

**IMPACT CONDITIONS IN SIDE IMPACT COLLISIONS
WITH FIXED ROADSIDE OBJECTS**

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Running Header: Fixed-Object Side Impact Conditions

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Abstract — Designing vehicles and roadside structures that are safer in side impact collisions is an emerging area of concern in roadside safety research. Selecting impact conditions that are relevant to the way side impact collisions occur in real world collisions is an important part of developing effective full-scale crash test procedures and evaluation criteria. If test impact conditions are unrealistically severe, improving the performance of roadside hardware for side impacts may appear unfeasible. If test impact conditions are not demanding enough, good performance in full-scale crash tests may not be indicative of good performance in real-world crashes. The purpose of this paper is to examine the best available accident data to determine what the reasonable worst case test impact conditions are for side impacts with roadside objects.

Keywords = side impact, fixed objects, impact conditions, collisions, accidents.

INTRODUCTION

Providing improved protection to vehicle occupants who are involved in side impact collisions has become a high priority of both government, industry and academic researchers in the past decade. One aspect of the side impact problem concerns side impacts with fixed roadside obstacles such as trees, utility poles, and guardrails. Some of these objects, like trees, occur naturally by the roadside. Other objects, like utility poles, are placed along the roadside though they do not contribute to the roadway function. Still other objects like luminaire supports, guardrails and signs, are placed along side the roadway to serve a specific purpose related to the roadway function. Objects that are placed along the roadside must be evaluated in full-scale vehicle crash tests to determine how effectively the object minimizes the hazards to vehicle occupants who may strike the object (Ross *et al* 1993).

The objective of this paper is to explore typical impact conditions in side impact collisions with fixed roadside objects such as utility poles, guardrail terminals and luminaire supports. This information is needed to determine reasonable worst-case impact scenarios for performing side impact crash tests on roadside safety objects. In the context of this paper, specifying impact conditions involves selection of a vehicle mass, impact velocity, impact angle and impact point. The analysis presented herein was based on U.S. vehicle registration data for 1980, 1983 and 1986; 1983 National Accident Sampling System (NASS) Continuous Sampling System (CSS) data; and the 1983 Fatal Accident Reporting System (FARS) data.

There have been numerous investigations of police-reported side-impact collisions. Fox, Good

and Joubert (1979) examined 879 police-reported pole collisions that occurred during an 8-month period in 1977 in an area around Melbourne, Australia. Mak and Mason (1980) collected in-depth collision information on 1,014 impacts with utility poles in Texas and Kentucky that occurred in a period between 1976 and 1979, 268 of which were side impact collisions with poles. Lestina, Gloyns and Rattenbury (1990) examined police-reported side impact collisions in the United Kingdom in the late 1980's. Hulke (1990) provided a number of anecdotal cases of vehicle-to-vehicle and vehicle-to-fixed object side impacts. Harteman *et al* (1976) examined occupant injury in both fixed-object and vehicle-to-vehicle side impacts in France while Lozzi (1981) performed a similar study in Australia. Most recently Troxel, Carney and Ray (1991) used police-reported accident data in the U.S. to characterize side impact collisions with fixed objects. More detailed descriptions of these earlier studies can be found in original papers or summarized in Troxel, Ray and Carney (1994).

DATA ANALYSIS

Most of the investigations discussed above used information from police accident reports and site visits to assess the severity of side impact collisions. Only the studies by Mak and Mason (1980) and Harteman (1976) attempted to reconstruct the impact velocity in specific side impact collisions. The objective of the present study is to determine typical worst case side impact conditions such that field-relevant side impact crash tests can be specified. Unfortunately, the data from the Mak and Mason study (1980) and from the Harteman study (1976) are each more than two decades old. The only other source of data that includes estimates of the impact velocity are the pre-1986 National Accident Sampling System (NASS) data (NHTSA 1987a).

The NASS is a data collection activity that has been sponsored by the U.S. Department of Transportation's National Highway Traffic Safety Administration since 1978 (NHTSA 1987a). The system is designed to collect data on a sample of collisions of varying severities such that estimates of nationwide collision frequencies can be estimated. Data has been collected by as many as 50 teams dispersed throughout the United States. The sample is collected to account for geographical and collision-severity bias so that, at least ideally, the resulting data provides a relatively unbiased estimate of the highway safety problem.

