Collisions With Slow-Moving Vehicles

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On occasion, a driver may overtake and collide with a slow-moving or stopped vehicle. When this occurs, the driver is typically blamed for being inattentive, driving too fast or failing to monitor driving conditions. Often, however, in-depth analysis reveals that an ordinary driver with normal human capabilities and limitations cannot reasonably perform the evasive response required to avoid a collision.

This prompts the question, "Given a particular set of circumstances, is time available for the motorist to detect the presence of such vehicles, perceive the hazard (closure rate), evaluate available alternative collision-avoidance opportunities, decide which alternative is best, then maneuver to avoid a collision?"

SLOW-MOVING VEHICLE CLASSIFICATION

Certain vehicles, including farm machinery and construction equipment, that have a top speed below 25 miles per hour (mph) are classified as "slow-moving vehicles" (SMVs). Such vehicles are recognized as potentially hazardous to other vehicles approaching them at normal highway speed; in practical terms, all motor vehicles stopped or traveling at less than 25 mph on a highway are hazardous.

THE SMV COLLISION HAZARD

Although it may seem logical that collisions with SMVs would be associated with contributing factors such as wet or icy conditions, night driving, or visual

Slow-moving vehicle emblems are required for farm machinery and construction equipment that travel less than 25 miles per hour on public highways.

obstructions such as hills, roadway curves or the presence of other vehicles, such is not the case. Landmark traffic studies conducted nearly 40 years ago by Stucky and Harkness at Ohio State University showed that most collisions between motor vehicles and farm tractors, or highway maintenance and construction equipment, were rear-end collisions that occurred on open, level highways, in dry weather conditions, during daylight hours and without visual obstructions (Harkness 4).

Based on these findings, other research was conducted to understand this growing problem and define controls. Post-accident interviews highlighted a key concern: Many motorists reported that they had seen the SMV and had recognized it as such, yet had failed to recognize the high rate of closure before it was too late to avoid a collision.

THE SMV EMBLEM

Help for motorists arrived in the 1960s, with development and widespread use of the SMV emblem—a solid triangle of bright fluorescent orange (highly visible in daylight) surrounded by a retroreflective red border (glows brightly when illuminated by headlights at night). This emblem alerts the motorist that s/he is approaching an SMV; it signals a high (fast) rate of closure, which allows the driver to take immediate action to avoid a collision.

Several groups, including National Safety Council, American Society of Agricultural Engineers (ASAE), National Institute for Farm Safety, Automotive Safety Foundation and National Safety League of Canada recommended use of the SMV emblem, as did many local, state and regional groups and associations. Its use was first recommended by ASAE in 1966 (S276.1); by American National Standards Institute (ANSI) in 1971 (B114.1); and by the Society of Automotive Engineers in 1983 (SAE J943).

OSHA has adopted the ASAE and ANSI recommendations in 29 CFR 1910.145. Under this standard, employers must equip each SMV with the emblem when operated on a highway. Most states now require all SMVs to be equipped with the emblem as well. Some also require SMVs to be equipped with vehicular hazard warning lights (flashers); these flashers must be activated when the SMV is being operated on any highway (day or night).

OTHER HIGHWAY VEHICLES

Passenger cars, light trucks and 18-wheel semis typically travel at or near the posted speed limit. However, a hazard can arise when such vehicles are moving slowly or stopped on a highway. When a driver approaches a slowed or stopped vehicle, his/her recognition of the closing rate hazard is handicapped by previous experience which creates the expectation that the vehicle is traveling at highway speed.

ELEMENTS OF HUMAN PERCEPTION-RESPONSE TIME

One may ask, "Why does a driver with normal human capabilities need help to avoid colliding with an SMV?" To appreciate the difficulty that a typical motorist may have in this situation, one must consider what factors affect human perception and reaction time.

Detection

By definition, perception-response time begins when an object first enters a driver's field of view. In most cases, the object will be within the driver's peripheral vision and, depending on factors such as exact location, contrast and movement, some time will elapse before the driver is aware that something is present.

Safe motor vehicle operation requires a driver to shift the point of visual focus between various items—such as the road ahead, instrument panel and rearview mirror—while driving. Each eye movement takes time, and only one point of focus can be seen clearly at any given moment. The length of time required to change from one point of visual focus to another is significant. In a study of "visually fit" airplane pilots, it was found that the length of time required to shift focus from distance vision to instrument panel was 1.5 seconds; the shift from instrument panel to distance vision was found to take 2.39 seconds (Woodson 795).

Identification

An object cannot be seen in detail until it has been brought into focus within the cone of foveal vision—that is, until the driver looks directly at it. Only after this has occurred can the driver begin the mental process of recognizing the object and comprehending the significance of its presence. If the object is moving, the driver must also assess its speed and direction. The cone of foveal vision spans only about two degrees. To appreciate this size, imagine the field of view one can see by looking through an opening (aperture) roughly the size of a postage stamp held at arm's length.

Minimum decision time is required for familiar, practiced situations; however, unexpected situations require more time.

Decision

In a driving situation, the driver must determine whether a change in speed or direction is required. Minimum decision time is required for familiar, practiced situations; however, unexpected situations require more time. Based on expectancy and the level of evaluation and decision making required, four kinds of reaction time have been recognized in the literature: reflex, simple, complex and discriminative (Baker 15/25-15/27).

- **Reflex reactions** require the shortest time because no thought is involved. An eye blink is usually a reflex action. Driving does not normally involve reflex reaction; however, when a strong, unexpected stimulus causes a reflex (hysterical or convulsive) driver reaction, the result can be disastrous.
- **Simple reactions** are most frequently involved in driving. These are practiced reactions to familiar situations (e.g., moving one's foot from the accelerator to the brake pedal in reaction to a changing traffic signal). Driver handbooks frequently cite 0.75 seconds as the perception-response time for a typical driver in such situations.
- **Complex reactions** require the driver to choose between two or more possible responses to somewhat familiar driving situations. This requires more time than a simple reaction. In fact, depending on the complexity of the stimulus, available choices and the driver's experience, a few seconds may be required.
- **Discriminative reactions** occur when an unfamiliar situation requires a driver to choose between several responses that are not habitual or practiced. This is the slowest reaction time. Complicated situations with slight urgency may require several seconds; when the situation is urgent, panic may cause a driver to either make an inappropriate response or fail to react.

Response

The last element of this equation is the time the nervous system needs to activate muscles involved in executing the chosen response plus the time for muscles to move in order to begin the action (e.g., turn the steering wheel, apply pressure to the brake pedal). Initiation of the response ends perception-response time. The time to complete the intended maneuver, such as lane changing or stopping, is not included.

NIGHTTIME: A SPECIAL SITUATION

As noted, a potentially hazardous situation exists whenever an SMV occupies a moving traffic lane on a highway. If this situation occurs at night on an unlit highway, the degree of hazard and risk of a serious accident increases because visual cues that help a driver perceive distance during daylight are no longer available.

For example, when a driver approaches a vehicle that does not display an SMV emblem or vehicular hazard warning lights, no cues alert him/her of an impending hazardous situation.

In addition, although the driver may see the taillights from a considerable distance, because of familiarity with taillights, the driver will likely assume the vehicle is moving at highway speed. If, however, the vehicle is stopped or moving slowly, will the driver recognize that this assumption is incorrect with sufficient time remaining to avoid a collision?

This depends primarily on the driver's ability to perceive that the visual angle of the taillights is not remaining constant, but is increasing. The size of this angle and the angular rate of change depend on the width of the slow or stopped vehicle (i.e., space between taillights), distance between the vehicles and the actual closing rate. It can be shown that large targets and slow closing rates favor the driver's ability to perceive and react in a timely manner, while small targets and fast closing rates handicap his/her ability to recognize the hazard.

QUANTIFYING DRIVER PERCEPTION-RESPONSE TIME

A human factors engineer attempts to apply the "rule of compatibility"—to determine whether the requirements of a particular task are compatible with normal human capabilities and limitations. To achieve this, s/he must determine the reasonable range of human response-reaction time given particular circumstances.

Experimental psychologists have undertaken many studies to measure response-reaction time both in the laboratory and in the field (Konz and Daccarett 75-79; Nagler and Nagler 261-274; Grime 466-486; Barrett, et al 19-24). