20 degrees produced peak vehicle accelerations of about 10-15g. The vehicle accelerations for Test 7 are shown in FIGURE 6. The main difference can be attributed to the amount of vehicle chassis contact with the ditch surfaces. For less severe tests, the chassis has little if any contact with the ground and only limits to the suspension travel induce high accelerations to the occupant compartment. Higher severity impacts resulted in noticeable chassis/soil interactions and this contact is evident in the vehicle accelerations.

Climb of the vehicle up the backslope could not be easily correlated to any of the impact conditions. In the following figures, different impact conditions have been plotted against the vehicle climb to identify any particular impact condition that causes the vehicle to climb out of the ditch. In FIGURE 7 the impact speed does not appear to have a strong correlation to vehicle climbing out of the ditch over the backslope. All speeds between 60 and 110 may result in the vehicle continuing out of the ditch. Similarly, one can see that rollover was not strongly related to impact speed.

In FIGURE 8, the vehicle climb on the backslope is plotted against the impact angle. As in FIGURE 7, there is no impact angle for which the vehicle is less likely to climb over the backslope. Rollover occurred for impacts at 20 degrees, but this did not occur for all 20 degree test cases.

A commonly used parameter for analysing longitudinal barriers is Impact Severity (IS). This is defined as:

$$IS = \frac{M(V\sin\theta)^2}{2}$$

In this parameter, the vehicle mass (M), speed (V), and impact angle (θ) are incorporated into one variable. As in the previous graphs, no clear relationship between IS and vehicle climb can be identified (FIGURE 9). These three figures suggest that no clear relationship can be identified between a vehicle's impact conditions and tendency to traverse V-ditches.

The vehicle's tendency to climb up the backslope of the V-ditch must have a relationship with the vehicle's dynamic characteristics. A further refinement of FIGURE 7 to separate the vehicle types is presented in FIGURE 11. In this diagram, the vehicle masses are separated. Only two tests were done with the heavy vehicle and thus it is difficult to draw any conclusions on the influence of vehicle weight. The 900 kg test vehicles comprised Peugeot, Fiat, Ford, and Talbot vehicle makes. All of these vehicles behaved similarly. None had any particular problems that would suggest the test vehicle selection influenced the results.

Vehicle rollover was observed in two of the experiments where the vehicle was free rolling during the test. In both of these tests, the vehicle was seen to contact the vehicle backslope as the vehicle reached the bottom of the ditch. This backslope contact induced sufficient roll motion that the vehicle continued to rollover. One rollover occurred at a relatively low speed (79 km/h). The test with the same angle and slightly higher speed (82 km/h) did not result in a rollover, although the vehicle nearly rolled over. A much higher impact speed (107 km/h) also resulted in rollover in the ditch. A significant impact with the backslope was not sufficient to hold the vehicle within the ditch at the higher speed test.

The rollover mechanism seems to start with the first contact of the vehicle with the backslope. At a 20 degree approach angle, the vehicle does not appreciably contact the foreslope. The rightmost edge of the bumper and lower frame contacts the backslope near the bottom and induces both roll and yaw moments. It is this combination vehicle rotations due to backslope contact that sets up the rollover instability. The right front sping compresses during the intial slope contact and the resulting unloading provides additional rollover loading. This sequence is illustrated in FIGURE 10.

Simulations of the tests were conducted in the PC-Crash environment. This program allows 3-D motions of the vehicle to be simulated for different terrains, but contacts of the frame and ground cannot be easily modelled to represent the same conditions observed in the tests. Each of the V-ditch tests were simulated and the trajectories of the vehicle were compared to see how accurate the vehicle dynamics were duplicated.

The first tests were simulated and used to calibrate the vehicle suspension settings (adjustable in the software) and the tire/ground friction properties. The friction setting with $\mu = 0.5$ gave the best agreement in tire/ground interaction and agrees well with the friction measured on the ditch material in Pori. Vehicle weight distributions were varied to determine their influence on the simulation results.