Prior to 1986 the NASS data included much more information about collisions with roadside objects. The NASS system was redesigned beginning in the 1986 data collection year to collect more information on vehicle to vehicle collisions. Sampling procedures and data collection items were significantly altered in the 1986 data collection year. The types of data collected and the sampling methodology varied from year to year in the 1984 and 1985 data collection years such that the last year with useful data on roadside collisions was 1983. For this reason, this paper deals only with the 1983 NASS data since, even though it is nearly 15 years old, it is the most recent data set with the information required (e.g., speed and angle estimates) to examine side impact conditions. The 1983 NASS data contains 846 fixed-object side-impact cases which, when extrapolated, represent 167,000 reported crashes nationwide.

The Fatal Accident Reporting System (FARS) is another nationwide accident database that is collected by the NHTSA (NHTSA 1987b). The FARS data is obtained from police reports filed in each state so that it represents the population of virtually all fatal roadway collisions. A

procedure similar to that used for the NASS data was used to identify the 1423 fatal single passenger-vehicle side impacts with fixed roadside objects in 1983. There is no attempt in the FARS data to reconstruct impact velocities.

The 1983 FARS data and the 1983 national registration data was used so that all three data sets (e.g., NASS, FARS and registration) could be used together without introducing data shifts caused by the use of different data collection years.

RESULTS

Vehicle Mass

The implications of smaller passenger cars on highway safety in general and roadside appurtenance design in particular have been widely discussed in the past decade. Viner has observed that mid-sized vehicles appear to be over-represented in rollover accidents and Partyka has recently demonstrated that the fatality rate increases with decreasing vehicle weight (Viner 1984; Partyka 1989). The fatality rate for 900-kg passenger cars is 50% greater than the fatality rate for 1800-kg passenger cars. Occupants of smaller cars appear to be at greater risk than larger car occupants in many types of collision scenarios.

This assertion does not hold for the particular case of side-impacts with fixed roadside objects. It is reasonable to assume that small car occupants will be more at risk in collisions that display certain kinds of mass-related properties. Presumably the over-representation of smaller cars in

overturn accidents occurs because smaller vehicles have inertial properties that may make them less stable than larger passenger vehicles. Partyka contends that the fatality rates she observed were dominated by vehicle-to-vehicle and overturn accidents (Partyka 1989). As will be shown below, there does not appear to be any mass-specific characteristic that increases the risk to vehicle occupants in side impact collisions with fixed objects.

If the distribution of vehicle masses in side-impact fixed roadside object collisions as measured in the FARS and NASS data were essentially the same as the population of all registered vehicles, one could conclude that no particular vehicle class is at any higher risk than any other vehicle class. If the distributions are not the same, one would conclude that some vehicles are at higher risk of being involved in a fixed object side-impact collision than others.

The mean vehicle mass from these three databases (registration, NASS and FARS) for the year 1983 are all quite similar as shown in Table 1. The mean weight of registered vehicles was 1395 kg, the mean weight of vehicles in side-impact fixed-object collisions of all severities (i.e., the NASS data) was 1442 kg and the mean for the fatal side-impact fixed-object collisions (i.e., the FARS data) was 1392 kg. The means are all approximately one tenth of a standard deviation apart. Although the mean values are quite similar for the three data sets, information about the means does not necessarily demonstrate that the similarity is statistically significant. The three distributions could have similar means while still having completely different distributions.

The data from the three data bases was sorted into 44 50-kg mass categories and the cumulative

probability density functions for the three distributions shown in Figure 1 were plotted. The registration and NASS data plots are essentially on top of each other. The FARS data diverges from the other two databases at a mass of 1400 kg and attains a maximum difference of 13 % at 1700 kg. This would seem to suggest that if there is a vehicle mass that is over-represented, it is in the mid-size mass range rather than the lighter vehicles. This difference, however, may well be statistically insignificant.

The Kolmogorov-Smirnov goodness-of-fit test statistic (K-S test) (Ang and Tang, 1975) for these three mass distributions is shown in Table 2. The maximum differences between the cumulative distributions were 4% between the registration and NASS data sets, and 13% between the registration and FARS data sets. The K-S test indicates that although these differences are observable they are not statistically significant, the three distributions are essentially identical at the 95% confidence level.

Partyka demonstrated that for fatal accidents of all types the fatality rate increased with decreasing weight (Partyka 1989); the fatality rate for 1000 kg vehicles was 50% greater than the rate observed for 1800-kg vehicles. The fatality rate for side impact collisions with fixed objects was calculated for the 1983 FARS and registration data as the number of fatalities (e.g., FARS data) per passenger car registered (registration data) in each of the 44 50-kg mass categories and is shown in Figure 2. The mean fatality rate for side impact fixed-object collisions was 1.44 fatal collisions per 100,000 vehicles registered in each 50-kg mass range. The fatality rate for side-impact fixed-object collisions was essentially constant for the 1983 FARS and registration data.

Thus, there was no discernible trend for the fatality rate for side-impact fixed-object collisions to increase with decreasing vehicle weight as is found for collisions in general.

A least squares linear regression of the fatality rate data was performed to determine if there was an underlying mass-related dependency. An analysis of the variances for this regression is summarized in Table 3. The slope of the regression line is essentially zero (1.2×10^{-4}) and, as shown in Table 3, the regression provides almost no information about the data. The scatter observed in Figure 2 can be considered essentially random at least with respect to the vehicle weight. Unlike some other types of collisions, the fatality rate for side-impacts with fixed roadside objects is not sensitive to the mass of the vehicle; an occupant of a large full-size passenger car experiences the same risk of fatality as the occupant of a small compact passenger car.

Impact Velocity

The NASS-CSS data contain data items for a variety of crash parameters including vehicle mass, longitudinal, lateral, and total velocity changes as well as the direction of force and the energy absorbed. These quantities are derived based on the results of the CRASH3 computer program which uses measurements of vehicle damage as the primary predictor of velocity change and energy dissipation (Campbell 1974).

Unfortunately, this approach has several flaws that suggest that the results of this analysis should be considered only as a first approximation. First, the CRASH3 program itself has been

frequently criticized for its inability to consistently predict change in velocity values for carefully controlled tests (Ray and Schofield 1987). A number of authors have questioned the accuracy of the CRASH3 velocity change estimates and have suggested that the prediction error may be as great as 35% (Smith and Noga 1982)

CRASH3 was primarily written to be used for vehicle to vehicle collisions. For narrow object collisions the add-on program POLES could be used to obtain velocity change estimates. In many cases, however, velocity estimates are not available because CRASH3 was not run and the appropriate deformation measurements were not made. The 1983 NASS-CSS data contain 846 side-impact single-vehicle single-collisions with fixed roadside objects. CRASH3 data items and derived variables are available for only 37 of the 846 cases (4%). The values reported herein, with the exception of the direction of force variable, are derived from this small subset of the available data base. Although CRASH3 has its faults, the CRASH3 estimates represent the best available accident-data evidence on vehicle impact velocities.

The velocity change values reported in the NASS data can be used as estimates of the impact velocity if it is assumed that the vehicle was brought to rest as a result of the collision. There is a practical upper limit to the lateral velocity a vehicle can attain in a side-impact, vehicles are unlikely to attain lateral velocities of 100 km/hr for example. Another argument that supports the assumption that vehicles are generally brought to rest in side impacts with fixed objects involves the issue of breakaway versus non-breakaway features. In earlier reports it has been shown that the most frequently struck objects are trees, utility poles and other narrow objects (Ray, Troxel

and Carney 1991). While some of these objects like sign supports and delineator posts do breakaway or yield the majority of collisions are with objects that do not breakaway such as trees and utility poles. When the fixed object does not breakaway the vehicle must come to rest. The assumption that the changes in lateral velocity can be used to represent lateral impact velocities is a reasonable first-order assumption for the majority of tree and utility pole collisions.

The absolute values of the changes in lateral, longitudinal and total velocity were obtained for the 37 cases and are reported in Table 4. The mean lateral velocity change was found to be 10 km/h and more than 90% of the cases had lateral velocity changes of less than 45 km/h. In all the cases the lateral velocity was less than 65 km/hr. The mean longitudinal velocity was found to be 6 km/h with approximately 95% of the values being less than 25 km/h. The frequency distributions for the lateral and longitudinal changes in velocity are shown in Figure 3.

Table 5 illustrates the increasing severity of injury with increasing total velocity change. The data in Table 5 represent only impacts that occurred centered on the passenger compartment. Half of all minor injuries occurred in collisions where the total change in velocity was less than 30 km/h. In contrast 62% of the severe and fatal injuries occurred in collisions where the total change in velocity was greater than 60 km/h. Increased energy dissipation appears to be related to the increased severity of injury experienced by the vehicle occupants in side-impact fixed-object collisions.

Injury can be defined as exposure to energy; more energy should be correlated with a higher

proportion of severe injuries. The values obtained for these 37 collision cases imply that even though the velocities associated with this type of collision are relatively small and involve relatively modest amounts of energy dissipation, the proportion of severe and moderately injured occupants increases as the total change in velocity increases in side-impacts with fixed-roadside objects.

The observed and hypothesized cumulative distributions for the lateral and longitudinal change in velocity are shown in Figure 3 and the central statistics are shown in Table 6. The shapes of the observed distributions suggest that the change in longitudinal and lateral velocities follow an exponential distribution. Two goodness-of-fit tests were performed on these data sets to determine how well the hypothesized distributions model the observed data. The Chi squared and Kolmogorov-Smirnov test statistics are summarized in Table 7. Based on these statistical tests, the lateral velocity change data is best modeled by a shifted exponential distribution with an x intercept of 1.1 km/h and a mean of 18.1 km/h. This curve is shown in Figure 3 as a dashed line. As is visually apparent, the curve fits the middle range of values quite well and fits poorly for the extreme values. One possible explanation for the poor fit for low changes in velocities is that these collisions may not be reported to the police as frequently and therefore are not included in the NASS data. Collisions that do not result in injury or serious vehicle damage are often not reported and such collisions may be characterized by a low change in velocity. The distribution with the best goodness-of-fit statistics indicates that the minimum change in lateral velocity is 1.1 km/h. The longitudinal change in velocity also appears to follow an exponential distribution with an x -intercept of 0.4 km/hr and a mean of 11 km/h.

An examination of the velocities also indicates that lateral and longitudinal velocities are negatively correlated. Large lateral velocities are generally associated with relatively small longitudinal velocities and vice versa. This is intuitively reasonable since all the velocity begins as longitudinal velocity when the vehicle is traveling normally down the road. As the vehicle spins, longitudinal velocity is transformed into lateral velocity. The practical worst case scenario would be represented by sliding sideways with no forward velocity component. The 90th percentile lateral velocity based on the observed 1983 NASS data is approximately 50 km/h. A lateral velocity of 50 km/h with no longitudinal velocity (e.g., sliding fully broadside) represents a practical worst case impact condition for side-impacts with fixed-objects.

Energy Dissipation

Objects placed along the roadside generally are required to meet some minimum safety criteria. Many devices like light poles and sign supports are required to breakaway or yield when struck by an errant vehicle. Fundamental to the proper design of these breakaway devices is knowledge about the energy dissipation characteristics of the vehicle and pole or sign. Obtaining a design value for energy dissipation is not straightforward, however, since it is not possible to measure energy directly. In this paper the CRASH3 estimates of velocity change will be used to simulate the energy dissipation distribution. Once this distribution is known an appropriate design value can then be selected.

Figure 4 shows the energy dissipation estimated by CRASH3 as well as a curve-fitted distribution for the energy dissipation. Both longitudinal and lateral changes in velocity were found to be

exponential distributions in the previous section so it is not surprising that energy dissipation is also distributed exponentially. Based on Figure 4, the 90th percentile energy dissipation for side-impacts with fixed-objects is approximately 100 kN-m. Full-scale crash tests of small passenger cars (e.g., 1979 Volkswagen Rabbits) impacting rigid instrumented poles at 40 km/hr have indicated that a little over 100 kN-m of energy is dissipated by the vehicle and the maximum dynamic crush is approximately 740 mm. This level of passenger compartment intrusion is not acceptable. Often obtaining breakaway performance at low energy levels is more challenging than at higher energy levels. The 10th percentile energy in Figure 4 is only 10 kN-m. The empirical distribution and the CRASH3 estimates are virtually identical yielding greater than 99% confidence for both the χ^2 and K-S tests.

Impact Angle

Side impact collisions have been shown in earlier reports to be associated primarily with narrow fixed objects such as utility poles and luminaire supports (Ray, Troxel and Carney 1991). In an impact with a narrow object, the yaw angle (the angle between the longitudinal direction of the vehicle and the direction of the velocity vector) is the only angle that must be specified. The impact angle is more conventionally defined as the angle between the longitudinal axis of a device and the approach path of the vehicle. Since a narrow object has no longitudinal axis the impact angle is ambiguous. There is no direct measure of the yaw angle given in the NASS data but an estimate of this quantity can be made using the direction of force (DOF) variable and the longitudinal and lateral change in velocity values.

The DOF is an estimate by the on-site NASS data collector of the orientation of the resultant force during the collision given to the nearest 30 degrees. The DOF was available for 61% of the cases so much more confidence can be placed in these estimates of the yaw angle than in estimates derived from the velocity values. A DOF of zero indicates that the force interaction was parallel with the center line of the vehicle whereas a DOF of 90 would indicate a force perpendicular to the center line of the vehicle. Figure 5 shows the distribution of the DOF for the 846 cases in the study sample. The mean DOF was found to be 56 degrees and the median value was 60 degrees. The most frequently observed DOF (e.g., the mode) was 90 degrees, a full broadside collision. Figure 5 also shows that the vehicle was moving forward in more than 80% of the impacts (e.g., the DOF was between zero and 90). Angles between 45 and 105 degrees account for almost 50 % of the DOF angles in the estimates.

Another estimate of the yaw angle can be obtained by calculating the arctangent of the longitudinal and lateral change in velocity estimated by the CRASH3 program. These estimates are very approximate because of the uncertainties in the two velocity values but the mean yaw angle was found to be 57 degrees with a standard deviation of 19 degrees. Both estimates of the yaw angle indicate that the mean yaw angle in side-impacts with fixed roadside objects is almost 60 degrees. While an impact angle of 60 degrees would be the most common orientation a reasonable practical worst case impact angle for performing full-scale tests would be 90 degrees.

Impact Point

One of the CRASH3 data items is the distance from the vehicle center of gravity to the centroid

of the damaged area. If this dimension is normalized by dividing by the wheelbase a non-dimensional measure of the impact location is obtained. Figure 6 shows the distribution of impact locations obtained in this manner. The most frequently struck portion of the vehicle is at zero on the non-dimensional scale, generally just behind the front seat near the B pillar in a typical passenger sedan. The second most frequently struck region is at 0.1, just in front of the center of gravity, an area near the A pillar. From this data it appears that nearly 60% of the fixed-object side-impacts occur between the A and B pillars. Impacts that occur between the A and B pillars will be very close to a front seat occupant. Earlier full-scale tests have used an impact point centered on the front seat occupant (Ray and Carney 1993; Hinch and Stout 1988).

The NASS data are based ultimately on police reported collisions since these serve as the initial stratification for the investigation teams. A collision is more likely to be reported if (1) there is an injury or (2) extensive damage to the vehicle occurs that requires the vehicle to be towed away. In light of this it is interesting to note that the region near the occupant and front wheel (impacts near 0.0 and 0.5) are the most common impact locations in the data base. Impacts occurring near 0.0 often cause injuries and impacts occurring near 0.5 often cause serious damage to the vehicle steering and suspension. The worst-case impact point would be a location centered on the occupant as indicated in Figure 6.

CONCLUSIONS

The forgoing sections have investigated typical passenger impact conditions in fixed-object side impact accidents based on the 1983 registration, NASS and FARS data. This examination of

impact conditions can be used to select meaningful field-relevant side impact test conditions for full-scale side impact crash tests of roadside safety hardware. Defining impact conditions for a test involve specifying (1) the vehicle mass, (2) the vehicle impact velocity, (3) the vehicle orientation, and (4) the impact point. The vehicle mass did not appear to be a good predictor of the risk to occupants in side impacts with fixed roadside objects. A test vehicle of any mass would, therefore, be as relevant to the real-world collision population as any other. A practical worst-case vehicle mass is probably represented by a small passenger vehicle like the 820-kg vehicle used in other full-scale crash tests. While the statistical risk to occupants is no different in small passenger vehicle than large passenger vehicles, smaller vehicles will minimize the amount of energy available for activating a yielding, slipping or fracturing roadside hardware device. For this reason the small 820-kg passenger car is consistent with identifying the worst-case vehicle mass.

Traditionally the roadside safety research community has used practical worst-case test conditions in full-scale crash testing. In keeping with this philosophy, a practical worst-case lateral impact velocity of 50 km/hr would represent the 90th percentile speed of fixed-object side impacts. Specifying a full-broadside collision with no longitudinal component would also make this impact a worst-case scenario since high lateral velocities seem to preclude high longitudinal velocities.

The mean orientation was found to be approximately 60 degrees using two different methods of analyzing the accident data. While an orientation angle of 60 degrees is the average of orientations found in the accident data the single most common impact orientation was a full-

broadside collision (e.g., 90 degrees). An impact orientation of 90 degrees would be in keeping with the practical worst-case philosophy of most roadside hardware testing.

The impact point is the last parameter needed to specify impact conditions. The accident data indicate that the most probable location in police-reported fixed-object side impact collisions is between the A and B pillars, the area next to the front seat occupant space. The most hazardous location for the impact to occur is when impacts are centered on the occupant since this places the occupant at great risk of injury. An impact point centered on the occupant and positioned on the front door is suggested as a reasonable worst-case impact location for fixed-object side impact collisions.

A full-scale side impact crash test of roadside safety features that involves the standard NCHRP Report 350 820-kg vehicle striking the device centered on the front-seat occupant at a velocity of 50 km/hr and an orientation of 90 degrees will provide a meaningful field-relevant crash test. Roadside hardware designed for these demanding impact conditions will provide an enhanced level of safety to vehicle occupants of fixed-object side impact collisions.

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Table 1: Summary Statistics for 1983

Data Source	Mean (kg)	Standard Deviation (kg)	Coefficient of Variation
	μ_{mass}	σ_{mass}	\ddot{a}_{mass}
Registration Data	1395	382	3.65
NASS Data	1442	346	4.17
FARS Data	1392	326	4.26

Table 2: K-S Goodness-of-Fit Test for Vehicle Mass - 1983

Data Sets	$(D_{44})^{\text{observed}}$	$D_{44,0.05}^{\text{critical}}$
Registration - NASS	0.0438	0.20
Registration - FARS	0.1324	0.20

Table 3: Analysis of Variance for Fatality Rate in Side-
Impacts Fixed-Object Accidents in 1983.

Source	Degrees of freedom	SSQ	MSSQ	F
Regression	1	0.2097	0.2097	0.2197
Residual	42	40.08	0.9542	
TOTAL	43	40.28		

Table 4: Change in Velocity Statistics for 37 Side Impact Collisions with Fixed Objects from the 1983 NASS data.

Variable	Mean (km/h)	Standard Deviation (km/h)	Coefficient of Variation
Lateral	10	9	0.86
Longitudinal	6	4	0.69
TOTAL	13	9	0.68

Table 5: Injury as a Function of Total Change in Velocity for Impacts Occurring Centered on the Passenger Compartment for 37 Side Impact Collisions with Fixed Objects in the 1983 NASS data

\ddot{V}_{total} (km/h)	Minor $0 \leq AIS < 2$	Moderate $2 \leq AIS < 3$	Severe $AIS \geq 4$	Unknown
0-30	50.0	23.8	12.5	50.0
30-60	36.5	33.3	25.0	50.0
60-100	13.5	23.8	37.5	0.0
100 >	0.0	19.1	25.0	0.0
TOTAL	100.0	100.0	100.0	100.0

Table 6: Change in Velocity Statistics for 37 Side Impact
Fixed Object Colisions from the 1985 NASS Data

	Observations	Mean (km/h)	Std. Dev. (km/h)	Coefficient of Variation
	N	μ_v	σ_v	\ddot{a}_v
Lateral Velocity	285	18	12	0.7080
Longitudinal Velocity	285	11	10	0.8824
Total Velocity	285	23	14	0.6170

Table 7: Goodness-of-fit Statistics for Velocity Change Distributions

	$(\mathbf{X}_{37}^2)^{\text{observed}}$	$(\mathbf{X}_{37,0.95}^2)^{\text{critical}}$	$(\mathbf{D}_{37})^{\text{observed}}$	$(\mathbf{D}_{37,0.05})^{\text{critical}}$
Lateral Velocity	26.9	52.2	0.09	0.22
Longitudinal Velocity	16.1	52.2	0.03	0.22