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Deceleration Factors on Off-Road Surfaces Applicable for Accident Reconstruction

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Abstract

This paper presents the results of full scale vehicle testing completed to examine deceleration factors, or friction coefficients, on various off-road and on-road surfaces. Of particular interest is the relationship between vehicle side slip and deceleration rates on soft, off-road, deformable soils. Vehicle testing was conducted at slip angles of 0, 30, 45, 60, and 90 degrees with locked and unlocked wheels. A comparison of the experimental data is made with respect to the theoretical prediction of deceleration being trigonometrically related to slip angle. Results indicate the theoretical prediction as fairly approximate through a portion of the side slip range. As side slip angles approach 90 degrees, actual measured values are higher than predicted.

Introduction

While completing an accident reconstruction analysis, it is important to utilize accurate and appropriate deceleration factors for the vehicle/surface combination under consideration. Often, a vehicle will traverse multiple surfaces and experience several different deceleration factors throughout an accident sequence. Considering an accident sequence in which a vehicle travels off the road in a side slip fashion and ultimately rolls over after its tires dig into the relatively soft ground, accuracy of the analysis relies significantly on how deceleration leading to trip is applied.

Although tire/road deceleration factors on asphalt and concrete surfaces are fairly well documented in the literature, a certain amount of variability exists in assigning deceleration factors on alternate surfaces such as gravel, sand, grass, and plowed fields. Several sources have reported deceleration factors for most of these surfaces (e.g., Fricke(1), Limpert(3), Collins(9), etc.), however, some ambiguity exists. Documented sources typically characterize locked wheel longitudinal deceleration. Also, the actual visual configuration of the test surfaces along with the test methodologies utilized to arrive at the reported values are typically not included.

The purpose of this research paper is threefold. First, deceleration factors on several off-road and on-road surfaces were evaluated. Second, the method of applying a deceleration factor to a vehicle traveling in a yaw or side slip manner with unlocked tires at various slip angles was examined and compared with test data. Third, a comparison was made, where applicable, between the results of this research and currently published values of deceleration factors.

Deceleration factors were obtained by dragging four different passenger cars and measuring the force(s) generated. The measurement method consisted of an agricultural tractor pulling the various test vehicles at predetermined slip angles in both locked and unlocked tire configurations. Force transducers were used to measure the horizontal forces produced by each pull and deceleration factors were calculated accordingly.

Theory

A *Drag factor* (f) is a non-dimensional number used to represent the deceleration of a vehicle. It is defined as the resultant force imposed on a vehicle opposing its direction of travel divided by the overall weight of the vehicle. The mathematical equation used to calculate the drag factor is

$$f = F \div w \qquad \text{(i)}$$

In a dynamic situation, as a vehicle is decelerating, the resultant force acts at the center of gravity (CG). Motion of the vehicle is therefore affected by this force, and it becomes necessary to determine the center of gravity location for the vehicles being tested. Center of gravity can be located in three dimensional space with respect to the vehicle coordinate system on the lateral, longitudinal, and vertical axes. Determination of the lateral and longitudinal location is completed by weighing the force reactions at each wheel while the vehicle is on a level surface and then performing a static force analysis. Determination of the vertical center of gravity location is accomplished by following the method outlined by Fricke(1) and others. One axle of the vehicle is raised vertically, and the resultant weight reactions are measured. These numbers are then compared to the level vehicle weight distribution, and using a comparative static force analysis, vertical CG location is calculated using the following equation:

$$h_{cg} = \left[\frac{l\sqrt{l^2-h^2} \bullet (wh-wf)}{(h \bullet w)} \right] + r \quad \text{(ii)}$$

where:

h_{cg} = CG vertical height, m
l = wheel base, m
h = Distance rear (front) axle raised, m
r = tire/wheel rolling radius, m
w_h = front (rear) axle raised weight, N
w_f = front (rear) axle weight, level, N
w = total vehicle weight, N
r= rolling radius of tire/wheel, m

One area of uncertainty which introduces inaccuracy into the results of vertical CG calculation concerns suspension and tire deflection resulting from weight shift. For the purposes of this testing, CG height was calculated by raising the front axle and measuring weight shift, and then by raising the rear axle and measuring weight shift. The results of these two calculations were then averaged and used as the resultant center of gravity height.

In modifying the test vehicles to evaluate slip angle deceleration forces, the main question to be answered is related to deceleration during side slip, and specifically its relationship to vehicle rollover. Following the relationship between slip angle and deceleration factor outlined by Orlowski (5), it is assumed that deceleration during a side slip (with free rolling wheels) is a function of slip angle and the locked wheels tire/surface longitudinal deceleration factor. When a vehicle is traveling in a yaw path or side slip condition with no driver input, resultant forces acting on the vehicle at the tire/surface interface are acting perpendicular to the rolling direction of each tire as demonstrated in figure 1. Tire rolling resistance and drive train type losses are usually assumed to be negligible. For this approach to modeling vehicle deceleration during side slip, the slip angle is defined as:

slip angle = heading angle - path angle (iii)

In general, the literature contains tabulations of deceleration factors on various surfaces for straight ahead locked wheels braking. If the assumption is made that a vehicle will experience this same deceleration factor during a 90 degree, locked wheels and/or unlocked wheels side slip event, an equivalent deceleration factor that a vehicle experiences at various slip angle orientations can be calculated by the following equation:

$$f_{decel} = f_{total} \times \sin(\text{slip angle}) \quad \text{(iv)}$$

Where:

f_{decel} = deceleration factor, dimensionless
f_{total} = Total deceleration factor, dimensionless
(i.e.. locked wheels tire/surface coefficient)

For the case in which a vehicle is traveling on a paved road surface, or firm off-road surface, this relationship makes intuitive sense. However, in the case of an off road trajectory on soft deformable soil, a vehicle will typically plow dirt with its leading tires. As a result, deceleration rates will sometimes increase until the critical rollover point is reached. This magnitude of deceleration is usually significantly larger than that generated at the tire/surface interface during a skid to stop test.

The propensity for a vehicle to rollover is dependent, among other things, on the drag factor. Figure 2 below shows a simple free body diagram of a vehicle and the forces which act on a vehicle in side slip. In the simplified model which neglects all suspension and tire compliance and treats the vehicle as a rigid body, the rollover threshold is defined as a ratio between the track width and vertical CG height of the vehicle.

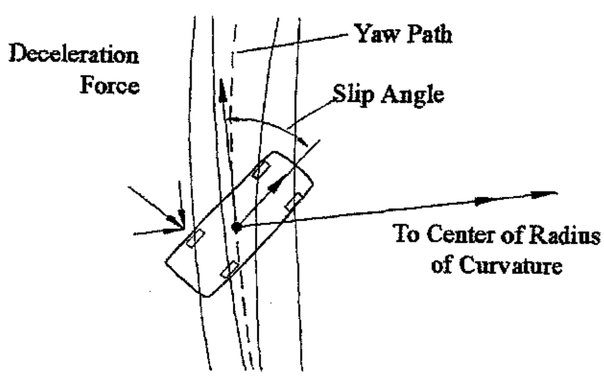

Figure No. 1. Vehicle in side slip yaw path

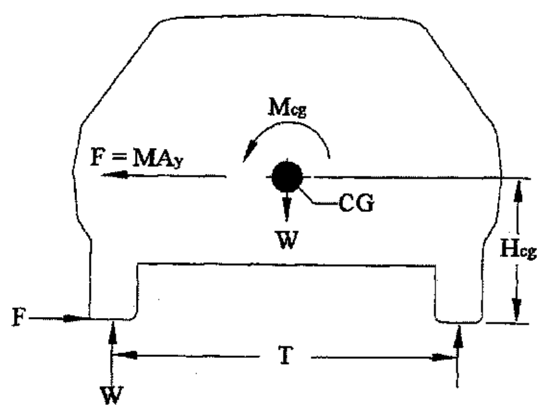

Figure No. 2. Simple rollover model

Summing the moments about the center of gravity of the vehicle and assuming no spring or tire compliance:

$$\Sigma M_{cg} = 0$$

$$F \times h_{cg} - w \times T \div 2 = 0 \quad (v)$$

where:

h_{cg} = center of gravity vertical height, m
T = track width, m
w = total vehicle weight, N
F = total deceleration force, N

Rearranging this equation, it is demonstrated that if the Force, F, hence drag factor, applied in deceleration exceeds the ratio of half the track width over CG height, rollover will result.

$$f > T \div 2 \div h_{cg} \quad (vi)$$

Of course, this simplified model overestimates the actual threshold at which rollover will occur. Typical deceleration factors which will cause rollover that do take suspension and tire compliance into consideration are reported in the literature (e.g. Gillespie (2)). Values for passenger vehicles are usually well in excess of 1.0g.