The vehicle path (in plan view) observed in the test is shown by the solid line in FIGURE 12. This line represents the path of the front right tire during the test. The dashed line represents the simulation results for the same tire. The most significant difference between the test and simulation results is observed in the vehicle path before the vehicle tire reached the bottom of the ditch. During the physical tests, the vehicle follows the impact angle (5 degrees in this test) for the first metre travelled into the ditch. After that, the vehicle deviates from a straight path, increasing its angle away from the road. The similar tendency is observed for the simulation, but not nearly as large a deviation from the original path. Part of this motion can be attributed to the vertical slope of the foreslope. However the discrepancy between the vehicle and simulation results can be attributed to the castor steering in the vehicle.

The front wheels of a car have a contact patch with the ground as illustrated in FIGURE 13. The contact patch and steering geometry is such that a small moment arm exists between the centre of the patch and vertical axis of steering rotation. This moment arm causes the vehicle steering to automatically centre due to normal drag forces on the tire. When a side load is applied to the tire, the steer axis will rotate until the drag forces cause the steering to centre.

As the vehicle enters the ditch in the 5 degree tests, the right tire follows the foreslope. The lateral force acting at the tire contact patch produces a steering moment. This moment induces a small steer angle towards the ditch centre. The opposite steer angle is generated as the vehicle climbs the backslope. If sufficient space was available (and no other external forces act on the vehicle) the steering motions due to the vehicle castor and gravitational loads would result in the vehicle being steered towards the bottom of the V-Ditch.

The simulation model does not include this castor effect and thus does not exhibit the same path. When a small steer angle was introduced to imitate the castor effect, an improved vehicle trajectory was observed.

Simulation of the vehicle impact with the V-ditch could not reproduce any of the rollovers observed in the tests. Vehicle motions for simulation 1 and 2 in FIGURE 14 represent different suspension settings (harder and softer settings). Changes to the inertial properties for the vehicle did not improve simulations of the rollover. Information for vehicle moments of inertia were obtained from NHTSA test data [3].

DISCUSSION

The collision violence of vehicles travelling in a V-ditch was not appreciably worse than the loading measured in standardised testing of road restraint systems, as long as a rollover did not occur. The rollovers observed tended to be quite violent even for the lowest speed tests (80 km/h).

A significant risk that was not measured in these (or similar) tests is the consequences of a vehicle travelling over the backslope and continuing into the roadside terrain. The backslope used in these tests was 1 m higher than the road and this was not sufficient to contain vehicles to the ditch. The speed was not observed to be significantly reduced as the vehicle exited the ditch. Often the vehicle was airborne as the backslope acted as a ramp. Subsequent impact with a pole, tree, or rock located beyond the ditch could have severe consequences for the vehicle trajectories observed in the tests. Many Scandinavian rural roads have little clear zone beyond the ditch. The only method of reducing the speed of vehicles leaving the ditch area would be to implement a different ditch geometry or introduce a road restraint system.

The steering actions investigated in two of the tests highlighted the sensitive nature of driver inputs on embankments. Two similar test conditions resulted in dramatically different outcomes because of the small differences in the timing of the steer input (equal steer angles were employed in each test). Simulations conducted at Chalmers had observed the risk of driver input while traversing a foreslope. The roll moment introduced by a driver attempting to steer back to the road combined with the slopes inclination leads to the increased rollover risk.

CONCLUSIONS

The impact of a vehicle with a V-ditch is a relatively unstable event. Impact conditions cannot be used to predict the outcome of the event in terms of rollover or extent of vehicle climb up the backslope. Small cars were observed to rollover for impact angles of 10 degrees and impact speeds of about 80 km/h. The backslope contact was a major factor in vehicle rollovers.

Simulation of the vehicle impacts did not successfully reproduce the vehicle motion observed in the tests. The main reason was the influence of castor on the vehicle steer motions. This effect caused simulations to underpredict the amount of lateral vehicle motion in the ditch. It was not expected that this castor effect would influence the vehicle dynamics over such a short travel distance and identified the importance of this parameter in vehicles travelling over embankments.

Rollovers of vehicles in the V-Ditch were a direct result of the backslope contact. Simulation of the V-ditch impacts without the frame to ground contact did not adequately model the vehicle motions in the ditch. As expected, this contact contributes to the rollover tendencies of the vehicle and must be incorporated in future modelling efforts.

Results of crash tests with a V-ditch consisting of different soil characteristics have not been received to date. These tests will be interesting to analyse and compare to the tests described above to identify the influence of the backslope contact on the resulting vehicle motions in the ditch.

