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A Scientific Approach to Tractor-Trailer Side Underride Analysis

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ABSTRACT

Crashes between passenger vehicles and large tractor trailer vehicles often result in serious injuries and death. There have been few studies of this class of crash involving the side of the large tractor trailers and the passenger vehicles. Studies have shown that side underrides are underreported in crash records. A literature search has shown that there are no generally accepted methodologies to document and scientifically reconstruct a side underride accident. Some of the problems existed because there was a general lack of information on the side underride crash. Rear underride crashes were being studied which yielded helpful information. This led the authors to study a series of trailer side underride crashes that were performed to determine if there were sufficient relationships between passenger vehicle body and roof styles and the side of large highway trailers to allow the development of a general formula for underride impact speed analysis of a vehicle where the roof and roof support structure of the vehicle was damaged. These tests provided valuable insight into the relationships between passenger vehicle roof structures and the sides of large box trailers.

INTRODUCTION

For the period of 1988 through 1993 a study by Braver notes that FARS reported an average annual value of 3033 crashes between trucks and cars which was fatal to one or more occupants of the passenger car. Studies done in the 1970s reported that 80% of fatal truck-car crashes in the U.S. involved underrides. An analysis of a sample of NASS/CDS data indicates that 27% of the fatal truck-car crashes reported involved underrides (Ref 1). It is the experience of the authors that side underride crashes are much more common than reported. The apparent reason for the under reporting is the lack of adequate identification and coding of the accident as an underride incident in the data collection system. It was reported that some enhancements have been made in recent years, but the quality of the police reporting system (Ref 1) still needs improvement.

The side underride, like its cousin the rear underride, has multiple causes; from driver error and impairment through highway geometry to the visibility and conspicuity of the tractor-trailer. This paper is concerned with the methodology to evaluate and reconstruct the underride crash once it has occurred. In reconstructing the crash, the analyst must evaluate the events and conditions leading up to the crash and the dynamics during and following the crash.

ANALYSIS BACKGROUND

NHTSA, in evaluating the design and need for a rear underride guard, conducted a series of crash tests involving cars and the rear of large tractor-trailers. The authors are not aware of any studies of underride crashes into the side of large trailers. Reconstructionists have used the methods and procedures (momentum, experience, etc.) developed for frontal car crashes to evaluate side underride crashes involving large trailers or similar vehicles. The Midwest Institute of Safety maintains a database containing a series of controlled crash tests involving passenger cars and tractor-trailers, typically found on the highways. The authors, having witnessed and studied these crashes, have concluded the majority of the reconstruction work tends to overestimate the speed of an underriding vehicle by using frontal crash methods. This is especially evident when the vehicle goes completely under the trailer and exits the other side with some amount of residual speed. In the crash tests performed some test vehicles completely passed under the trailers at speeds in the upper twenties. It is predicted that few sedan and hardtop passenger vehicles can experience a collision speed above 35 mph involving only the car roof structure and not pass completely under a box trailer. Vans, some pickups and full size station wagons generally will not pass completely under a box trailer below 40 mph. Sufficient tests on these types of vehicles have not been performed to establish an upper limit where they experience a complete underride.

One method of estimation of the vehicle's impact speed can be an Evidence-Based-Estimation (EBE) or empirically based equations similar to that done by Campbell (Ref 3). The following analysis is based on the EBE method. It takes into account the energy that is being absorbed in plastic deformation of the roof structure as well as the energy absorbed in sliding along the trailer undercarriage, etc. The answer can be combined with pre-crash (skidding/sliding) and post-crash (exit) speeds of the vehicle to determine the approach speed of the underriding vehicle.

UNDERRIDE CRASH TESTING STUDY

TEST PROCEDURE

Crash tests maintained by the Midwest Institute of Safety (MITS) (Ref 6) were used to develop an equation that provides an estimate of the speed of impact of the underriding vehicle. The database contains the original 32 underride tests with a test speed range from 7 to 37 mph from which the equation was developed as well as subsequent tests. These subsequent tests have confirmed the validity of the developed equation for passenger cars and expanded its applicability to other light vehicles. The collected data provided necessary evidence and typically includes the following:

1. Vehicle identification data such as the year, make, model and VIN
2. Actual weights at the test site
3. Test speeds
4. Collision angle
5. Damage percentage (which is a ratio of the roof post-crash area divided by the roof pre-crash area)
6. Photographs and video tape

The impact angles and number of vehicles tested at a particular angle in the testing were:

Style	45º	60º	65º	90º
2 door	5	4	3	8
4 door*	7	1	1	3

* includes station wagon configuration

The cars were in neutral, the engine not running and at a normal driving attitude. Steering was tied off to ensure the vehicles would track into the selected crash point. A push vehicle was used to accelerate the vehicles into the side underride crash with the trailer. The test trailers were box trailers attached to tractors weighing greater than 18,000 pounds.