Values of deceleration factors derived during testing are reported in this research paper in reduced form as average values. The subject testing was conducted mainly to evaluate resistance to travel at slip angles and report the trends. It is not an intention of the authors to attempt to redefine the tables of deceleration values in general use by the accident reconstruction community. Analogies to currently published data are made where applicable for the purpose of comparison of the data. With this in mind, no statistical analyses are reported since the testing completed for any individual surface is essentially one sample, and not indicative of an entire population.

Test Procedures and Equipment

Test vehicles utilized are as follows: 1985 Ford Tempo, 1988 Oldsmobile Delta 88, 1974 Chevrolet Chevelle, and 1968 Oldsmobile Vista Cruiser. The vehicles were documented and photographed prior to testing. Table 1 contains a tabulation of mass and center of gravity (CG) location for each vehicle as tested. Photographs 1 through 4 in the appendix depict the vehicles. The Tempo and Delta 88 vehicles are depicted in photographs 1 and 2. Photograph 3 represents the Chevelle in its test configuration. Photograph 4 depicts the Vista Cruiser prior to removal of the body

Testing for this project was completed during two distinct periods. Initial testing was conducted with the Tempo and Delta 88 vehicles. Test setup for these vehicles consisted of securing chains to attachment points at the exterior left side

Table No. 1. Test Vehicle Data

Vehicle	Olds 88	Ford Tempo	Chevelle	Vista Cruiser
Total (kg)	1723	1275	1333	1355
Front (kg)	973	804	758	802
Rear (kg)	750	471	575	553
CG Aft of axle	1.29 m	0.92 m	1.23 m	1.25 m
CG Vertical	0.52 m	0.63 m	0.57 m	0.53 m

of each respective vehicle at axle centerline height and/or vertical CG height. The chains were then triangulated and secured to a pull vehicle. The pulling vehicle was a 64 kW (85 HP) Massey Ferguson agricultural tractor. Figure 3 in th appendix illustrates test set up for this round of testing. Pull forces were measured using a 4,500 kg (10,000 lb) load cell.

Using this pulling configuration, resistance to vehicular trav during side slip was measured. Problems arose during these tests and were similar to the those encountered by DeLeys (4 in that this pulling configuration would not provide the lateral force required to produce tire side slip with unlocked wheels at slip angles other than 90 degrees. A true side slip condition could not develop and, therefore, the forces measured in this series of tests were mostly concentrated in straight pulls and broadside pulls.

At slip angles other than 90 degrees, the side force generated at the tire/ground interface, hence a lateral force component with respect to the tractor, caused the vehicle to rotate about the tractor attachment point until it was aligned with the tractor direction of travel. Obviously, this was not a problem at 90 degrees slip because there is no force component in the vehicle longitudinal direction. In order to counteract this problem, the front wheels of the Tempo and Delta 88 were turned all the way right to negate the aligning moment. Although data collection in this mode for the 45 degree pulls would not yield comparative results, testing at 45 degrees wa conducted for completeness. These two vehicles were pulled at 45 degree slip angles both with the wheels unlocked and front wheels turned to the full right lock position, and with a wheels locked and front tires straight.

The second round of testing was conducted with a revised te apparatus that would induce a vehicle slip angle. A universal/swivel joint was fabricated and attached to the vehicle at its center of gravity. Rotation about the yaw axis was restricted while rotation about the pitch and roll axes wa allowed. The apparatus developed for this testing was attached to the Chevrolet Chevelle and Oldsmobile Vista Cruiser automobiles. After documenting vehicle weight and

CG location, the vehicle bodies were removed to facilitate mounting of the pulling apparatus at the center of gravity, and to allow for ease of configuration changes between pulls. Figure 4 in the appendix illustrates the pulling apparatus designed for these tests.

The pulling apparatus consisted of a slip joint linked together by a force transducer. The entire apparatus was adjustable to three angular positions that allowed the vehicle to be pulled at nominal slip angles of 30, 60, and 90 degrees. Actual slip angles measured during testing were 35, 63, and 90 degrees, respectively. The apparatus employed two load cells, one 2,268 Kg (5,000 lb) unit and one 1,361 Kg (3,000 lb) unit. One load cell, mounted on the slip joint, strictly measured the drag forces imposed in the direction of vehicular travel. The other load cell measured the force perpendicular to the drag force which would be synonymous with centripetal force during a yaw sequence. Therefore, all forces developed at the tire/ground interface during a typical yaw path, or side slip event were measured.

Once fabrication of the pulling apparatus was complete, a pre-test trial evaluation of the pulling apparatus was conducted. The Chevelle and Vista Cruiser vehicles were ballasted with metal weights until their original weights and CG heights were replicated. Based on the trial testing, it was determined that vehicle weight needed to be reduced for the tractor to properly pull the vehicle in the side slip tests. Although the tractor was fairly large, it was evident during the 30 degree side slip pulls that the evaluation vehicles would redirect the direction of travel of the tractor. Weight of these vehicles was reduced to approximately 1,361 kg (3000 lb). Percentage weight distribution was kept constant, and CG location was verified.

The actual testing sequence began with placement of the respective drag vehicle on a particular surface. The vehicle was then attached to the tractor at the appropriate slip angle. Load cells were zeroed, and tension was introduced to the chains, cables, or links, depending upon which vehicle was being pulled. A distance of 100 feet was then marked off for each pull. Pulling was completed in a steady state manner at a constant speed of approximately 0.8 kph (0.5 mph). The load cells sampled at a rate of approximately once per second so that there were approximately 140 data points per pull. In total, sixty eight pulls were completed over the various vehicle/surface combinations.

Table No. 2 Vehicle/Surface test matrix

Table no. 2: Test Matrix																				
	Ford Tempo					Oldsmobile Delta 88					Chevrolet Chevelle					Oldsmobile Vista Cruiser				
Slip Angle (deg)	0	30	45	60	90	0	30	45	60	90	0	30	45	60	90	0	30	45	60	90
Coastal Grass	X		X		X	X		X		X	X	X		X	X	X	X		X	X
Black Dirt	X		X		X	X		X		X	X	X		X	X					
Corn Rows	X		X		X	X		X		X	X	X		X	X					
Sandy Dirt											X	X		X	X					
Asphalt											X	X		X		X	X		X	X
Asphalt/Excess Tar											X									
Gravel/Dirt Road											X									
Sand/Dirt Road											X									

Results and Discussion

Testing was conducted on various surfaces which included: 1) dry coastal grass, 2) loose black dirt with foliage, 3) unplowed, harvested, corn field, 4) sandy soil, 5) asphalt, 6) asphalt with excess tar, 7) gravel/dirt road, and 8) sandy dirt road. Photographs 5 through 12 in the appendix depict the various test surfaces.

The coastal grass surface was an uncut cattle pasture. Average height of the grass was approximately 0.15 m (6 in). Disced black dirt/foliage was a harvested corn field that had been cultivated with a disc harrow to a depth of approximately 0.08 m (3 inches). The foliage present consisted of remaining corn stalks and shucks. The corn rows surface was a corn field that had been harvested, but not yet cultivated. Bedded rows were still in place as well as rooted stalks at the apex of the rows. Testing was conducted on this surface oriented both parallel and perpendicular to the rows. Sandy soil was a cultivated field which was predominantly sand as opposed to black dirt. Cultivated depth in the sandy soil field was approximately 0.11 m (4 to 5 in). For all testing the soil was dry. The last rain had occurred approximately 4 weeks previous.

On-road surface 6 was an asphalt parking lot. Asphalt with excess tar was a Texas state highway covered with an aggregate seal coat. This generally means that the road surface was sprayed with heated tar and then covered with gravel. Surfaces 7 and 8 were located on a typical unpaved dirt road. Sections of the road were chosen where there was a preponderance of gravel for surface 7, and where there was mostly sand for surface 8. Table number 2 is a matrix representing the testing completed.

As already mentioned, the first series of tests were conducted with the Tempo and Delta 88 vehicles. The pulling apparatus fabricated for the Tempo was designed to apply pulling forces from two separate vertical elevations, center of gravity height (high pull) and axle centerline height (low pull). Pulling forces on the Oldsmobile were applied at the axle centerline.

Graphs 1 through 8 in the appendix report average deceleration rates measured on the various surfaces during this first series of tests. Two trends develop throughout the data. First, the deceleration rates are slightly reduced in the longitudinal locked wheels configuration as compared to each respective 90 degree side slip pull. In general, the average deceleration rates at the 90 degree configuration were approximately 10% to 30% higher than each respective zero degree configuration. Second, vertical location of pull force application did have a significant effect on the deceleration values at the 90 degree configuration.

Looking at the results for the Ford Tempo concerning high pull force application and low pull force application, the test data indicates that deceleration factors derived in the subject testing are dependent on the point of force application. The apparent reasoning for this phenomenon, which was observed during the tests, concerns action of vehicle suspension. With force application at the CG level, the vehicle rolls toward the force which in turn causes the leading tires to carry more of the vehicle's weight. In soft soil, the increased load forces the leading tires to dig even deeper into the ground and more plowing results. In testing with force application administered at axle centerline level, less vehicle body roll results. Therefore, weight transfer to the leading tires/wheels is less and the vehicle slides across the surface with less resistance.

Two complications regarding the first series of tests which are related to point of pull force application and the inability to introduce a meaningful slip angle caused the authors to question the results obtained. Although force application on the high pulls was at the correct vertical height on the Tempo, the force was not applied at the absolute longitudinal and lateral center of gravity. Additionally, the results of the 45 degree slip angle tests did not yield realistic, or useful, data. As a result, it became apparent that vehicle alteration would have to be completed in order that pull force could be administered at the absolute center of gravity. Therefore, two additional test vehicles were located, and a second series of tests were completed.

As discussed previously, two full frame vehicles were utilized for the second series of testing. After general documentation, the bodies of the Chevrolet Chevelle and Oldsmobile Vista Cruiser were removed and a pulling apparatus was attached to introduce a slip angle and to constrain vehicle motion during the tests. The results obtained during this second phase of testing correlated in similar fashion with the previous testing in that higher deceleration forces were obtained at the 90 degree slip angle as compared to straight ahead locked wheel braking.

Graphs 9 through 13 in the appendix contain a synopsis of deceleration values obtained during the second series of test Results between the zero degree and 90 degree pulls show a significant trend. On the relatively firm surfaces of asphalt and coastal grass, the 90 degree pulls are approximately 10% higher than zero degree pulls. However, in the deformable soils, the 90 degree pull generated a significantly higher deceleration factor as compared to the zero degree pull with maximum difference of 45% on the black dirt surface.

Higher deceleration rates at a 90 degree slip angle on the deformable surfaces is easily understood from the standpoin that as slip angle increases, the leading tires/wheels are projecting a larger vertical surface area to the direction of travel. As the slip angle approaches 90 degrees, more and more dirt is plowed as compared to the zero degree configuration. However, since the same phenomenon was displayed on the grass and asphalt surfaces where no plowir of dirt occurred, other factors must also affect tire/surface deceleration rate.

While traveling in a side slip, a component of vehicle motio is directed perpendicular to the tire tread pattern. Observations made during testing on grass and asphalt surfaces indicated that the leading tires would repeatedly "snag and release" on macroscopic surface features. This phenomenon probably contributed to the deceleration values to being biased slightly higher for the 90 degree orientation pulls. At typical vehicle speed, this snag and release phenomenon would probably be decreased somewhat becaus of the decreased instantaneous time of tire/surface contact.

Following the analysis conducted by Orlowski (5), the theoretical prediction for vehicle deceleration in side slip is trigonometrically related to slip angle. The subject testing was conducted to experimentally analyze this relationship. Results suggest that this relationship is a reasonable approximation for slip angles possibly up to 60 degrees. In the deformable surface tests, a significant divergence from theoretically predicted values began to develop in the 45 to (degree slip angle range. On the firm non-deformable surfaces, resulting data points tend to follow a curve approximating the predicted sinusoid except that the actual deceleration forces measured at 90 degrees slip angle are higher than the corresponding zero degree locked wheels tests.

Looking at the data corresponding to the tangential force which acts as a deceleration force, results indicate that for a significant portion of the range from zero to 90 degrees, the theoretical model is a reasonable predictor of deceleration force. As the slip angle passes through the 45 to 60 degree range, the model begins to underestimate actual values.

graphs 14 through 18 report the results of the deceleration data along with the theoretical curve and a linear regression model. In general, results from the 30 degree slip angle tests are close to, but slightly smaller than, the theoretical prediction. Tests run at a 60 degree slip angle tend to be larger than predicted. 90 degree tests are significantly higher than predicted.

As is demonstrated graphically on the tables, the relationship between measured deceleration factors appears fairly linear with respect to slip angle especially for the off-road deformable surfaces. Linear regression analysis was performed on the data and the resulting straight lines plotted. Because of the random nature of experimental data, the y-intercept points from the linear regression model would not necessarily be equal to zero, therefore in performing the analysis, intercept values were set to zero. Considering graphs 14 through 18, there seems to be a general agreement, numerically, between longitudinal, locked wheel deceleration and the 60 degree slip angle tests.

A comparison of the experimentally derived data with published sources was completed and the principle comparisons were made with Fricke(1) and Limpert(3) and Collins(9). The applicable comparisons for this research paper were in the area of off road coefficients. Table 3 is a tabulation of the appropriate values. Consideration of this table indicates the subject testing in general resulted in values tending to fall on the high side of the published values.

Table No. 3. Comparison of experimental data with published values

Surface	Verifact	Fricke (1)	Limpert(3)	Collins (9)
Dirt	0.78	0.65	0.6	0.65
Grass	0.54	n/a	0.35	n/a
Sand/ Gravel	0.67	0.55	0.40-0.70	0.55
Asphalt/ excess tar	0.64	0.50-0.60	n/a	n/a

Observations

During the subject testing, several observations were made regarding test setup and results. For the 30 degree side slip tests, it was noted the tractor used to pull the test vehicle was not heavy enough to introduce an absolute slip angle at the 30 degree orientation. At a slip orientation of 30 degrees, the side force of the car tended to steer the tractor in an arced path. While it was apparent the car was slipping, its contribution to redirecting the tractor would have acted to decrease the slip angle slightly. Thus the aggregate deceleration factor measured would tend to be underestimated.

In all the testing performed, the vehicle significantly unloaded the trailing wheels, but never did tip up or roll over.

Considering the deceleration factors measured on the off-road surfaces, one may infer that a rollover situation should have developed. Since this did not happen, it is appropriate to explain why not. Out of necessity, the tests were conducted at a relatively slow, steady state speed of approximately 0.8 kph. At this slow speed, in the 90 degree configuration, the wheels acted like a plow and pushed a significant amount of dirt. As the mound built up, the pull force increased, but also as the mound grew the point of resisting force application on the tire raised vertically from the contact patch up toward the axle centerline. Therefore vertical distance between force application at the tire/ground area and pull force at the center of gravity decreased, and correspondingly, the force required to produce rollover also increased.

As the side slip tests were performed, soil buildup in front of the wheels and tires was noted during the 60 and 90 degree tests. At 60 degrees, the wheels were free to turn, but the build up of soil was fairly significant and the resulting rotation was very minimal. Of course at 90 degrees, wheel rotation was essentially non-existent. At the 30 degree orientation, wheel rotation was fairly significant with nearly as much rotation as a straight unbraked wheel. In this orientation, weight shift was fairly minimal and the wheels did not dig into the ground significantly. As expected, deceleration force measured at 30 degrees slip angle was significantly reduced as compared to the 60 and 90 degree tests.

The off-road deformable soil test surfaces utilized were all agricultural fields. The black dirt and sandy soil fields were cultivated with a disc harrow prior to testing. This cultivation resulted in a uniform loose soil depth, depending on the field of 0.08 m to 0.13 m. During testing, the vehicle plowed soil to the appropriate depth and did not tend to go deeper than the cultivated depth. The harvested corn field as discussed earlier had bedded rows. This description refers to the method in which it was planted. Prior to planting, the field was disced to a uniform depth. As planting was completed, dirt was mounded up from the sides toward the center of each row. The resulting profile of the field perpendicular to the rows resembled a repeating "W" shaped cross section. Cultivated soil depth at the base of each row was essentially zero, and at the peak of each row was approximately 0.15 m (6 in).

Testing on the asphalt /excess tar surface and on the gravel/sand dirt road was only conducted in the zero degree locked wheels configuration. Average deceleration factor measured on the excess tar surface (0.64g) was significantly lower than that measured on the paved asphalt surface (0.80 g). During testing on the excess tar surface, ambient temperature was approximately 311 K (100 deg F). As this test was conducted, excess tar leeched up from the pavement onto the tires and acted like a lubricant between the tire/road interface.

Conclusions

Based on the testing completed there is a definite variation in the behavior of deceleration factors on non-deformable vs. deformable surfaces. Differences in measured deceleration factors between zero and 90 degree side slip pulls on the harder surfaces tended to be between 10% and 30% higher and up to 45% higher on the deformable surfaces for the 90 degree orientation. This result is reminiscent to that reported by Stonex(10).

Not only was there a fairly pronounced difference in deceleration force between zero and 90 degree orientations, but also in test vehicle setup and location of force application. In testing where pull force was applied at the absolute CG, recorded values were typically at least 20 % higher for 90 degree pulls.

The data indicate the theoretical model is a reasonably good predictor of deceleration factor up to about 60 degrees side slip. In moving above 60 degrees, behavior began to diverge based on the surface under consideration. Results on the coastal grass surface, which was essentially non-deformable, show deceleration results to be biased slightly higher than predicted, but the overall data suggests that a sinusoidal type pattern is followed.

Results on the deformable surfaces of black dirt/foliage, sandy soil, and harvested corn rows agree to a reasonable degree with the theoretical prediction up to about 60 degrees side slip. After that point, however, the data diverges significantly. Graphic plots of the resultant data indicate that an approximate linear relationship is followed between slip angle and deceleration factor.

The overall tendency throughout the testing indicates that location of the force application on the test vehicle directly affects deceleration forces generated. Pulling from the absolute CG location gives the test vehicle a chance to load its suspension in a more realistic manner, and weight transfer results. In the testing completed during series one where the vehicle was pulled from a point or points laterally offset from the CG, pull forces typically did not generate lateral body roll as compared to the second series of tests. In testing conducted on the soft, deformable surfaces, the leading side tires would dig more aggressively when the vehicle was pulled from the CG. This resulted in a higher deceleration factor for each respective surface during the second series of testing.

Deceleration rates derived in the subject testing from the longitudinal locked wheels configuration were generally higher than published values for similar surfaces. Both the dirt and grass surfaces reported a value significantly higher than tabulated values would suggest.

The trends exhibited in the data are relatively consistent, respectively, on both deformable and firm surfaces, however, additional testing would be appropriate for further validation.

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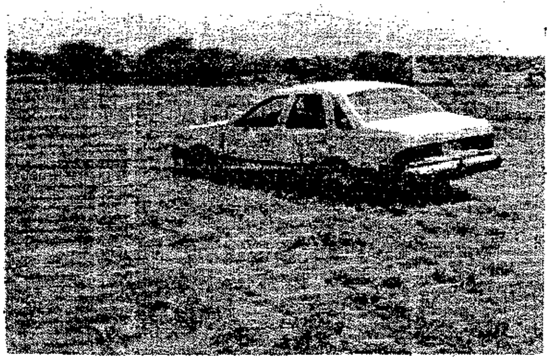
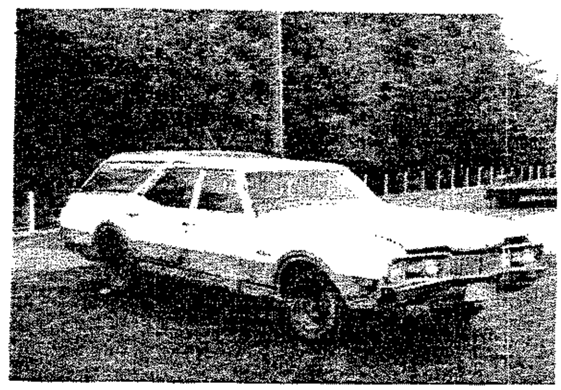
The appendix for this paper, which includes the following eight pages, contains photographs of the test vehicles and te surfaces, graphical plots of test results, and illustrations of test instrumentation and setup.



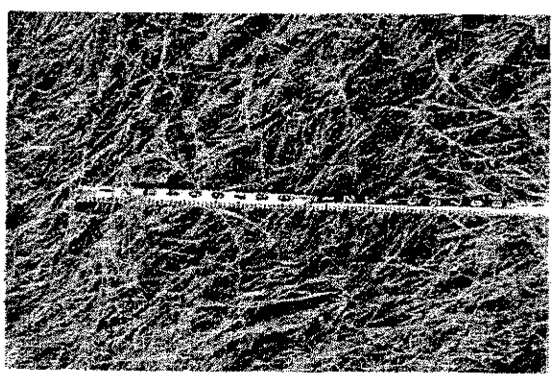
Photograph #1: 1985 Ford Tempo.

Photograph #2: 1988 Oldsmobile Delta 88.

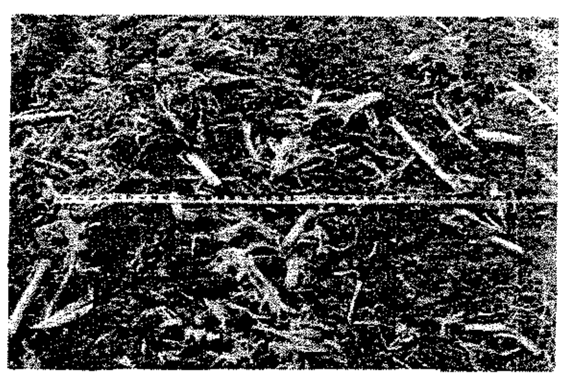
Photograph #3: 1974 Chevrolet Chevelle in Pull Configuration.



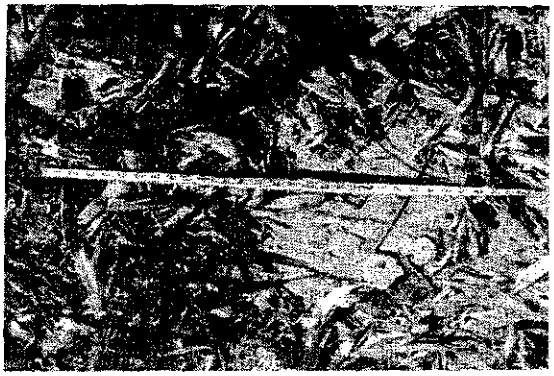
Photograph #4: 1968 Oldsmobile Vista Cruiser.



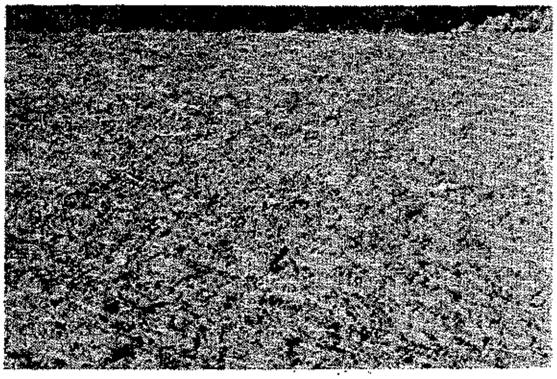
Photograph #5: Dry Coastal Grass.



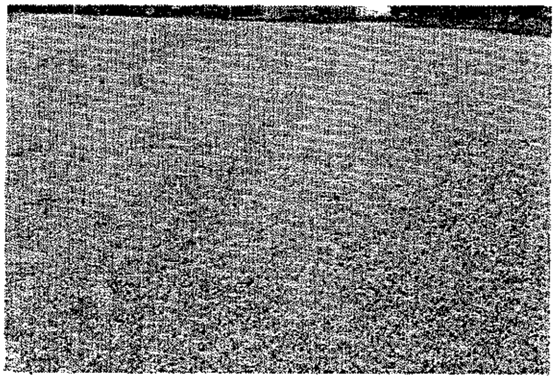
Photograph #6: Loose Black Dirt with Foliage.



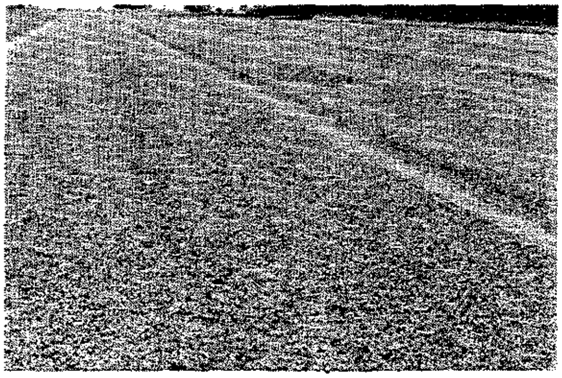
Photograph #7: Unplowed, Harvested, Corn Field.



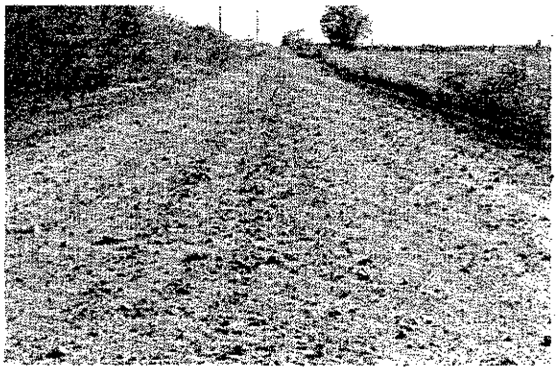
Photograph #8: Sandy Soil.



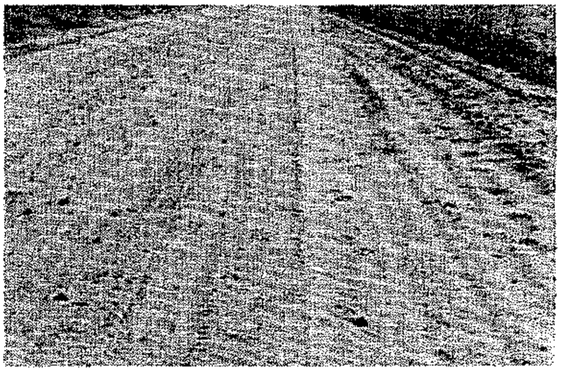
Photograph #9: Asphalt.



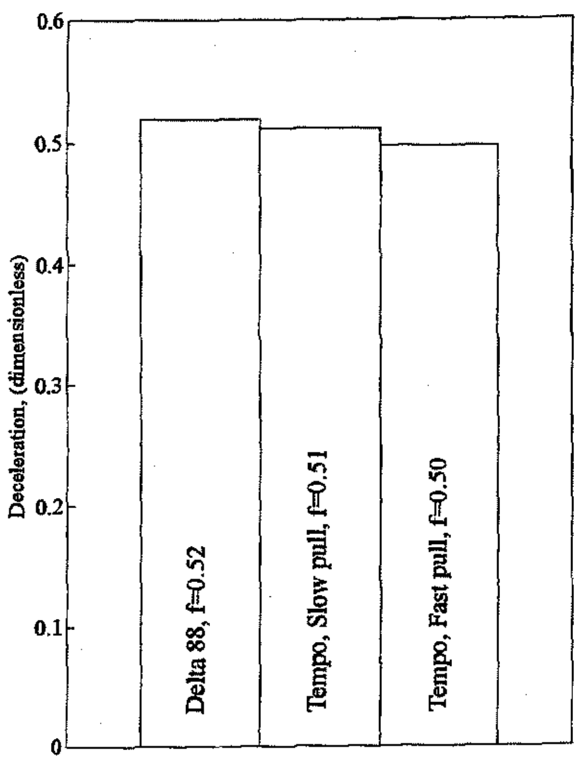
Photograph #10: Asphalt with Excess Tar.



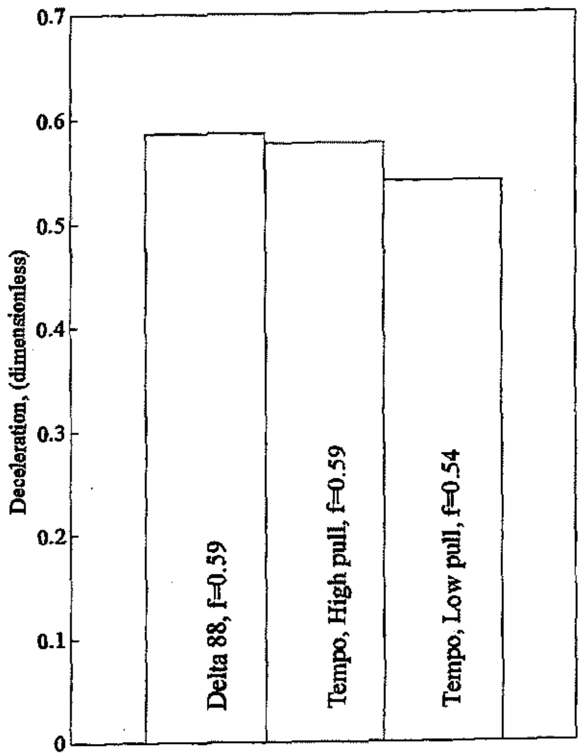
Photograph #11: Gravel/Dirt Road



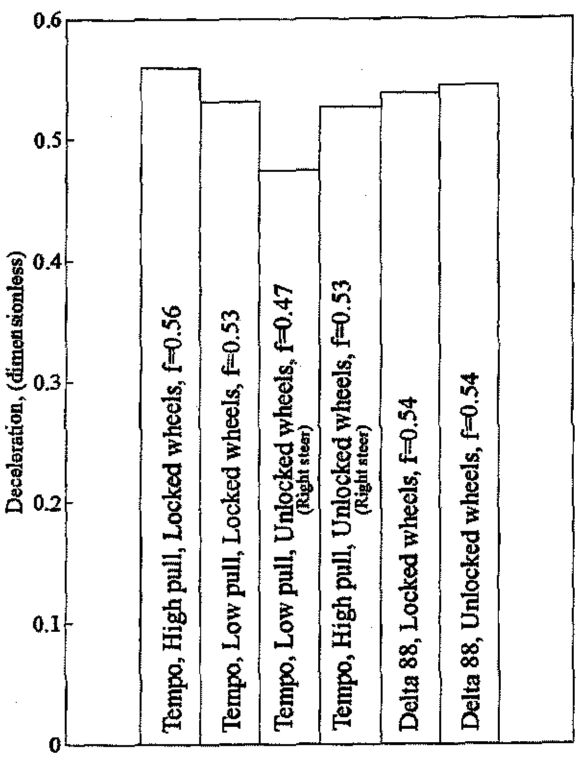
Photograph #12: Sandy Dirt Road



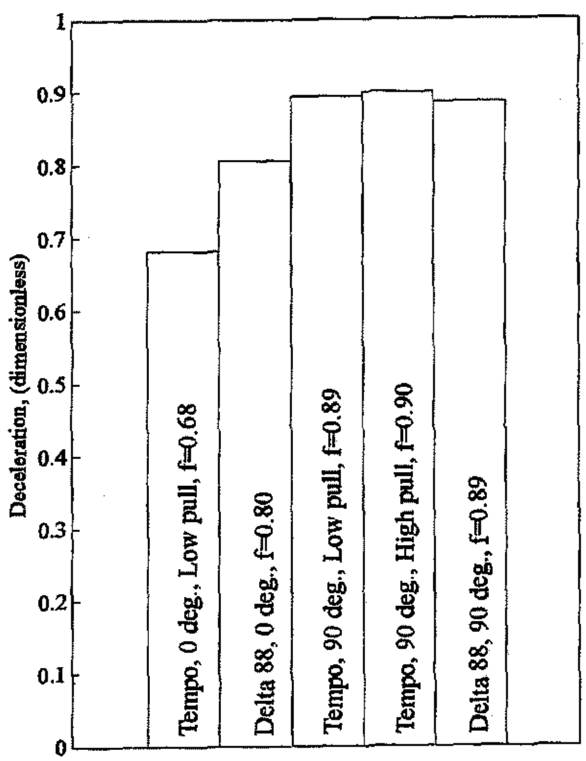
Graph 1: Deceleration rates on coastal grass at a 0 degree slip angle. (series one testing)



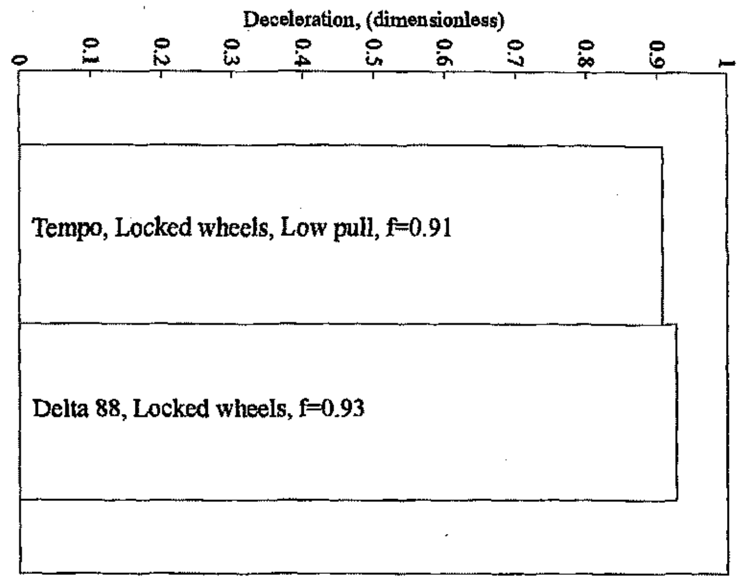
Graph 2: Deceleration rates on coastal grass at a 90 degree slip angle. (series one testing)



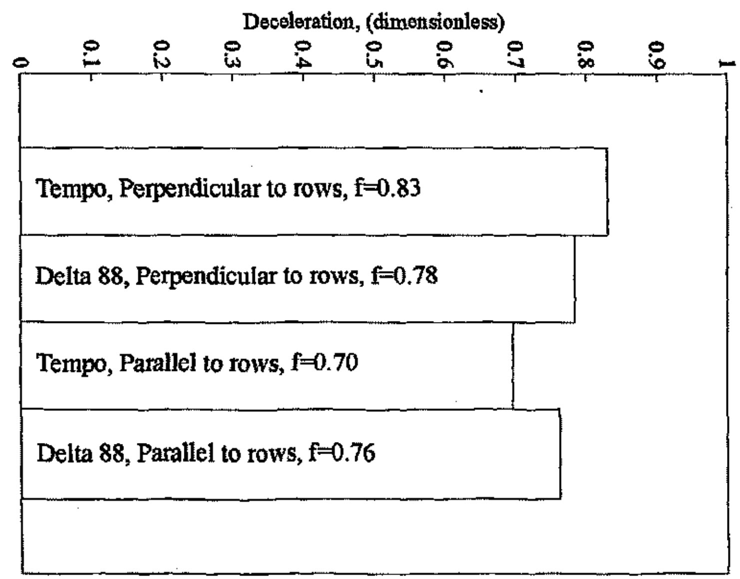
Graph 3: Deceleration rates on coastal grass at a 45 degree slip angle. (series one testing)



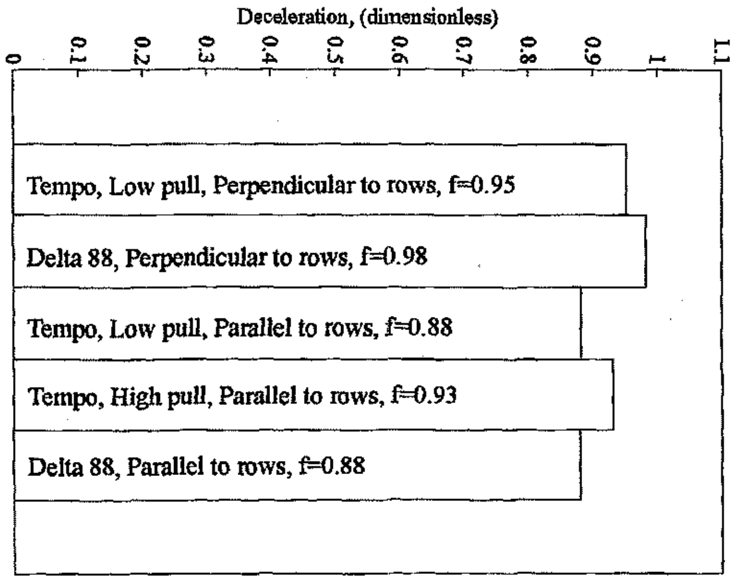
Graph 4: Deceleration rates on black dirt/foliage at 0 and 90 degree slip angles. (series one testing)



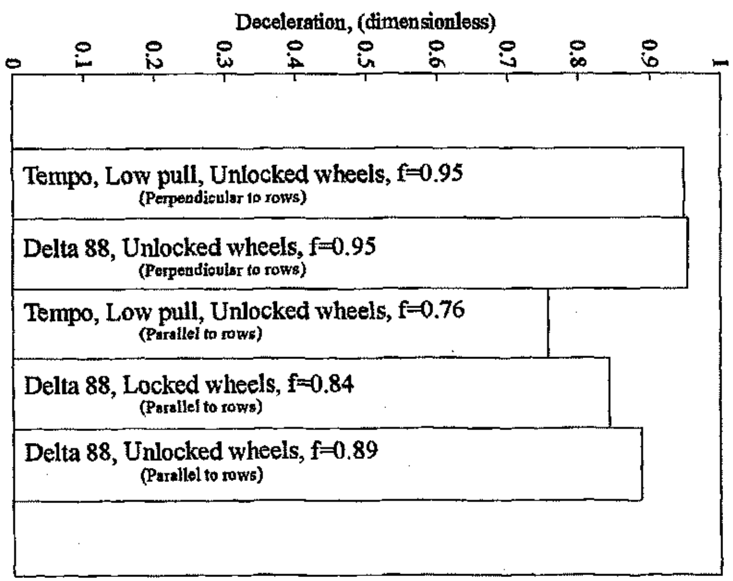
Graph 5: Deceleration rates on black dirt and foliage at a 45 degree slip angle. (series one testing)



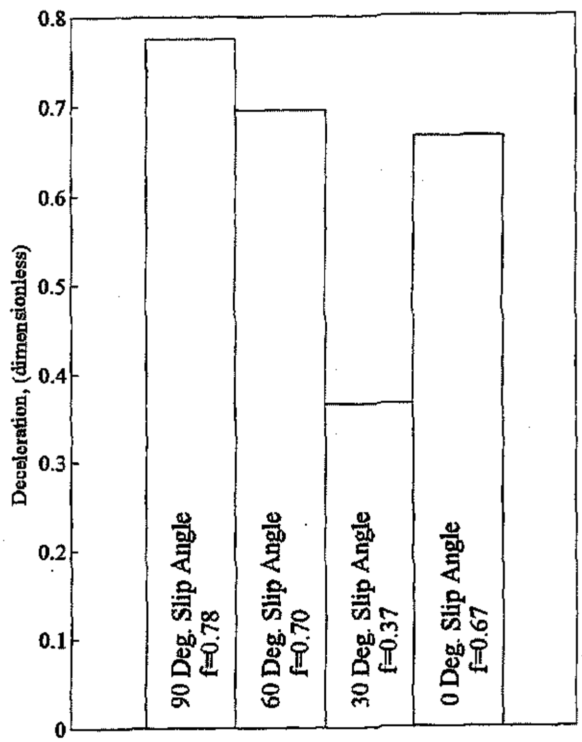
Graph 6: Deceleration rates on harvested corn rows at a 0 degree slip angle. (series one testing)



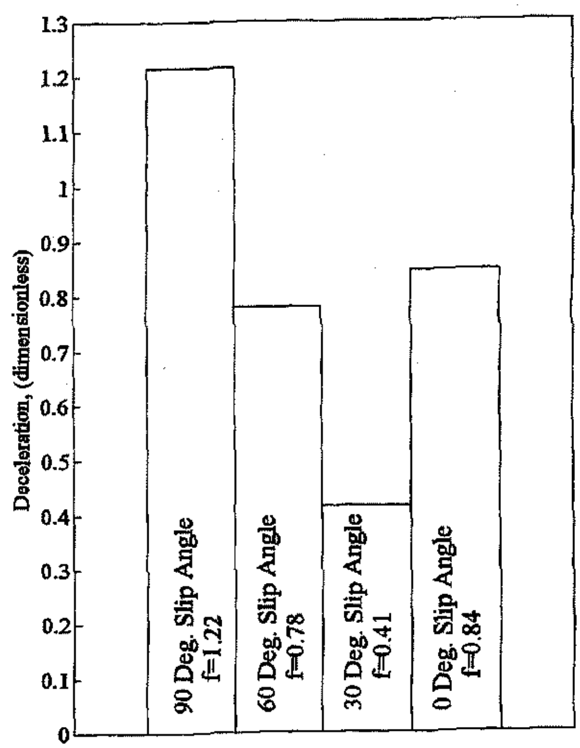
Graph 7: Deceleration rates on harvested corn rows at a 90 degree slip angle. (series one testing)