Future research is planned to improve the simulation models. Critical issues identified from these tests are the steering and suspension characteristics of the vehicles leading to castoring of the vehicle. Tire/soil contact models should also be investigated to understand the forces on the tire contact patches and understand the lateral loads possible on tires. Through these additions to existing models, new roadside geometries and restraint systems can be investigated so that that will improve roadside safety.

ACKNOWLEDGEMENTS

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REFERENCES

1 VU94, Swedish National Road Administration, 1995

2 *Roadside Design Guide*, American Association of State Highway Transportation Organizations, 1990

3 Garrott, W.R., Measured vehicle inertial parameters—NHTSA's data through September 1992, Society of Automotive Engineering Paper 930897, 1993

TABLE 1: Matrix of Test Conditions

Vehicle Size [kg]	**Speed [km/h]**	**Angle [deg]**	**Comments**
900	80	5	V-Ditch
900	100	5	V-Ditch
1500	80	5	V-Ditch
900	80	10	V-Ditch
1500	80	10	V-Ditch
900	80	10	V-Ditch, Steering
900	80	20	V-Ditch
900	110	20	V-Ditch
900	100	10	U-Ditch
900	110	10	V-Ditch with Small Barrier

TABLE 2: Test Results

Test	Vehicle Size [kg]	Speed [km/h]	Angle [deg]	Climb Height on Backslope [m]	Comments
1	900	84	4	over	Climbed up and over back slope
2	900	78	3	0.2	Shallow angle, contained in ditch
3	900	102	6	1.4	Vehicle climbs partially up backslope, directed up foreslope and onto road
4	1500	81	4	1.6	Vehicle climbs partially up backslope, directed up foreslope and onto road
5	900	82	20	over	Significant impact with backslope
6	900	79	20	1.5	Impact with backslope, Rollover in ditch
7	900	107	19	over	Rollover and climbed over backslope
8	900	83	10	over	Climbed up and over back slope
9	900	84	9	No contact	Steering, barely entered ditch
10	900	62	10	over	Climbed up and over back slope
11	1500	82	10	over	Climbed up and over back slope
12	900	82	11	1.2	Steering, rolled while on backslope
13	900	83	10	1.3	Steering, contained in ditch
14	900	100	10	Over	Climbed up and over back slope
15	900	96	10	Over	U-Ditch, easily climbed up backslope
16	900	105	10	N/A	V-Ditch with barrier, rollover