Speeds of the push vehicle were determined by a VC 2000, police radar units and the push vehicles speedometer. The speed measurements from the three sources were compared and confirmed the speed at the point the push vehicle had to brake and release the underriding vehicle. The track was slightly downhill so there was little change in speed between the point of coasting and the point of impact.

TEST RESULTS

The authors found several factors which effect the calculation of the impact speed of the underriding vehicle. The attributing factors are:

1. Angle of the impact
2. Crush pattern of the roof
3. Crush area of the roof
4. Deformation to the vehicle pillars and frame
5. Lateral tire marks from the underriding vehicle or possibly the trailer interaction between the underriding vehicle with any trailer components (dollies, slider frames rear wheels spare tire cages, etc.)
6. Post crash movement caused by the tractor-trailer if it was moving at the time of impact.
7. Exit speeds or stopping distance from the off side of the trailer in the event of a complete underride.

During calculations these factors should be studied and identified for correctly computing the impact speed. A discussion of each is included below.

ANGLE OF IMPACT

The impact angle employs a vehicle fixed coordinate system. The x-axis of the coordinate system is fixed to the impact side of the trailer. The y-axis is the leading side of the underriding vehicle. The impact angle is the angle formed between the impact side of the trailer and the leading side of the underriding vehicle when the vehicle is pointed in the same direction it is traveling (see figure 1). This angle will be 90° or less.

The contact angle between the underriding vehicle and the tractor-trailer affects the pattern of damage and how the energy is dissipated during the collision. If the angle of impact is relatively shallow the vehicle will be in contact with the trailer over a longer distance. This will expose the underriding vehicle to a greater opportunity to contact underbelly structures such as the dollies, the spare tire and/or hangers, toolboxes or tractor or trailer tires.

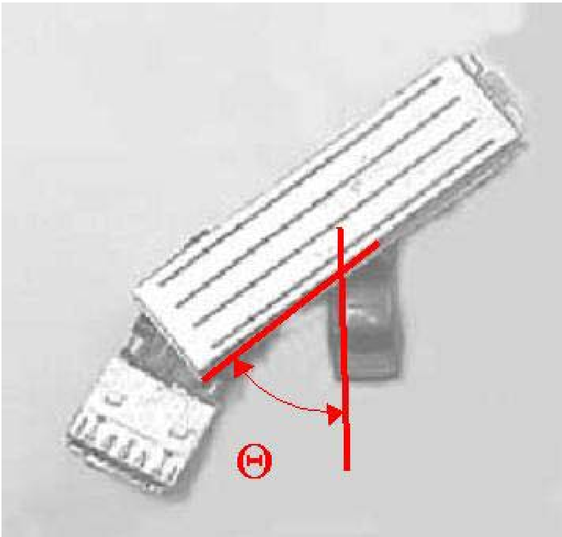

Figure 1. Contact Angle

Depending on the angle of impact there may be a greater likelihood the underriding vehicle will rotate. At some shallow angle there may be redirection instead of underride entrapment, or the vehicle will contact the tractor or trailer tires and spin off.

CRUSH PATTERN

In a side underride the vehicle roof panel and support structures experience two primary types of crush patterns. The first and most common is the rearward crush where the roof rail and panel separate from the pillars. The 'A' pillars deform rearward and downward. Then as the upper 'A' pillar deforms the leading edge of the roof panel 'catches' on the edge of the trailer frame. The 'A' pillars tear from the roof panel at the roof rail and the roof panel crushes or folds rearward and is then flattened depending upon the extent of the underride.

The second type of crush pattern is called wedging. In wedging the leading edge of the roof panel does not 'catch' on the edge of the trailer, rather it travels just below the trailer bed frame. This does not typically tear the roof panel from the pillars rather the roof panel and pillars are compressed as the roof forms a wedge between the trailer underbelly and the underriding vehicle. Depending upon the weight of the trailer and the vehicle speed, the vehicle may raise the trailer during the wedging.