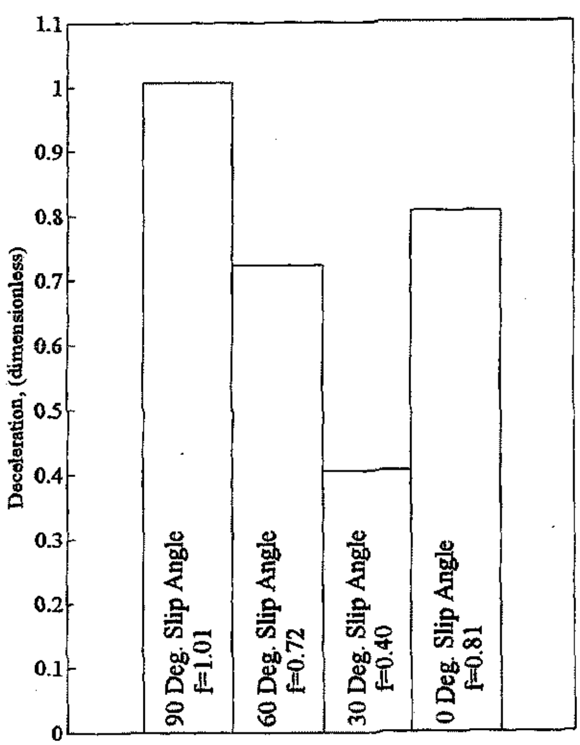
Graph 8: Deceleration rates on harvested corn rows at a 45 degree slip angle. (series one testing)



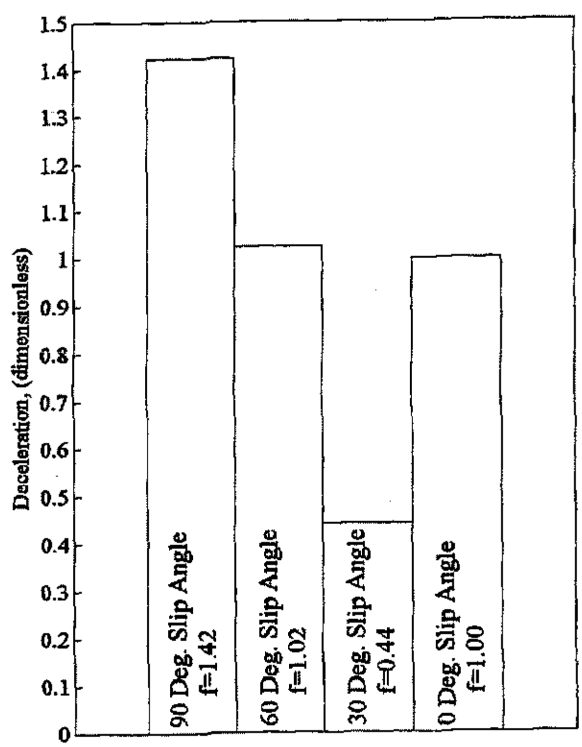
Graph 9: Combined deceleration rates on coastal grass for the Chevelle and Vista Cruiser. (series two testing)



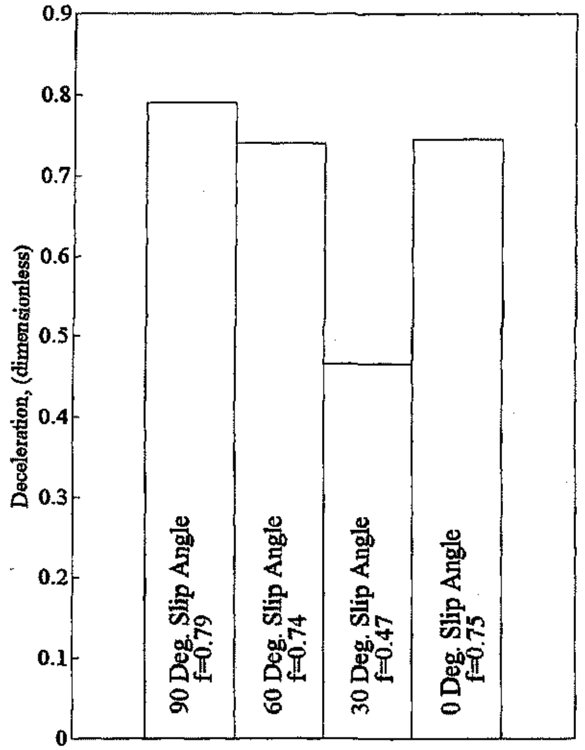
Graph 10: Deceleration rates on black dirt and foliage for the Chevelle. (series two testing)



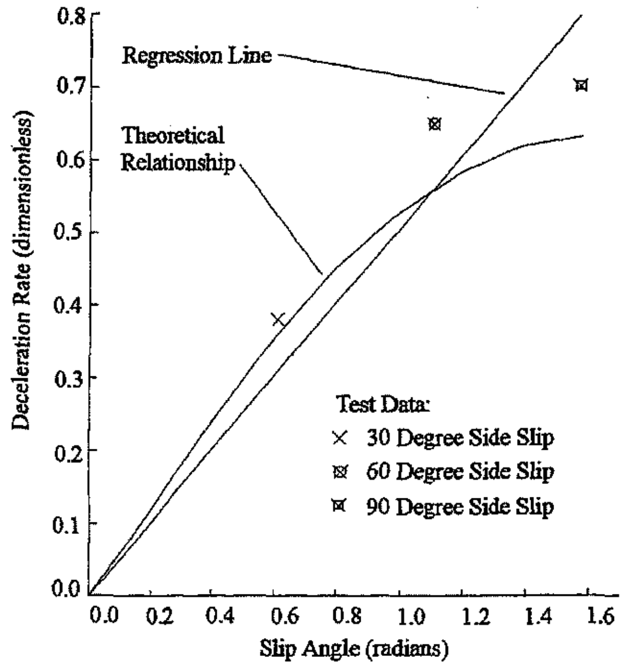
Graph 11: Deceleration rates on bedded corn rows for the Chevelle. (series two testing)



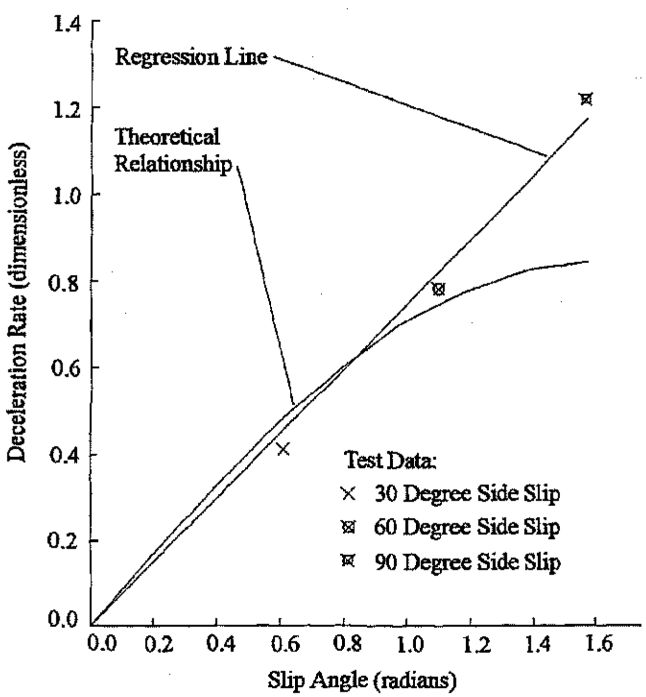
Graph 12: Deceleration rates on sandy soil for the Chevelle. (series two testing)



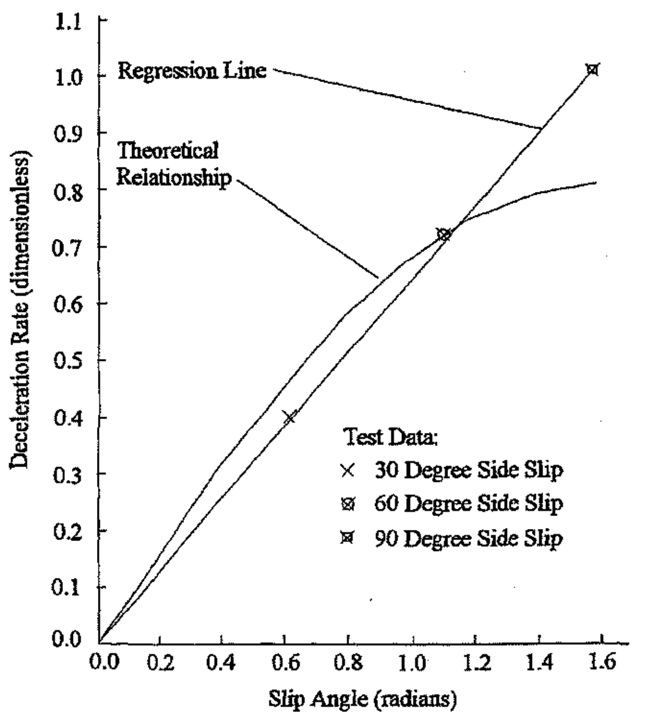
Graph 13: Combined deceleration rates on asphalt for the Chevelle and Vista Cruiser. (series two testing)