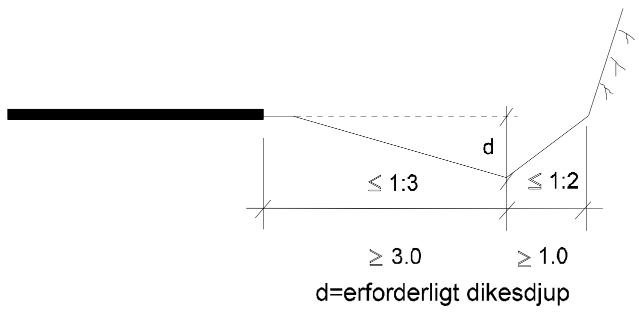

FIGURE 1: Road profile

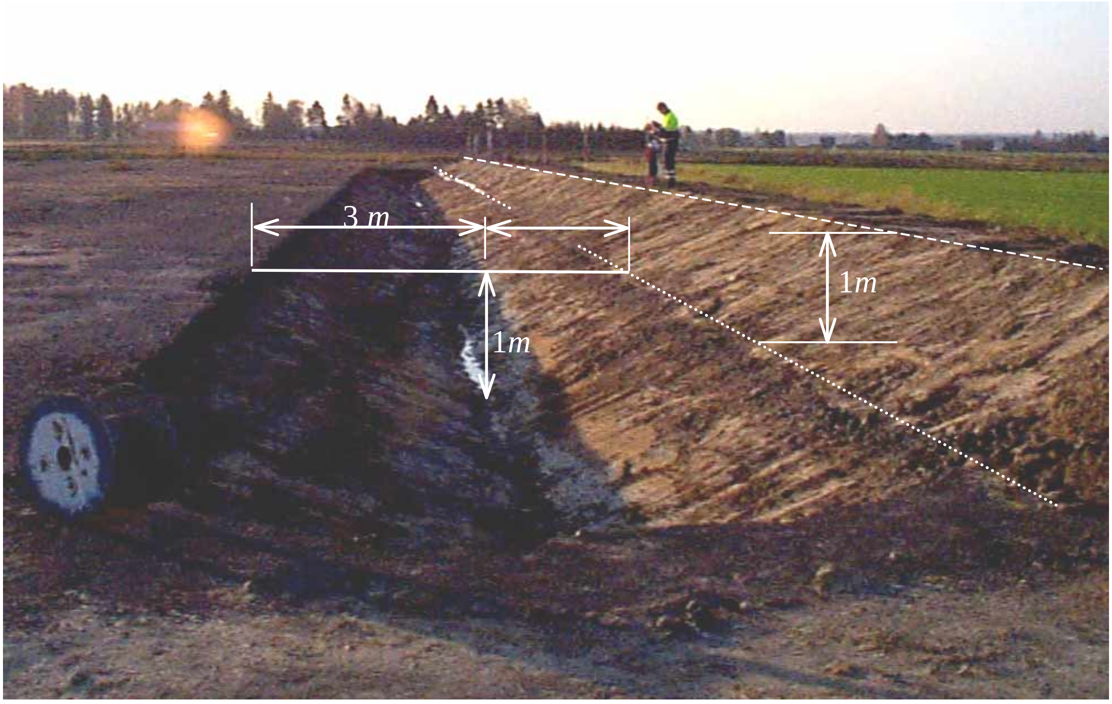

FIGURE 2: Ditch profile for crash testing

FIGURE 3: Test vehicle in ditch

FIGURE 4: U Shaped Ditch (Loose Gravel Bottom)

