Vehicle roof strength as it relates to contained occupant injury prevention during rollover crashes

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Abstract

This paper presents a theoretical estimate of the roof strength required to protect contained occupants during a rollover crash assuming an effective restraint system is implemented in the vehicle. To date a number of road safety advocates have suggested that a roof's Strength-to-vehicle Weight Ratio (SWR) must be a minimum of 3.5, as measured according to the US Federal Motor Vehicle Safety Standard (FMVSS) 216 protocol, to protect contained occupants from severe or fatal injury. To date these conclusions have been based on real world crash data, statistics and crash test data. This study further validates the conclusions reached by these researchers using a purely mathematical approach that utilises Newtonian laws of physics, empirical values from rollover crash test data and the FMVSS 216 test protocol.

The mathematical derivation identifies what proportion of crash energy each component of the vehicle absorbs. The analysis considers both friction between the vehicle and the roadway and deformation of the vehicle. By identifying the energy that must be absorbed through deformation of the vehicle's roof using the FMVSS 216 five inches (127 mm) of roof crush strength limit as a constraint, it was possible to calculate theoretically using some broad empirical assumptions generated from rollover crash test data, that a SWR of 3.6 is required to prevent serious and fatal injuries.

Keywords

Rollover, roof strength, FMVSS 216

Introduction

Researchers [1,2,3] have undertaken studies of roof strength however to date none have involved mathematical derivations based on the laws of physics and energy dissipation over the length of a rollover crash. These researchers used observations of rollover crashes and results from rollover crash testing to identify that the minimum roof strength (measured using the FMVSS 216 methodology) to protect contained occupants from serious or fatal injury should be a SWR of 3.5 or greater. Similarly, other researchers at the Insurance Institute for Highway Safety (IIHS) have presented a statistical investigation of US rollover crashes and concluded that the lower boundary for what should be considered "good" roof strength was a SWR of 4.0 [4,5].

Friedman and others [6,7] extended previous investigations [1,2,3] by comparing the results from various studies by US National Highway Traffic Safety Administration (NHTSA), IIHS and others, as shown in Figure 1. Paver et al [8] discuss the Integrated Bending Moment (IBM) injury criterion they proposed and is shown in Figure 1. Issues concerning Figure 1 and the Jordan Rollover Systems (JRS) tests are further discussed by Chirwa et al [9]. From this graphical comparison Friedman concluded that vehicles should possess a SWR of 4.0 or more to provide adequate protection to contained occupants in rollover crashes.

Friedman compared data from a series of previous studies he and collaborating researchers carried out, as well as results from IIHS statistical studies [4]. These studies were then plotted, as seen in Figure 1, such that the various transitions between a high and low risk of injury or ejection were aligned. This transition between high and low risk is highlighted by the white region in Figure 1.

The analysis presented in this paper explores whether a theoretical threshold level of roof strength exists, confirming the results of Figure 1, for a single vehicle tripped lateral rollover crash on level ground. Such a derivation has not been carried out to date.

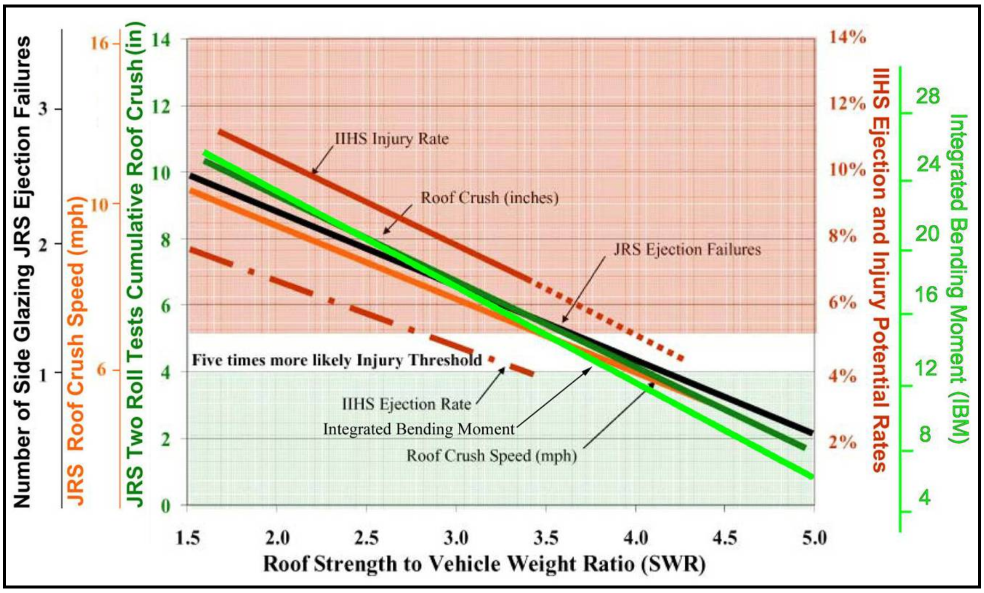

Figure 1: Comparison of IIHS injury rate and JRS injury criteria for different roof strengths [8]

Theoretical Analysis of Roof Strength

While the analysis to determine the SWR for a vehicle subjected to a rollover crash is complex using physics and mathematical equations, it can be greatly simplified by making a number of broad assumptions. The intention of the following derivation is not to look at any one crash in detail in an attempt to calculate mathematically a vehicle's SWR, but to assess a SWR threshold that will prevent significant roof collapse and therefore minimise the probability of serious/fatal neck injuries.

In order to do this the following initial assumptions need to be made:

1. The rollover crash to which the vehicle is subjected is similar to a FMVSS 208 dolly rollover crash test [10].
2. The vehicle analysed is the Malibu sedan vehicle tested by General Motors (GM) [11] and therefore vehicle kinematics of the Malibu II series of rollover crash tests and particularly Test 3, for which a detailed analysis was undertaken by the first Author of this paper [12], is typical of any vehicle during an FMVSS 208 dolly rollover.
3. The total energy (E_T) of the system (i.e. the rolling Malibu vehicle) will be equal to the total kinetic energy and gravitational potential energy of the system when the test is initiated.

On the basis of these four assumptions, at time = 0 sec, there will be three components of kinetic energy, namely vertical (E_{Kv}), horizontal (E_{Kh}) and rotational (E_{Kr}), and one of gravitational potential energy (E_P) which make up the total energy of the system. That is:

$$E_T = E_{Kv} + E_{Kh} + E_{Kr} + E_P \tag{1}$$

Substituting for each component of energy known energy expressions [13], Equation (1) expands to give the following,

$$E_T = \frac{1}{2}mv_v^2 + \frac{1}{2}mv_h^2 + \frac{1}{2}I\omega^2 + mgh \tag{2}$$

where m is the vehicle's mass, I is the vehicle's moment of inertia, v_v is the vertical velocity of the vehicle's centre of gravity (COG), v_h is the horizontal velocity of the vehicle's COG, ω is the vehicle's rotational velocity, h the height of the vehicle's COG, and g is the gravitational acceleration constant of

9.81 m/sec^2. Equation (2) shows that the three principal velocities and height of the vehicle's COG must be determined to estimate the total energy of the system.

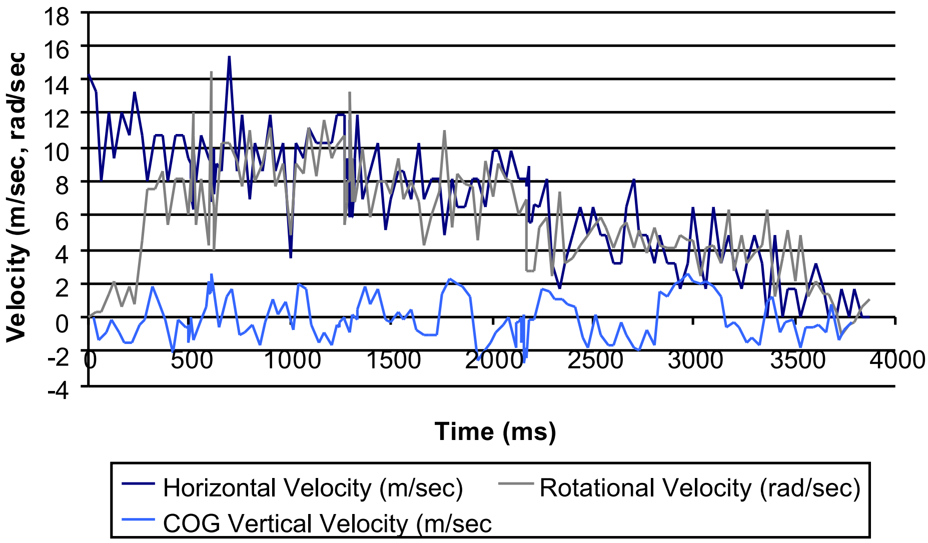

Figure 2: Comparison of principal velocities of the vehicle during the Malibu II Test 3 rollover crash test.

The velocities of the vehicle were estimated using the plots of the three principal velocities from Malibu II Test 3, shown in Figure 2. These plots are very similar to the velocity-versus-time plots of other Malibu vehicles, such as those presented by the authors of the Malibu studies [11, 14]. Malibu II crash test video footage showing external views of the rolling vehicle, including side and end track views, and internal views of the contained and restrained ATDs, has been made publicly available and has been analysed by the author. The video footage of Test 3 was analysed, using the methodology outlined in previous publications of the author [12, 15], resulting in the plots presented in Figure 2.

Figure 2 shows the vertical and rotational velocity at $t=0$ are 0. Thus Equation (2) can be further simplified to,

$$E_T = \frac{1}{2} m({v_h}^2 + 2gh) \tag{3}$$

Using Figure 2 and the specific protocol from the FMVSS 208 dolly rollover test [16], the horizontal velocity of the vehicle at $t=0$ was adopted as v_h = 14.3 m/sec. Further analysis of the video footage of Test 3 identified that the vehicle's COG was 1.06 metres from the ground at the start of the crash test. The overall energy was thus calculated as,

$$E_T = \frac{1}{2} m(14.3^2 + 20.8) = 112.6m \tag{4}$$

E_T will be dissipated over the period of the rollover crash by two principal components. These are E_{fric} being the loss of energy due to friction and E_δ being the loss of energy due to deformation. Thus

$$E_T - \left(E_{fric} + E_\delta\right) = 0 \tag{5}$$

E_{fric} can be estimated by estimating work carried out by the frictional force during the period of time the vehicle is in contact with the ground. Thus, E_{fric} can be calculated as,

$$E_{fric} = Work = E_{Kf} - E_{Ki} = \frac{1}{2} m v_f^2 - \frac{1}{2} m v_i^2 = \frac{1}{2} m\left(v_f^2 - v_i^2\right) \tag{6}$$

where E_{Ki} is the initial kinetic energy of the vehicle and E_{Kf} is the final kinetic energy of the vehicle, if it is assumed the vehicle is a non-deforming rigid steel structure. Because the friction force acts in the horizontal direction, i.e. opposing the horizontal motion of the vehicle, it is the magnitude of the vehicle's horizontal velocity that makes up the velocity components in Equation (6). Thus, v_f is the vehicle's speed immediately after impact with the ground and v_i is the vehicle's speed immediately before impact with the ground. The final velocity of the vehicle (v_f) in Equation (6) can be simplified using the following equation

$$v_f = v_i + a\Delta t \tag{7}$$

where a is the deceleration the vehicle underwent while in contact with the ground and Δt is the length of time the vehicle was in contact with the ground. Equation (7) assumes that the rate of deceleration due to friction is a constant. This rate of deceleration has been identified by road safety experts [17] as,

$$a = fg \tag{8}$$

where f is the deceleration drag factor and g = 9.81 m/sec^2.

The coefficient of friction for steel against bitumen and for tyres against bitumen ranges from 0.55 to 0.7 [17,18]. In this instance, a value of around 0.6 is adopted for f. Substituting Equation (8) into Equation (7) gives,

$$v_f = v_i + 0.6g\Delta t \tag{9}$$

Thus using Equation (9), Equation (6) becomes,

$$E_{fric} = \frac{1}{2}m\left[(v_i + 0.6g\Delta t)^2 - v_i^2\right] = \frac{1}{2}m\left[0.36g^2\Delta t^2 + 1.2g\Delta t \times v_i\right] \tag{10}$$

The resulting equation defines energy loss due to friction over the period of vehicle-to-ground contact for any individual contact with the ground. The overall loss of energy due to friction will be the sum of each of these individual contacts or,

$$\sum E_{fric} = \frac{1}{2}m\sum 0.36g^2\Delta t^2 + 1.2g\Delta t \times v_i \tag{11}$$

The time interval Δt was determined by examining the video footage of the Malibu II Test 3 rollover and establishing the number of frames, and hence duration in seconds, each part of the vehicle was in contact with the ground. It should be pointed out that the estimate of the time interval Δt is an average value and was assumed to be the same regardless of whether the vehicle's roof deformed or not during the rollover event.

The velocit v_i was identified from the video analysis described in previous work [12,15] and presented in Figure 2. The resulting loss of energy due to friction was then determined using Equation (11). This frictional energy was then subtracted from the total energy

$$E_\delta = E_T - E_{fric} = 112.6m - 71.6m = 41.0m \tag{12}$$

where E_δ is identified as the remainder of the energy left and assumed to be as a result of the deformation of the vehicle dissipated through deformation of the vehicle body, roof and wheels/suspension. Precisely what share of this energy the deformation of each component of the vehicle dissipates must be further determined in order to estimate the energy dissipated by the roof deformation processes ($E_{\delta r}$). To estimate this, an analysis of video footage of the eight Malibu II tests was undertaken [12]. The analysis identified the frequency and duration of vehicle-to-ground impacts that the various components of the vehicle underwent during these rollovers.

It was identified that on average the vehicle's roof was in contact with the ground for approximately 33% of the total time any component of the vehicle was in contact with the ground. It was thus assumed that the proportion of E_δ absorbed by the roof of the vehicle was proportional to the duration each component was in contact with the ground and thus also 33%. Therefore the estimated energy dissipated by the roof of the vehicle ($E_{\delta r}$) was assumed as

$$E_{\delta r} = 0.33 \times E_{\delta} = 0.33 \times 41.0m = 13.5m \quad (13)$$

Additional analysis is still required to calculate the amount of energy dissipated to deform the roof during each individual roof-to-ground contact. The variable kinematics of the rolling vehicle dictate that different parts of the roof will contact the ground resulting in varying magnitudes of deformation with each impact.

Further observations of the Malibu II test videos (Table 1) indicate that typically a total of six (rounded up from an average of 5.5) roof-to-ground impacts occurred during the Malibu II rollover tests. Thus, if each impact is assumed to absorb the same amount of roof deformation energy then,

$$E_{impact} \approx \frac{E_{\delta r}}{6} \quad (14)$$

Table 1: Summary of vehicle-to-ground contacts during Malibu II rollover crash tests where misses (vehicle remains airborne) is in brackets.

Malibu II test number	**Roof contacts**		**Vehicle body contacts**		**Tyre contacts**	
	Right (Near) side	**Left (Far) side**	**Right (Near) side**	**Left (Far) side**	**Right (Near) side**	**Left (Far) side**
1	2 (2)	3 (1)	4 (0)	3 (0)	4 (0)	3 (0)
2	4 (0)	3 (1)	3 (1)	2 (1)	4 (0)	2 (1)
3	2 (2)	4 (0)	1 (3)	3 (0)	4 (0)	1 (2)
4	3 (0)	3 (0)	3 (0)	2 (1)	2 (2)	3 (0)
5	3 (0)	2 (1)	4 (0)	3 (0)	4 (0)	3 (0)
6	2 (2)	2 (2)	5 (0)	3 (1)	5 (0)	4 (0)
7	2 (2)	3 (1)	2 (2)	3 (0)	4 (0)	3 (0)
8	3 (0)	3 (0)	3 (1)	3 (0)	4 (0)	3 (0)
Reinforced roof vehicles	11 (4)	10 (5)	16 (1)	11 (2)	17 (0)	12 (1)
Production roof vehicles	10 (4)	13 (1)	9 (6)	11 (1)	14 (2)	10 (2)
Total	21 (8)	23 (6)	25 (7)	22 (3)	31 (2)	22 (3)

Substituting the value from Equation (13) into Equation (14), the amount of energy to deform the roof (E_{impact}) becomes,

$$E_{impact} \approx 2.25m \quad (15)$$

The next key assumption underlying this analysis is that a vehicle's roof must not undergo structural failure, i.e. the vehicle's roof undergoes no plastic (permanent) deformation but rather small amounts of elastic deformation. This assumption is based on the findings and conclusions of previously published work of the author [12,15] which identified that plastic deformation of a vehicle's roof structure increases the probability of severe/fatal injury, and on the basis of DeHaven's [19] crashworthiness principles, i.e. that the roof needs to be strong enough so that the survival space is not compromised in order to prevent injury to a vehicle occupant during a rollover crash. Thus, if a vehicle only deforms elastically, it is more than likely it does so in a linear elastic manner.

The roof deformation characteristics from quasi-static FMVSS 216 tests of a selection of vehicle roofs are shown in Figure 3. These plots indicate that during the period of elastic deformation the roof's deformation curve appears to follow a linear elastic relationship.

