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ABSTRACT

Full-scale crash tests are the traditional method used to assess the safety of a roadside object. Crash test evaluation criteria should relate the observable response of the vehicle and the struck object to the likely risk of injury to vehicle occupants in similar real-world collisions. Side impact collisions are one particularly serious type of impacts for which no evaluation guidelines currently exist. A simple method for determining human risk in a side impact collision with a roadside object from the velocity profile of the impacted face of the struck object will be presented in this paper. This method not only eliminates the use of anthropometric test devices (ATDs) in crash tests, but also gives conservative values to account for the variable occupant position at the time of impact.

KEYWORDS

Crash test, side impact, roadside hardware, roadside safety.

INTRODUCTION

Side impact collisions with roadside objects are responsible for many injuries and deaths on highways in the United States.*(1)* Recommendations for performing side impact full-scale crash tests of roadside objects have been developed in order that hardware developers, researchers and policy makers can evaluate the impact performance of such devices.*(2)(3)* Evaluating the results of side impact collisions, however, has been difficult since there are no widely recognized evaluation criteria that relate observable roadside object crash test results to the risk of injury to a hypothetical occupant. One way to assess the degree of risk used by the vehicle design and regulatory community is to use instrumented anthropometric test devices (ATD) in full-scale crash tests. The use of instrumented ATDs in roadside hardware crash tests has waned in the past decade and there is resistance to using them in future crash tests due to (1) the expense of purchasing and maintaining ATDs as well as (2) questions about their reliability and biofidelity in complex multi-directional impact events.

Another disadvantage of using ATDs is that they measure the accelerations experienced in one specific test. Unlike the crash tests used in the automobile design industry, roadside object crash tests usually involve complex multi-directional occupant and vehicle motions. Several nearly identical tests may provide different ATD responses depending on the initial position of the ATD and the specific sequence of events in the impact. A method that does not depend on the use of an instrumented ATD is, therefore, desirable for roadside hardware side impact crash tests. An evaluation method should estimate the reasonable worst cost occupant injuries in a specific impact. The purpose of this paper is to present a simple evaluation criteria that can be used to evaluate the likely risk of injury in a full-scale crash test without the use of an ATD.

There are three primary injury mechanisms in side impact collisions with roadside objects: injuries to the head, thorax and pelvis. The National Highway Traffic Safety Administration has developed specific ATD-measured injury criteria for each of these body regions: the Head Injury Criteria (HIC), the Thoracic Trauma Index (TTI) and the pelvis acceleration (P_y).*(4)* Although relating ATD responses to the risk of injury to a living human is both complex and controversial, biomechanics researchers have attempted to assess the relationship between the HIC, TTI and P_y to the probability of sustaining a life threatening injury. In general a HIC of 1000, a TTI of 90 g's and pelvic accelerations of 130 g's are considered to represent approximately a 20 percent probability of sustaining a life threatening injury under similar conditions in a real-world collision. In the following sections, the chance of sustaining a life threatening injury in a reasonable worst case roadside object side impact collision scenario is likewise estimated to be less than 20 percent.

COLLISION CHARACTERISTICS

Unlike more typical roadside feature crash tests where intrusion into the passenger compartment is relatively small, side impact collisions with roadside objects like poles, trees and guardrail terminals are characterized by large intrusions into the occupant compartment. When there is relatively little occupant compartment intrusion it is often adequate to treat the vehicle as an essentially rigid body and the occupant as another rigid body translating within the boundaries of the occupant compartment. This is the basis of the flail space technique and the occupant risk criteria first proposed by Michie.*(5)(6)* In side impact collisions with roadside objects, however, the occupant interacts directly with the door structure of the vehicle. The intrusion of the door is so extensive and so rapid that the rigid body assumption is not valid. In effect, the struck door acts nearly independently of the vehicle center of gravity. Finite element simulations have demonstrated that the occupant is unaffected by the rigid body motion of the vehicle in a side impact, the occupant interacts exclusively with the interior door of the vehicle and the struck object.*(7)* A typical flail space approach based on rigid body kinematics of the vehicle center of gravity and the occupant will not, therefore, produce meaningful results.