CRUSH AREA

Measuring the roof crush of the vehicle develops a profile showing the deformation. The profile will establish the angle and area of the roof crush, and if the side or rear pillars have shifted. The roof panel typically suffers significant deformation. Because of this, the method that has proven most reliable to establish the roof crush is to measure the remaining undeformed roof panel and pillar locations, then obtain an exemplar for comparison. The measurement should be made from an undeformed location. For example, measure from the rear bumper if the rear pillars have shifted or from the rear edge and corners of the roof if the pillars at that location have not shifted. The profile may be as complex as the damage dictates; however, typically there is a straight line at the edge of the crush created by the flat edge of the trailer. Therefore, the crush profile may be only a left side and right side measurement of the remaining undamaged roof panel. Often the angle of the roof crush reflects the relative angle of impact between the two vehicles; however, this is not always the case, especially when there is rotation of the underriding vehicle.

In some instances there may be displacement of the pillars following the direction of the thrust, 'match boxing', or of the entire remaining roof structure caused by 'bend down'. 'Match boxing' is the condition where the lateral forces that are transmitted through the roof rails, headers and pillars deform the off side pillars outward and the on side pillars inward, usually at the belt line. 'Bend down' is the condition where the longitudinal forces are transmitted through the roof rails and pillars. The roof is collapsed rearward to one of the pillars, then the moment arm produced by that pillar to the rocker panel causes the vehicle structure to bend at the rocker panel rather than continuing to crush the roof structure. The profile formed by measuring the undamaged remains of the roof panel will not include any movement of the pillars.

Figure 2. 'Bend Down' Condition

The pillar lateral shift should be noted and when there is a range of speed established, significant pillar shift may indicate the speed is at the higher end of the range.

Where 'bend down' has occurred reasonable speed calculations have been obtained by including the amount of rearward pillar shift, measured at the roof rail, as additional crush on the Damage Index. This is done because the bend down reflects energy to deform the vehicle during the underride process and is not accounted for in any other manner. There may be underrides where the vehicle experiences a complete or partial underride and 'bend down' occurs as well as other collateral damage such as pillars pulling away from adjacent structure and the roof deforming rearward and downward crushing the rear structure of the vehicle. In these instances it should be realized that speed calculations underestimate the crash speed.

LATERAL TIRE MARKS

Either vehicle can produce lateral tire marks during an underride. These should be documented to establish the distance of the trailer or underriding vehicle movement and the surface type and condition. Typically a trailer will not move laterally unless the coefficient of friction is lower than dry pavement. When the trailer does move laterally the impact will generally be toward the rear of the trailer. This should produce visible trailer tire scuffs on pavement or furrows on softer surface areas. The underriding vehicle will increase in tendency to experience lateral movement with rotation as the impact angle decreases. The related vehicle rotation and lateral scuffing should be documented so the dissipated energy required for that movement can be combined with the deformation energy in the impact speed calculations.

Other tire marks can be produced during the underride since the trailer is often moving at the time of the underride. This can cause the underriding vehicle to experience lateral tire scuffing during the crash as the trailer continues to a stop. Careful examination of the physical evidence can separate crash produced gouges, scrapes, tire marks and debris from those produced post-crash.

TRAILER INTERACTIONS

A trailer or straight truck typically has components that hang down from the trailer floor sub frame. These components can include:

1. Spare tire hangers
2. Trailer support dollies
3. Underride guards
4. Tires and suspension components
5. Rear axle slider frames
6. Trailer undercarriage frames
7. Special trailer components

Each of these components is different in nature. They are designed for totally different uses, and deform in different ways when involved in a crash. When performing speed analysis of an underriding vehicle that has been damaged by and/or caused damage to these types of components, the damage to the underriding vehicle and to the components(s) must be assessed. For example, a simple underride bar or tire hanger cage offers very little resistance to a vehicle that strikes them from the side because they were not designed for lateral loads.

The damage caused to a vehicle contacting these components varies in location and pattern. After all the damage is evaluated the information can be incorporated into calculating the initial crash speed range.

EXIT OR POST CRASH SPEEDS

When a vehicle experiences a complete underride and continues beyond the trailer it has an exit speed or post crash speed. The distance the vehicle traveled beyond the trailer can be measured directly or established from photographs. The post-crash speed, or exit speed, should be developed using conventional analysis (momentum, etc) and then combined with the calculated collision damage to obtain the crash speed.

The following is a description of an empirical approach developed by the authors for side underride crash speed, which accounts for several of these factors.

ESTIMATING COLLISION SPEEDS FROM ROOF STRUCTURE CRUSH DATA

DAMAGE MATRIX INDEX DEVELOPMENT

The Damage Matrix Index (DIM) is based on work performed by Campbell (Ref 3). He found that the crash energy involved in the deformation during a frontal crash can be represented in a matrix overlaid onto the vehicle schematic. Each cell of the matrix represents a certain amount of energy which can translate into speed.

This same principle of energy distribution has been used with the roof crush and pillar deformation to develop the speed determination. The cells that contain the roof rails and pillars have higher values than the cells that contain only the roof. Values are also applied to the glass areas of the windshield and rear window. The variation in cell energy values of the matrix account for the stiffness variations associated with roof rail and pillars versus roof panel and glass. The developed matrix allows for the estimation of speed over a range from very slow to approximately 35 mph where vehicles are prone to passing clear under a box semi-trailer. Additional research using a wider range of trailer configurations and vehicle types is necessary to confirm that the procedure applies to additional configurations of trailer and vehicles.

The empirical process determined the crush energy value is 1504 for a complete pass through. Each cell or box in the damage matrix represents the proportional amount of energy absorbed or managed when that cell is crushed. If the entirety of the roof panel is crushed, all of the 36 (6x6) matrix sections are determined to be completely damaged with a total crush energy value of 1504.

Therefore, one can utilize a Damage Index Matrix (DIM) by dividing the roof into subdivisions relating to the roof and roof supports of the vehicle for crush energy. The actual damage profile is overlaid onto the damage index matrix, then the damage indices can be totaled in order to arrive at the Damage Index (D_I) value which allows for the calculation of a collision speed. In developing the DIM certain assumptions were made (Ref 5):

1. Laterally the entire pre-impact roof area can be divided into 6 rows; includes the glass area of the windshield and the rear window.
2. Longitudinally, from the left side to the right side, the entire pre-impact roof panel can be divided into 6 columns, 3 left and 3 right.
3. The side rail of the roof requires more energy to be deformed than the central roof panel.
4. The vertical support column members known as the 'A', 'B', and 'C' pillar, front to rear respectively, create a stiffer component and require more energy to be deformed.

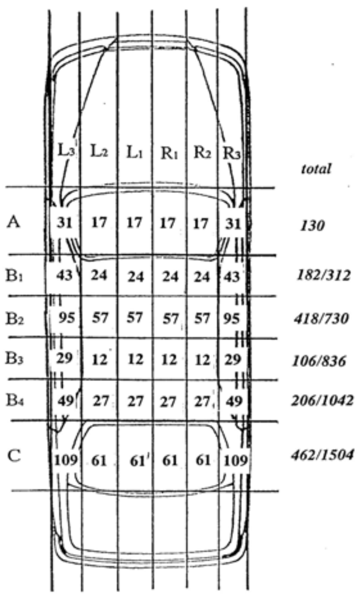

Figure 3. Damage Index Matrix

As a result of the previous discussion a DIM has been developed and is shown in figure 3. As future tests are performed and new data is analyzed the DIM may be revised to accommodate different body styles or designs of roof and roof support systems or found to accommodate them within its current configuration.

IMPACT EQUATION DEVELOPMENT

Conceptually the inductive approach was adopted. This approach uses the results of field experience and testing from which empirically an equation was developed. The equation was then used in further testing to verify its performance. The methodology utilized was to organize all the vehicle test speeds on an x-axis with the collision angles, weights and damage percentages as vertical parameters, and then determine the most appropriate Damage Index (D_I) value [see Figure 3 and associated discussion]. The D_I is a function of the impact energy that causes the damage and is therefore related to the kinetic energy dissipated as a result of damage. In general, the speed associated with this energy dissipation, V_d can be formulated in the following manner:

$$V_d = A \times \sqrt{D_I \times B} \qquad \text{[mph]}$$

(Equation 1)

Where D_I (is the damage energy [ft-lb],
A is a function of the impact angle, and
B is related to the underriding vehicle weight.

Equation (1) is similar to the well-established kinetic energy equation:

$$E = 1/2\,(m V^2)$$

when solved for the velocity, V yields:

$$V = \sqrt{2E / m}$$

(Equation 2)

where V is the velocity (speed),
E is the Kinetic Energy of the vehicle and
m is the mass.

In equation (1) the term A is unitless. Since the calculated speed has a unit of miles per hour [mph] and the vehicle has a weight of pounds [lb], by combining equations (1) and (2) equation (3) is arrived at ($2E = D_I$).

$$V_d = A \times \sqrt{D_I / m \times B}$$

(Equation 3)

Since mass = Weight/32.2 from Newton's First Law and substituting that value, equation (4) is:

$$V_d = A \times \sqrt{D_I \times 32.2 / W \times B}$$

(Equation 4)

It followed that if the roof was 100% damaged all the energy that it would take to totally deform the roof would have been attenuated. The impact angle being 90° then there would be no energy loss in lateral sliding as there would be where $\theta < 90°$. Different terms and amounts of damage were analyzed to establish the most proper term for A. It was found that

$$A = \frac{1}{\sin \Theta}$$

(Equation 5)

is the most appropriate.

When all the terms are combined, the equations become:

$$V_d = (1/\sin\Theta)\sqrt{D_I \times (1530/W)}$$; and

(equation 6)

The constant, 1530 performs the function of combining dissimilar units so the result of the equation is expressed in miles per hour.

Where D_I is the energy of damage,
W is the vehicle weight in [lb],
Θ is the impact angle in [deg],

In some collision configurations the striking vehicles experienced a complete underride and still had sufficient energy to have an exit speed, V_{exit}. The vehicle exit speed, V_{exit}, can be associated to a remaining energy, which was not absorbed during the complete roof damage during the underride process. For these test results, the calculated or empirically obtained collision speed of the underriding vehicle V_c must include the exit speed, V_{exit}, in the following manner,

$$V_c = \sqrt{V_d^2 + V_{exit}^2} \text{ [mph]}$$

(Equation 7)

Where V_{exit} is the exit speed in [mph],
V_d is the velocity associated with the damage
V_c is the calculated crash speed of the underriding vehicle in [mph].

When there is no exit speed or other speed components to combine, then the calculated crash speed of the underriding vehicle V_c equals the velocity associated with the damage (V_d).

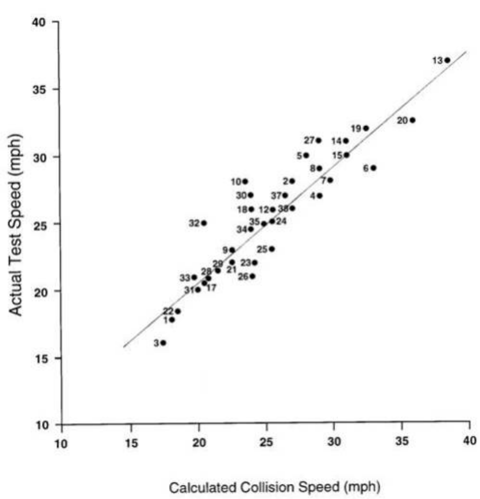

Figure 4. Actual versus Calculated Speeds

Figure 4 demonstrates the correlation of the calculated collision speed based on Evidence-Based Equation (7) and the known impact speed of the crash test. For this graph, 32 data points are plotted against known (actual test) collision speeds [mph].

A linear regression analysis determined the slope was 0.8612 and the coefficient of correlation R-squared, was 0.8508, indicating an excellent correlation. This might be reflected in the fact that a majority of data points are very close to the correlated straight line despite the variables discussed previously. In using this EBE based equation, many variables (e.g., side friction between the underride vehicle roof structure and the trailer structure), although not explicitly listed are accounted for in the final result. Continued testing has shown a similar correlation factor, further validating the derived equation.

Current methods for reconstruction based on energy in crush (CRASH, etc.) are validated on approximately six crash tests using older vehicles. This newly developed EBE impact equation provides evidence that there is a significant relationship between contact angle, weight and types of vehicles and the impact speed of the underriding vehicle.

CONCLUSION

Underride crash testing has established that sufficient relationships between different body and roof styles exist and will support a general formula for scientific underride speed analysis. This will in turn provide more accurate information for researchers to evaluate the parameters of side underride crashes and develop design criteria for effective trailer side underride protection devices.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

A Term incorporating the relative angle of the collision.

B Term incorporating the constants, conversion factors and weights.

Complete Underride Condition where the underriding vehicle passes completely under the trailer and still has some speed as it exits.

CRASH Calspan Reconstruction of Automobile Speeds on the Highway

V_c Collision Speed – Speed of the underriding vehicle at the onset of the underride.

V_d Speed associated with damage calculated using the underride formula.

D_I Damage Index – Sum of the Damage Index Matrix sections representing the roof deformation.

DIM Damage Index Matrix – Roof map with numeric values for the 6 x 6 matrix divisions.

V_{exit} Speed of the underriding vehicle remaining after a vehicle experiences a complete underride and exits to the other side of the overriding trailer.

EBE Evidence Based Estimation – Collision speed derived from the physical evidence of the roof and support structure deformation. The calculation is based upon data compiled and analyzed from test crashes.

θ Relative Angle – The angle formed between the leading contact side of an underriding vehicle and the contact side of the overriding trailer.