If, unlike the current FMVSS 216 requirements[1], the maximum allowable elastic deformation is adopted as 127 mm (5 inches) it is possible to calculate the roof SWR to maintain roof integrity, i.e. prevent it from failing and forming a collapsing plastic mechanism. A deformation of 127 mm was adopted as it has been identified by Honikman and Friedman [3] as the level of deformation that minimises glazing

[1] The current FMVSS 216 rule requires the SWR of the vehicle's roof to be 1.5 or greater at 127 mm of roof crush, but does not restrict the vehicle's roof from undergoing plastic deformation.

breakages and contained occupant injuries. Hence, the energy dissipated with each ground strike can be calculated using the force deformation relationship characterised in Figure 4.

Thus, the energy dissipated in each impact is the shaded area in Figure 4, i.e.

$$E_{impact} = \frac{1}{2} F_{\max} \times 0.127 \text{ Nm} \tag{16}$$

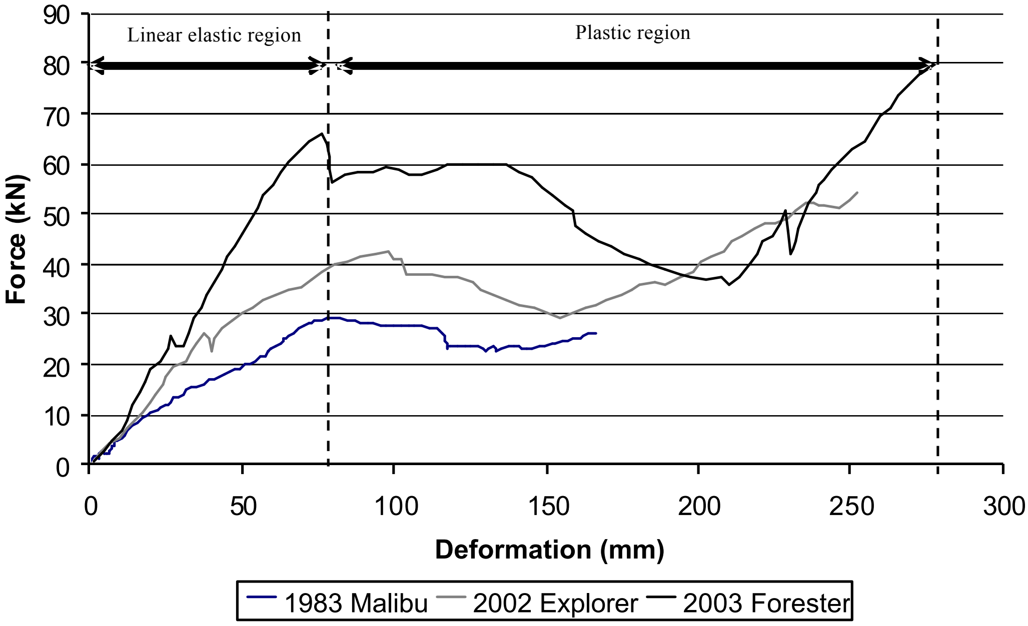

Figure 3: Comparison of FMVSS 216 deformation for a range of vehicles [14, 16]

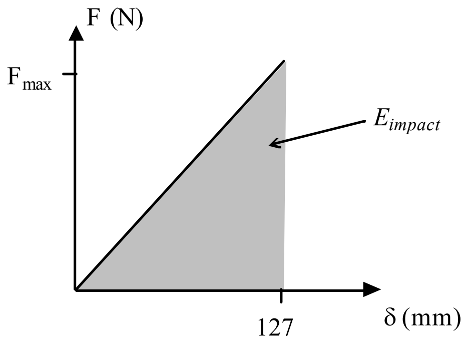

Figure 4: Energy absorbed (E_{impact}) by the vehicle's roof deforming elastically

Therefore, rearranging Equation (16), the maximum force, in Newtons, required to deform a linearly elastically deforming roof to 127 mm would be,

$$F_{\max} = \frac{2E_{impact}}{0.127} = 15.75 E_{impact} \tag{17}$$

Conversion of the units of F_{max} from Newtons (N) to kilograms (kg) is required when substituting Equation (15) into Equation (17). This gives the following value for F_{max} as

$$F_{\max} = \frac{15.75 E_{impact}}{9.81} = 1.605 E_{impact} = 3.61m \qquad (18)$$

where '*m*' is the mass of the vehicle in kilograms. The *SWR* is defined by the following relationship,

$$SWR = \frac{F_{\max}}{m} \qquad (19)$$

Thus, using Equation (18) and Equation (19) an estimate for the required SWR of the Malibu vehicle undergoing a FMVSS 208 rollover, using the assumptions identified above, is 3.61.

In order to compare this result with the plot presented Figure 1, a formula for roof strength, in terms of deformation (x) must be identified. Hence, the result in Equation (16) can be expressed as

$$E_{impact} = \frac{1}{2} F_{\max} x \qquad (20)$$

Rearranging this and substituting Equation (15) into Equation (20) results the following function F_{max} (in kilograms) in terms of the roof displacement x

$$F_{\max} = \frac{4.5}{9.81x} m \qquad (21)$$

The final general equation for the roof's *SWR* is thus,

$$SWR = \frac{F_{\max}}{m} = \frac{1}{2.18x} \qquad (22)$$

Figure 5 compares the summary plots published by Friedman (Figure 1) and Equation (22).

To compare the plot of Equation (22) with those plotted by Friedman (2008), the 127 mm deformation point using Equation (22) was aligned in the centre of this white (minor to serious injury transition) region. The result, plotted in Figure 5, indicates that Equation (22), while not linear aligns with those plots summarised by Friedman.

This alignment is particularly close in the critical region in terms of required SWR to minimise injury in a rollover crash. Therefore, this theoretical derivation further supports the work of other road safety researchers [4,5,6,7], in identifying a minimum SWR requirement of 3.5 to 4.0 to prevent serious injury to contained occupants.

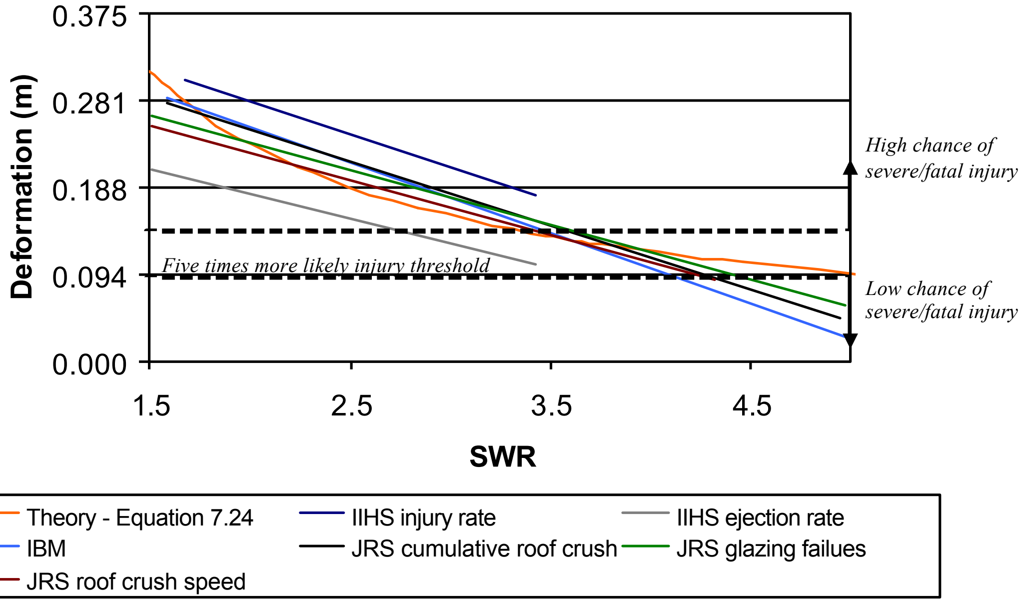

Figure 5: Comparison of Friedman's [6] summary and Equation (22), including injury risk regions highlighted

Conclusions

This paper presents a methodology for calculating the roof strength required to prevent serious or fatal injuries to contained occupants in a rollover. On the basis of a number of simplifying assumptions, observations from the Malibu II test series rollover crash data [12,15], NHTSA's rollover injury prevention requirement of restricting roof crush to less than 5" (127 mm), that the roof would not undergo permanent (plastic) deformation, and Newtonian physics, a SWR limit at which fatal and serious injuries and the risk of ejection would be minimised was calculated as 3.6.

A function relating SWR to roof displacement based on this mathematical derivation represented by Equation (22) was compared to plotted injury risk versus roof SWR curves presented by Freidman, Paver et al, and Friedman and Grzebieta [6,7,8]. This result, while not conclusive on its own, is consistent with other published research work [4,5,6,7,12,15] that identify roof strength is important to ensuring occupant safety in rollover crashes and needs to be of the order of 3.5 to 4.0 or greater.

Acknowledgments

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