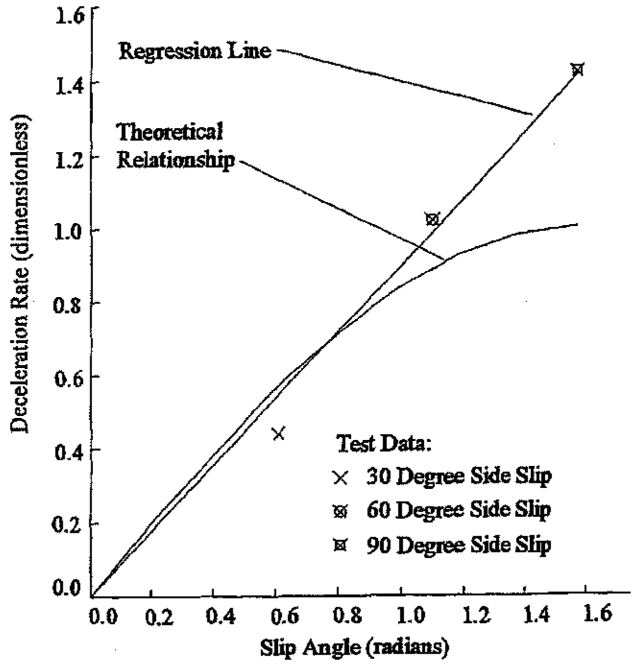
Graph 14: Coastal Grass Surface, Theoretical Relationship and Linear Regression (series two testing).



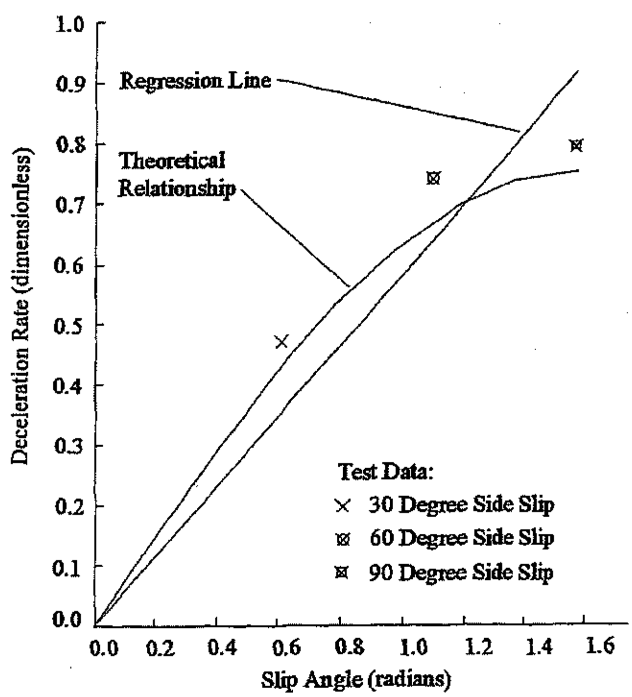
Graph 15: Black Dirt with Foliage Surface Theoretical Relationship and Linear Regression (series two testing).



Graph 16: Corn Rows Surface Theoretical Relationship and Linear Regression (series two testing).



Graph 17: Sandy Soil Surface, Theoretical Relationship and Linear Regression (series two testing).



Graph 18: Paved Asphalt Surface, Theoretical Relationship and Linear Regression (series two testing).

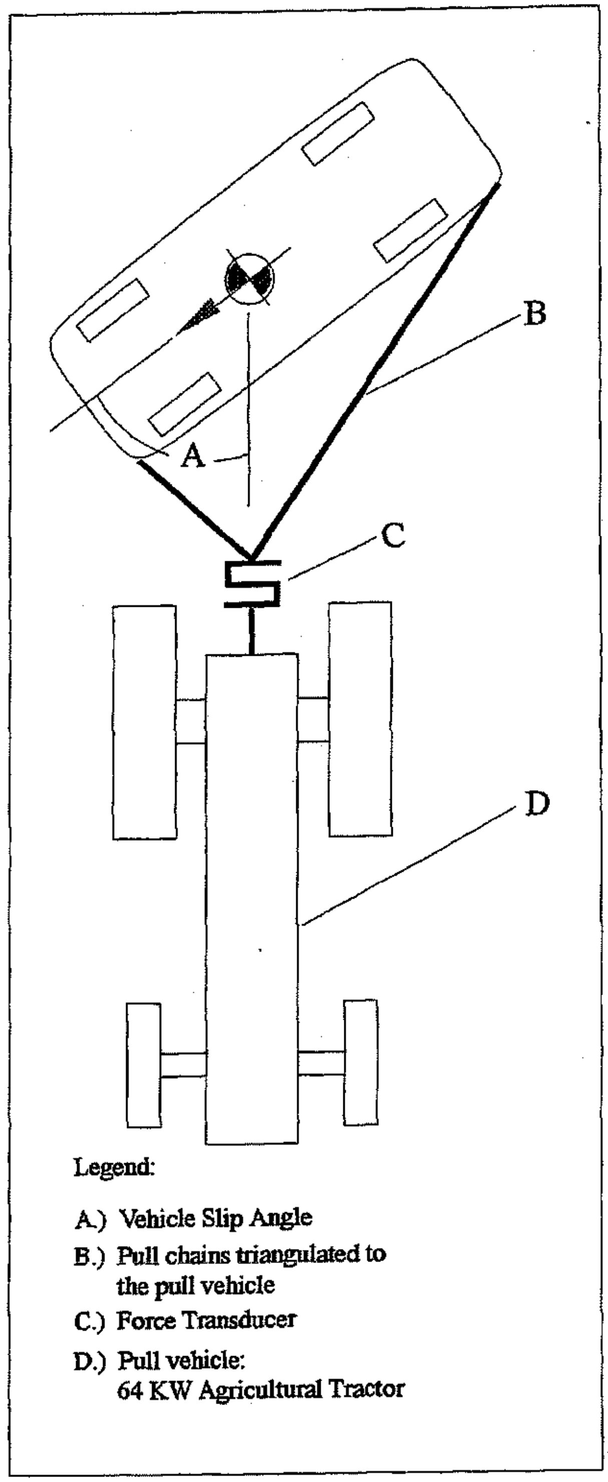
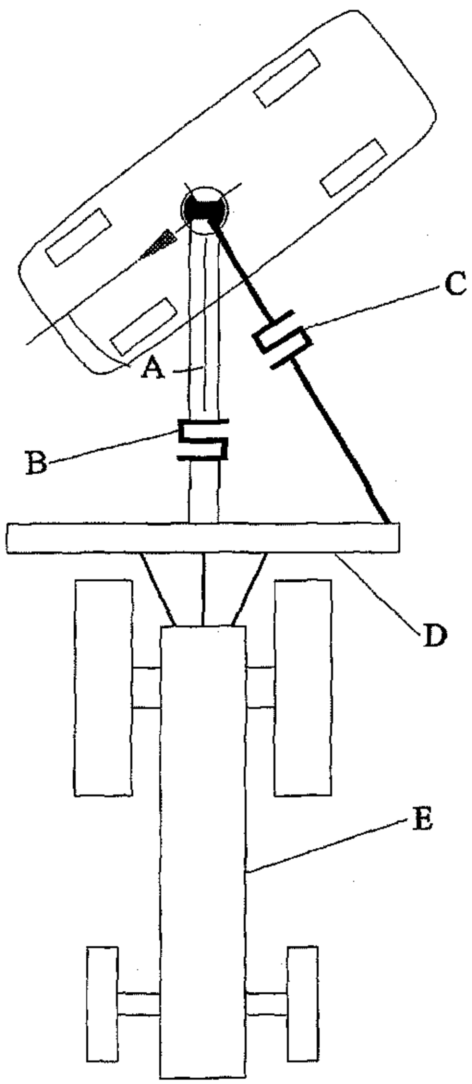


Figure No. 3: Pull configuration setup utilized for the first series of testing.



Legend:

A.) Vehicle Slip Angle

B.) Force Transducer in the main pull link (Deceleration force)

C.) Force Transducer in the cable link to measure lateral force (Centripetal force equivalent)

D.) Tractor attachment bar (Secured to three point hitch)

E.) Pull vehicle: 64 KW Agricultural Tractor

Figure No. 4: Pull configuration setup utilized for the second series of testing.