Figure 1 shows a typical response of a vehicle door from a finite element simulation of a side impact with a guardrail terminal. The thick line represents the velocity history of the impact face of the guardrail terminal. Prior to the impact with the vehicle, the terminal is at rest. When struck by the vehicle at approximately 0.005 sec, the impact face of the terminal begins to translate, steadily gaining speed. The thin line represents the interior face of the impact-side door. Prior to impact the vehicle, including both the door and the occupant, are traveling at a constant pre-impact velocity, in this case 13,888 mm/sec (e.g., 50 km/hr). There is a delay of several milliseconds when the vehicle first strikes the impact face of the guardrail before the inner door begins to decrease velocity. The door, however, quickly decelerates, approaching a common velocity with the impact face of the guardrail terminal at approximately 0.015 sec.

The velocity of the inner door bottoms out for a short period (e.g., about 0.010 sec) while the door is being crushed flat (i.e., the outer and inner door are crushed together) and then accelerates to reach a common velocity with the impacting face of the guardrail terminal. From approximately 0.025 sec onward, the inner door and impact face of the guardrail terminal travel at the same velocity since they are occupying essentially the same physical space.

The velocity profile of the inner door is the kinematic boundary condition with which the occupant interacts. If the occupant were in contact with the door prior to impact, as would be the case if the vehicle slides sideways for a long time prior to impact, the head, thorax and pelvis of the occupant will experience a very rapid change in velocity when the occupant strikes the inner door. On the other hand, if the occupant is away from the impact (e.g., toward the center of the vehicle), the occupant may strike the inner door when the inner door is moving considerably faster. The precise occupant kinematics and the resulting trauma would, therefore, depend on the initial position and velocity of the occupant as well as the response of the inner door and terminal.

The response of anthropometric test devices (ATD) in full-scale side impact crash tests have been shown to exhibit exactly this type of position sensitivity.*(8)(9)* Two otherwise identical tests may result in dramatically different ATD responses if the initial conditions of the ATD are different. In assessing the results of a full-scale crash test, the occupant should be presumed to be in the practical worst case position since the human occupant of a real-world collision may be located in a wide variety of positions within the vehicle. Any evaluation criteria should assess the likely injury when the occupant strikes the interior with the reasonable worst case position and impact conditions.

HEAD INJURY

While head injuries are not specifically addressed in the NHTSA side impact crash test evaluations procedures contained in FMVSS 214, they are an important injury mechanism in impacts with tall roadside objects like poles and trees.*(10)* The Head Injury Criteria (HIC) is a commonly used frontal impact evaluation criteria that has been used for decades to assess the level of head injury risk in frontal collisions. A HIC of 1000 is conventionally considered to represent the threshold where linear skull fractures will begin to appear.*(13)* There is some precedent for using the HIC in lateral impacts although, strictly speaking, the HIC has never been validated for measuring lateral head trauma.*(11)* Unfortunately, there is no other measure of head trauma available so the HIC is used herein.

The HIC is also only appropriate for cases where there is contact between the head and the vehicle interior. If a roadside object does not extend above the bottom of the side door window it is not necessary to calculate the HIC since no contact would be possible with the struck object and therefore no head injury would be likely.

The HIC is given by the following expression:*(12)*

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \; dt \right]^{2.5} \left[t_2 - t_1 \right]$$

where t_1 = beginning of the evaluation interval in sec,

t_2 = end of the evaluation interval in sec and

a = the instantaneous resultant acceleration of the head in g's,

The time interval, t_2-t_1, must be chosen such that the difference is less than 36 msec and in such a way that value of HIC is maximized.

Head injury is thought to be related to the magnitude of the acceleration and the time duration of that acceleration. The head can sustain high accelerations if the loading is relatively short and lesser accelerations if the time duration is relatively long as illustrated by the Wayne State tolerance curve.*(13)* The quantity t_2-t_1 can be replaced by the value Δt yielding the following:

$$HIC \cdot g = \Delta t \left[\frac{1}{\Delta t} \int_{t}^{t+\Delta t} a \; g \; dt \right]^{2.5}$$

If both sides are multiplied by the acceleration due to gravity, g, the integral of the acceleration is simply the change in velocity that occurs during the time period Δt so the integral can be replaced by the symbol ΔV yielding:

$$HIC = \Delta t \left[\frac{\Delta V}{g \, \Delta t} \right]^{2.5}$$

In graphical terms, the quantity $\Delta V/\Delta t$ represents the slope of a curve on a velocity time history like Figure 2. Larger slopes will result in larger values of the HIC.

When calculating the HIC, the time interval, Δt, must be less than 36 msec as specified by the NHTSA calculation procedures. While there is no specific lower limit specified in FMVSS 208 for Δt, the practical lower limit would be the data acquisition rate.*(12)* While ATD data is collected and filtered at 1650 Hz (SAE J211 Class 1000), vehicle data is usually collected and filtered at 300 Hz (SAE J211 Class 180). If there is no ATD in the test vehicle, the acceleration data based on vehicle and barrier accelerations would be collected at 300 Hz. Further, for plotting purposes acceleration data is often filtered with a cut off frequency of 100 Hz (Class 60). Sampling and filtering to Class 60 would result in a sample each 10 msec. Early tests that were the basis for developing the HIC involved head form drop tests onto rigid surfaces. The interaction time (e.g., the time where the head form and the rigid surface were in contact) in most of these tests was on the order of 12 msec. Assuming a practical lower bound time interval of 10 msec, therefore, appears to have both experimental and physical significance.

If the time interval for calculation, Δt, is assumed to be 10 msec, the critical HIC is taken as 1000 and the acceleration due to gravity is taken as roughly 10 m/s^2 the previous expression can be rewritten as:

$$\left[\frac{\Delta V}{\Delta t}\right]_{\max} \leq 10\sqrt[2.5]{\frac{1000}{0.01}} = 1000\ m/\sec^2$$

Thus, the maximum slope of the velocity time history of the hypothetical occupant's head during any 10 msec wide time interval must be less than 1000 m/s^2 (or approximately 100 g's). If the maximum slope is less than 1000 m/s^2, the HIC measured by an ATD should be less than critical HIC value of 1000.

Figure 2 shows a hypothetical time history for a side impact collision. The thick solid line represents the velocity time history of the impact face of a roadside object. The dashed lines represent the hypothetical time history of the head of a vehicle occupant. Just prior to the instant of impact, the occupant and vehicle are both traveling at the pre-impact velocity of V_o. Case I represents a situation where the head of the occupant is already in contact with the impact-side door of the vehicle when the vehicle strikes the roadside object. As soon as the vehicle strikes the roadside object, the head of the occupant begins to decelerate until it reaches a common velocity with the intruding door and impact face of the roadside object. The time required to reach the common velocity V_c is Δt. Case II represents a situation where the occupant is initially positioned far away from the door. The occupant travels at the pre-impact velocity V_o and then slows down to the common velocity in a period of Δt seconds, after striking the door.

The common velocity of the impacted object, door and occupant, V_c, is the velocity attained by the struck object 10 msec from the initial impact with the vehicle if the head of the occupant was in contact with the door prior to impact. In this case the HIC could be estimated as:

$$\left[\frac{\Delta V_{\max}}{\Delta t_{\min}}\right] = \left[\frac{V_o - V_c}{\Delta t}\right] < 1000$$

If $\Delta t_{\min}$ is taken as 0.01 sec, the maximum difference in velocity, $\Delta V_{\max}$, between the initial pre-impact vehicle velocity and any point on the struck-object time history after 10 msec must be less than 10 m/s in order for the HIC to be less than 1000. This leads to a statement of the head injury criteria for side impacts with roadside hardware:

> The difference between the vehicle impact velocity and the velocity of the impact face of the struck object must be less than 10 m/sec at every point in the struck object velocity time history after 10 msec from impact.

This evaluation criteria can be easily applied if the velocity time history of the impact face of the struck object is know. The reasonable worst case change in velocity that results in the worst likely injury is found by identifying the maximum difference between the vehicle impact velocity and the struck object velocity 10 msec after the initial impact.

THORACIC INJURY

The TTI is given by the following expression:

$$TTI(d) = \frac{1}{2}\left[T_{12} + \max(LURY\ or\ LLRY)\right]$$

where

TTI(d) = the thoracic trauma index,

T_{12} = the peak lateral acceleration of the T_{12} spinal segment in g's,

LURY = the peak left upper rib Y acceleration in g's and

LLRY = the peak left lower rib Y acceleration in g's.

The TTI(d) is an average peak acceleration of the ATD thorax. If the average peak acceleration of the thorax can be estimated from either full-scale crash test data or finite element simulations it should correlate well with the TTI(d) since they are both measures of the same physical phenomena. The overall average acceleration of the thorax can be estimated using elementary kinematics as follows:

$$V_f = V_i + a \Delta t$$

where V_f = the final velocity of the thorax,
V_i = the initial velocity of the thorax,
a = the average acceleration of the thorax during the time period and
Δt = interaction time of the ATD with the intruding object.

Assuming the average peak acceleration of the ATD is approximately equal to the TTI while the ATD is in contact with the door (i.e., TTI·g = a), yields the following equation:

$$TTI \cdot g = \frac{V_f - V_i}{\Delta t} = \frac{\Delta V}{\Delta t} < 90g$$

The vehicle and the ATD are traveling at a velocity V_o before the impact. The vehicle door first impacts the roadside object and begins to decelerate until the roadside object and the door reach a common velocity. Depending on the position of the ATD at the time of vehicle impact, the ATD then strikes the intruding door and object. ΔV is maximized when the ATD is leaning against the door at the time of impact. The door and the ATD strike the object and decelerate to reach a common velocity with the intruding object.

Simulations of vehicle impacts with roadside hardware indicate that the interaction time between the ATD thorax and door could be as low as 15 msec.*(8)* In order to be consistent with the Δt used for predicting head injury and also since using 10 msec is more conservative than 15 msec, the smallest reasonable Δt is used here as 10 msec. Approximating g as 10 m/s^2, the reasonable worst case TTI is:

$$TTI \cdot g = \frac{(V_o - V_c)}{\Delta t} = \frac{(V_o - V_c)}{0.010} < 90 \ \cdot \ 10 \ m/\sec^2$$
$$\Delta V_{\max} \leq 90 \ \cdot \ 10 \ \cdot \ (0.010) = 9 \ m/\sec$$

This leads to the thoracic injury criteria for roadside hardware impacts:

> The maximum difference between the impact velocity of the vehicle and the velocity of the impact face of the struck object must be less than 9 m/sec at every point after 10 msec from impact.

The thorax criteria can be applied in a manner identical to that used for the HIC. The largest difference between the vehicle impact velocity and the velocity of the struck object is calculated after 10 msec from impact. The difference in velocity must be less than 9 m/s in order for the TTI to be less than 90 g's. In most scenarios, the maximum difference will be found very early in the impact, usually just after the 10 msec limit.

PELVIS INJURY

Pelvis injury is included as an evaluation criteria in the NHTSA FMVSS 214 side impact standard so it is also included herein for consistency. The peak lateral acceleration of the pelvis must be less than 130 g's for acceptable performance. The peak lateral acceleration can be approximated by the largest slope on a velocity time history so the pelvis injury criteria can be written as:

$$\left(P_y \cdot g\right)_{\max} = \left[\frac{\Delta V}{\Delta t}\right]_{\max} \leq 130 \cdot 0g = 1{,}300 \, m/\sec^2$$

If the minimum possible Δt is estimated as 10 msec, then the maximum allowable change in velocity is

$$\Delta V_{\max} \leq 130 \cdot 10 \cdot (0.01) = 13.0\ m/\sec$$

The pelvis injury criteria can therefore be stated as:

> The maximum difference between the vehicle impact velocity and the velocity of the impacted face of the struck object, should not be greater than 13 m/sec at every point on the velocity time history of the struck object 10 msec after vehicle impact.

The pelvis injury criterion, therefore, has a form that is identical to the HIC and TTI criteria discussed above.

EXAMPLE

Applying these criteria is very simple given the availability of the time history of the impact face of the fixed object. The largest difference between a horizontal line representing the initial impact velocity of the vehicle and the velocity time history of the roadside object should be measured. The difference in velocities should be examined everywhere in the time history after 10 msec from the initial vehicle impact for determining occupant injury.

The above method of determining the potential risk of injury to an occupant when involved in a side impact with a roadside object, is demonstrated here by using the velocity profile of an Enquist-Svensen-Vanke (ESV) pole obtained from a full-scale test conducted by the Federal Highway Administration in 1991.*(14)* The test involved a 48.1 km/hr impact of a 1984 Honda Civic and the ESV pole on the driver side door of the vehicle. An instrumented ATD was placed in the driver seat of the test vehicle to obtain occupant responses to the impact event. The acceleration responses obtained from the ATD were used to calculate the Head Injury Criteria (HIC) and the Thoracic Trauma Index (TTI) which were 503 and 97g respectively. Unfortunately, the pelvis accelerations were not recorded in this test. The velocity profile of the impact face of the ESV pole was measured using a film analysis of the impact event. The resulting velocity profile of the struck object is shown in Figure 3. The time of vehicle impact in Figure 3 is 0.00 sec and the thick horizontal line shows the initial vehicle velocity, 13.36 m/sec. The cross-hatched region in the graph, 10 msec after vehicle impact is the critical region where the velocity difference should not be greater than: 10 m/sec to avoid serious head, 9 m/sec to avoid serious thoracic injury and 13 m/sec to avoid serious pelvis injury. The velocity profile of the struck object indicates that the maximum difference between vehicle impact velocity and velocity of struck object occurs just after impact but the evaluation criteria as described above will use the difference 10 msec after impact. The velocity of the pole 10 msec after impact is 0.6 m/sec so the maximum difference is 13.36 - 0.6 = 12.76 m/sec. Since the difference in velocities is greater than 9 m/sec, it can be concluded that serious or fatal head and thoracic injury could be caused in an impact with the given roadside hardware at the given vehicle impact velocity. Serious pelvic injury may not be caused as the velocity difference is just less than 13 m/sec.

The maximum worst likely values of HIC, TTI and P_y calculated using the method described in this paper are therefore 1276, 128 g and 128 g respectively. The occupant injury values obtained through these calculations are compared to the observed values using the ATD in Table 1. The estimated values shown in Table 1 all exceed the actual observed values showing that the method is conservative. The evaluation method suggested above would result in this test being considered a failure since the HIC and TTI both exceeded acceptable levels. The actual test was also considered a failure since the occupant injury parameters measured by the ATD were also in the unacceptable range. The actual values were smaller because the ATD in the test did not strike the door until later in the event. The results indicate that the simple method used to calculate the occupant injury gives reasonable yet conservative values that can be used to evaluate the results of a crash test.

CONCLUSION

As can be seen from the above discussion, all three injury criteria are related to the velocity time history of the intruding object.

$$
\begin{aligned}
{}^{t>0.010}\Delta V_{\max} &\leq 10.0\ m/\sec\ \ (head\,injury) \\
{}^{t>0.010}\Delta V_{\max} &\leq\ \ 9.0\ m/\sec\ \ (thoracic\,injury) \\
{}^{t>0.010}\Delta V_{\max} &\leq 13.0\ m/\sec\ \ (pelvis\,injury)
\end{aligned}
$$

Since the limiting value is given by the thoracic injury criteria, a single conservative evaluation criteria would be that the maximum difference between the initial impact velocity of the vehicle and any point of the struck object velocity time history after 10 msec must be less than 9 m/s. While an ATD in a specific test may result in lower values, the criteria shown above will result in conservative values that can be used to design and evaluate roadside safety hardware.

The method described in the foregoing sections provides an easily calculated measure of the worst-case occupant trauma that may be expected in similar real-world impacts. This method has the advantage of being easy to use while also being directly linked to observable established biomechanics evaluation parameters and the likelihood of real-world injury.

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Table 1. Comparison of calculated and recorded occupant injury values.

Injury criteria	91S003	
	Maximum Estimated	Observed
HIC	1276	503
TTI	128 g	97
P_y	128 g	- *
Pass or Fail	fail	fail

* Not measured in the full-scale test.

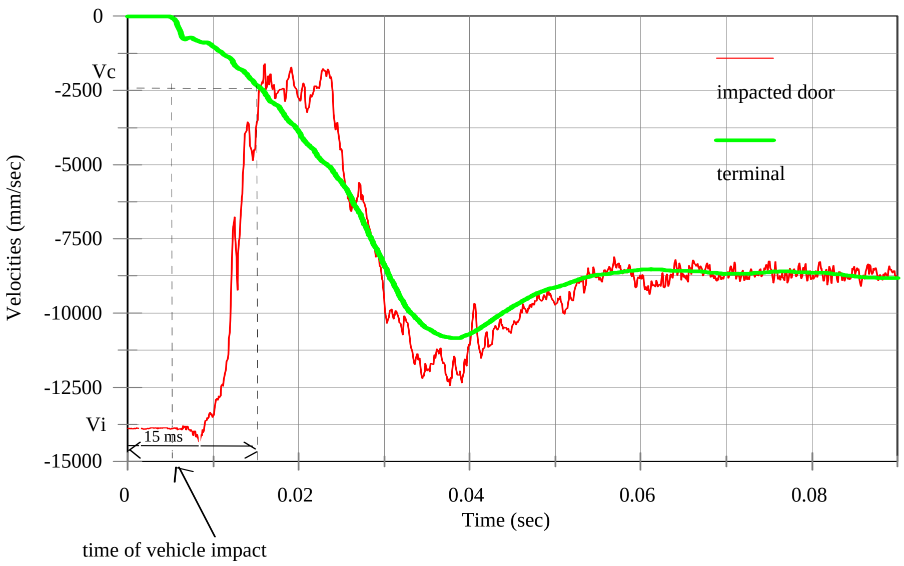

Figure 1. Impacted door and terminal velocity profiles for a vehicle impacting a guardrail terminal at 13,888 mm/sec (50 km/hr).

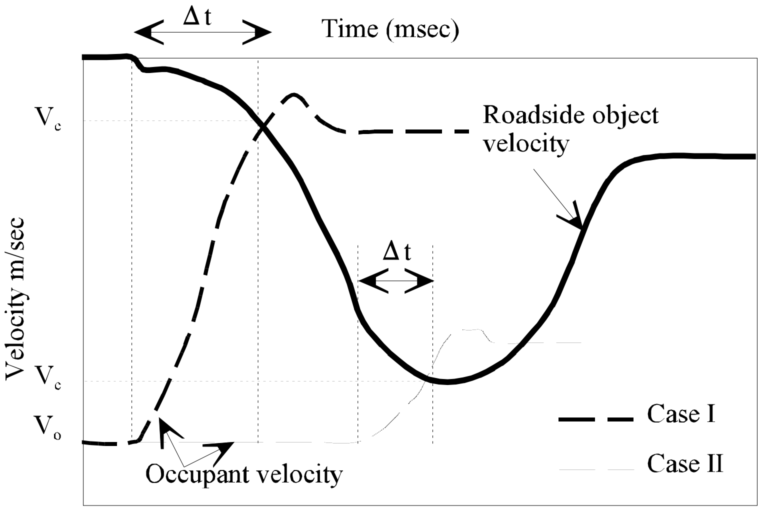

Figure 2. Hypothetical velocity time histories of the impacted object and the occupant.

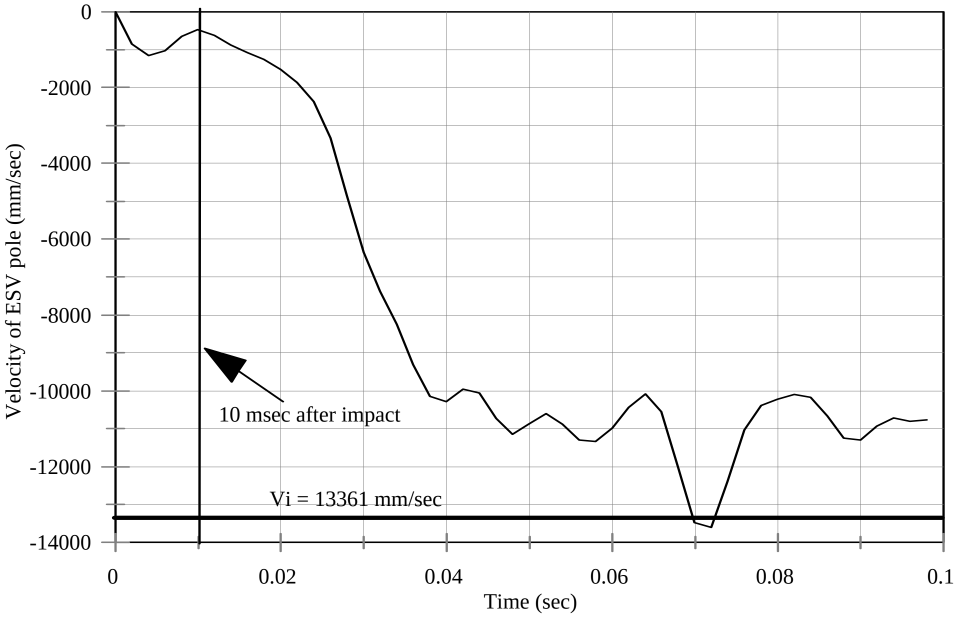

Figure 3. Velocity profile of an ESV pole when struck by a 1984 Honda Civic (test number: 91S003).