FIGURE 5: Ditch with Low Barrier on Backslope

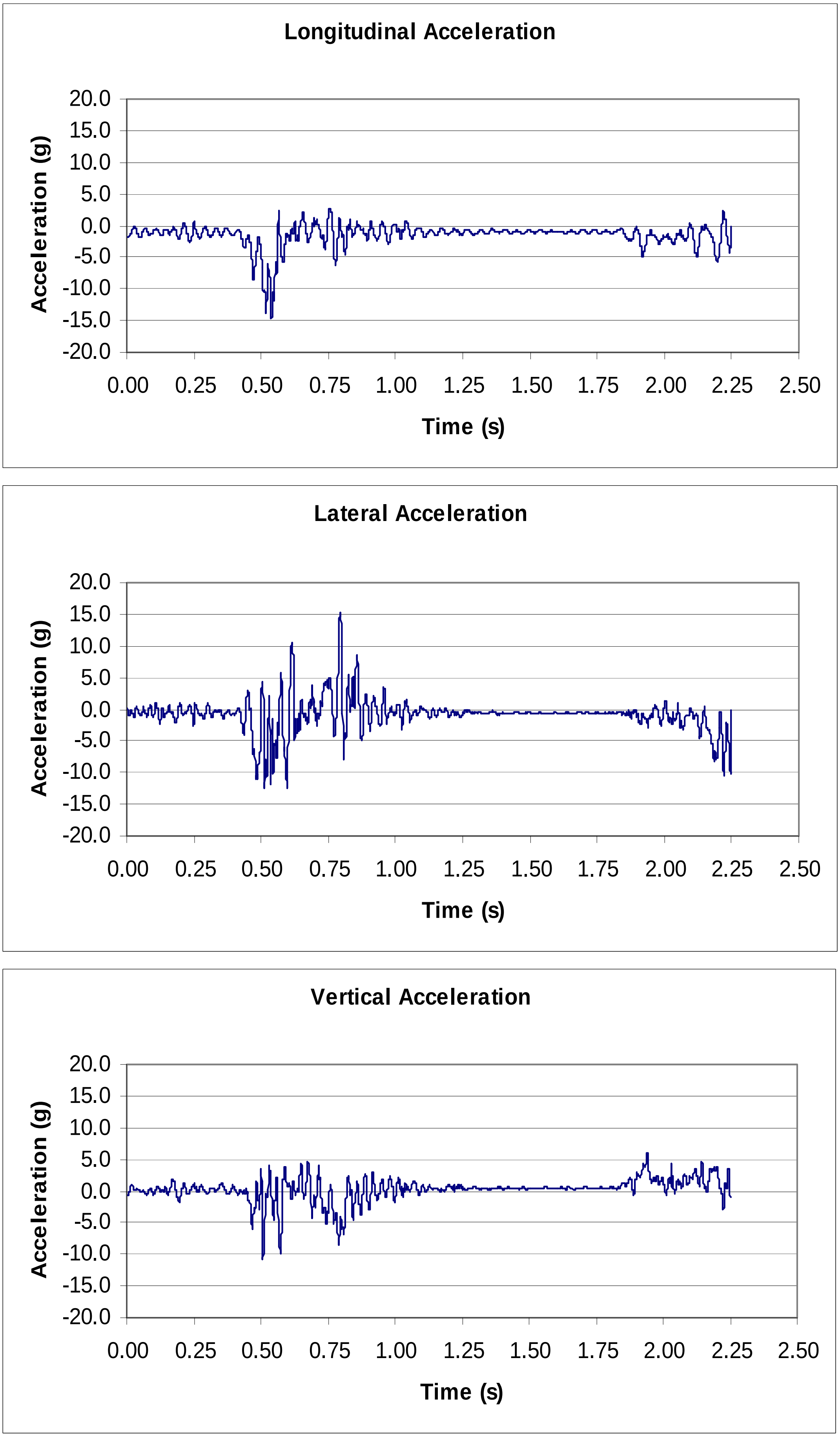

FIGURE 6: Vehicle Accelerations for Test 7

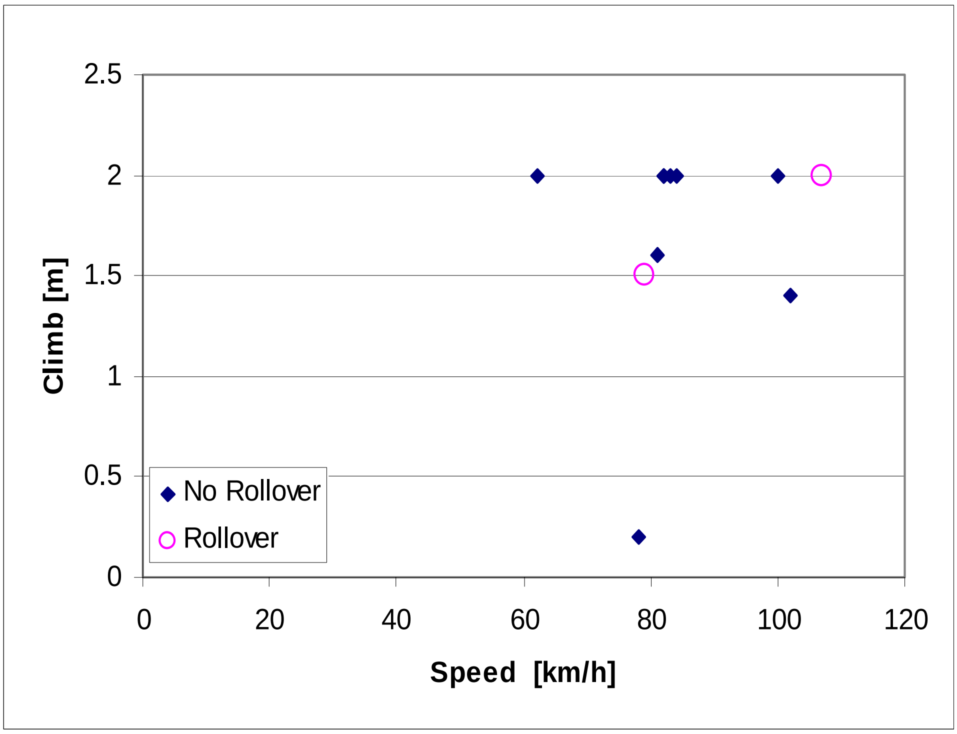

FIGURE 7: Influence of Speed on Vehicle Motion in the Ditch

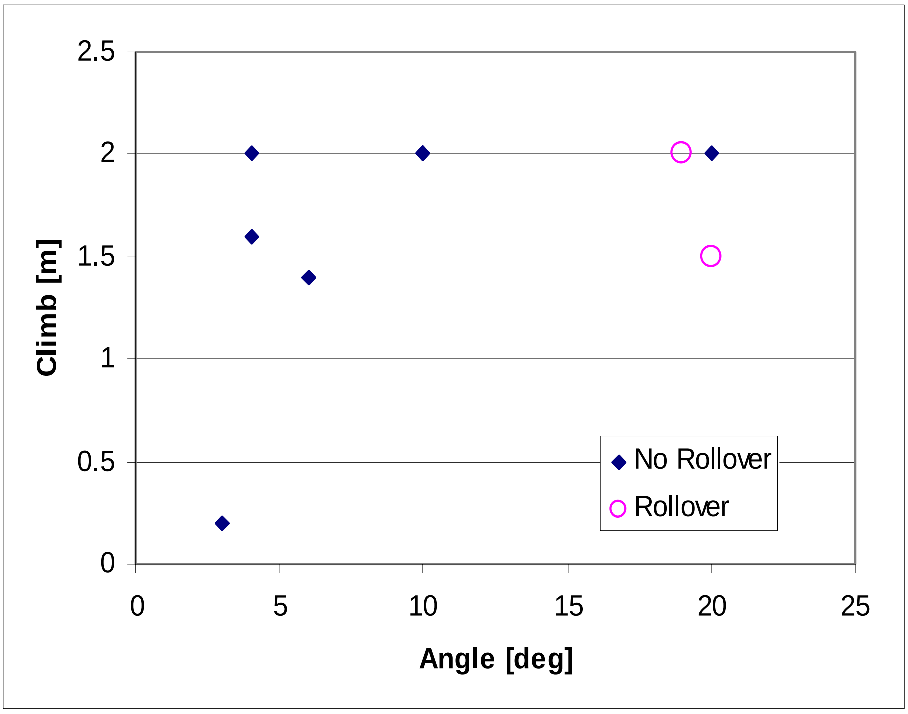

FIGURE 8: Influence of Angle on Vehicle Motion in the Ditch

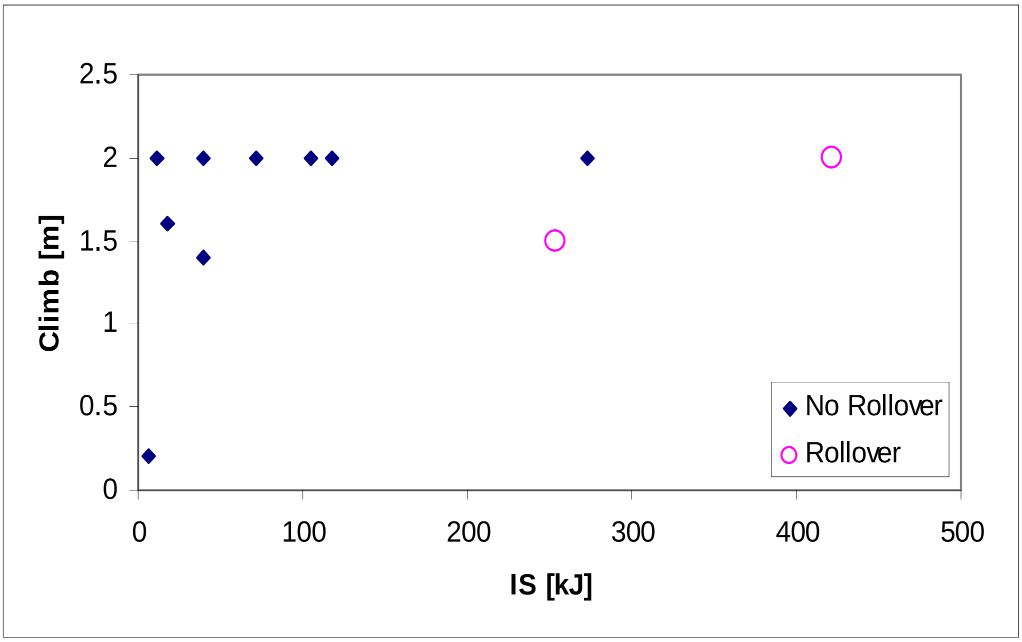

FIGURE 9: Influence of Impact Severity on Vehicle Climb

FIGURE 10: Rollover Sequence From Backslope Contact

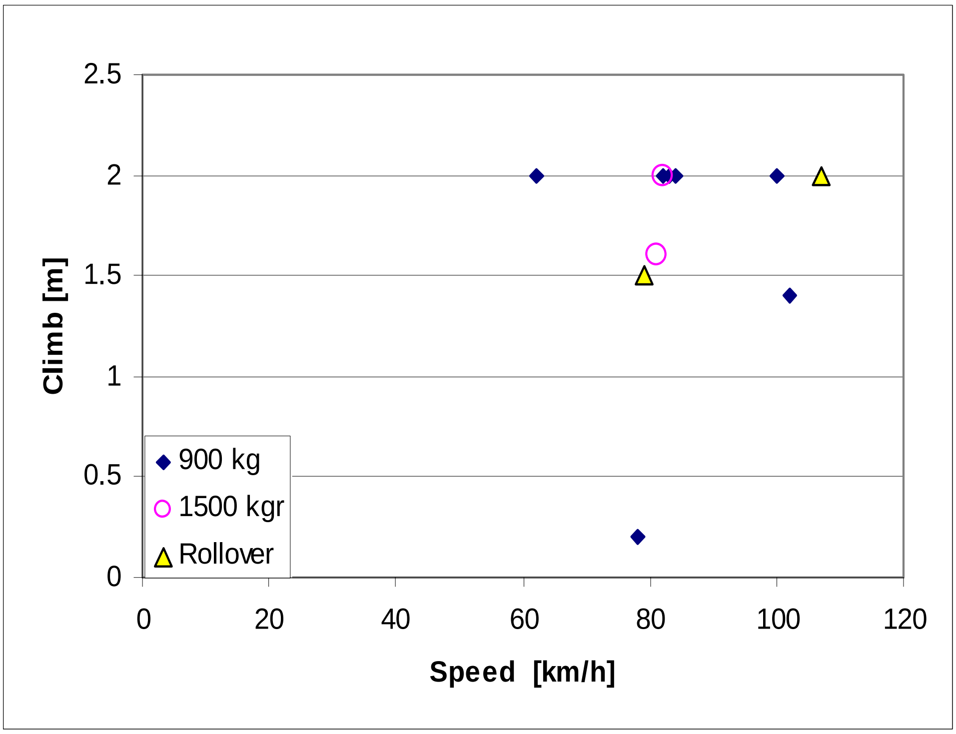

FIGURE 11: The Influence of Vehicle Size and Impact Speed on Climb

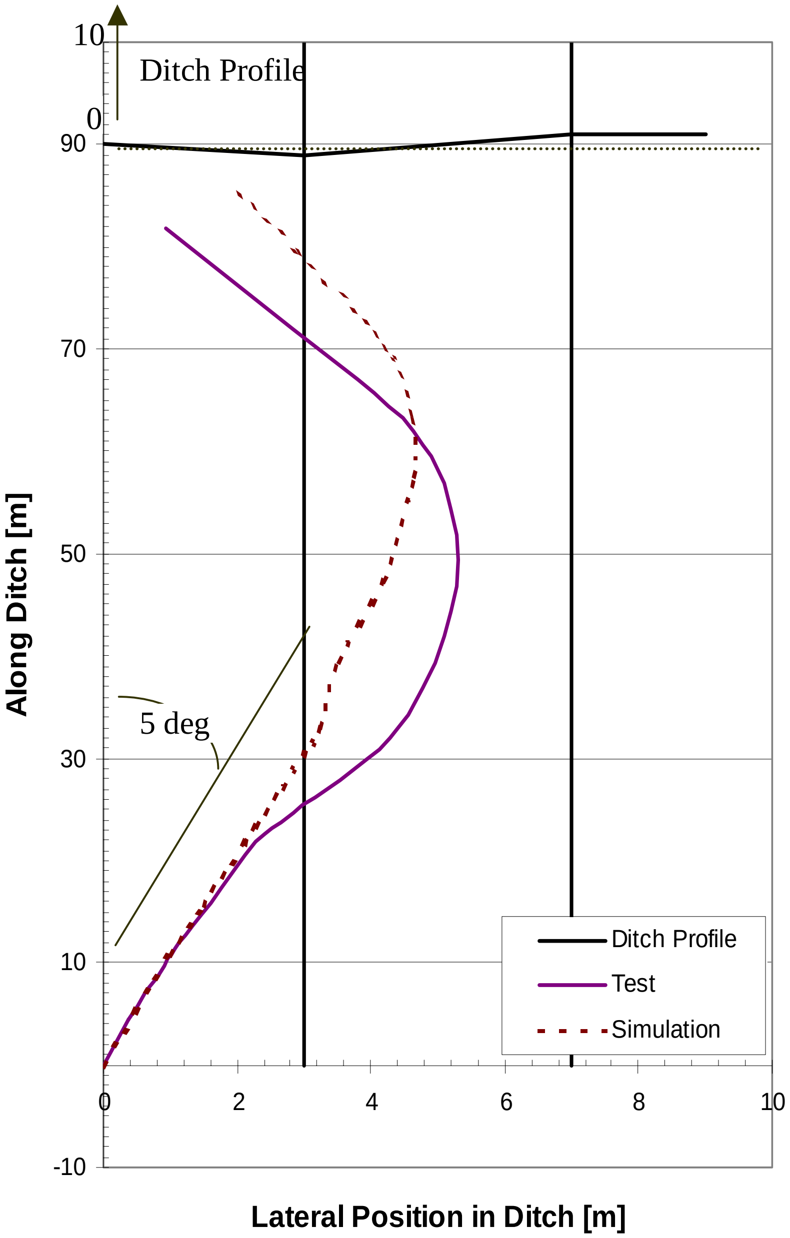

FIGURE 12: Vehicle Path in Test 3 (5 degrees 102 km/h)

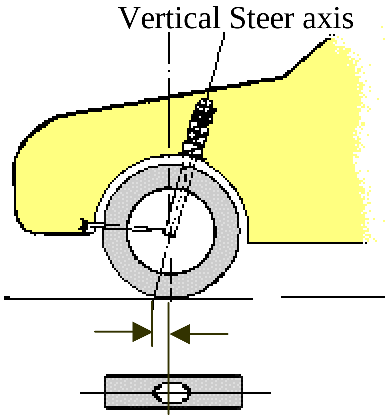

FIGURE 13: Vehicle Tire Contact on Road

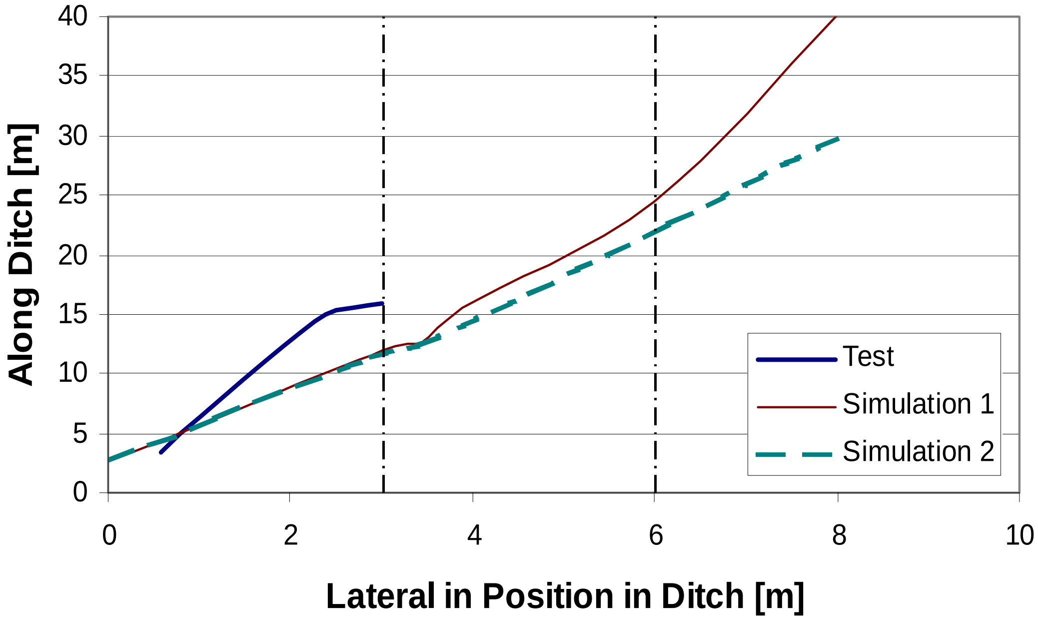

FIGURE 14: Simulation and Test Results in Test 6 - Rollover (20 deg. & 82 km/h)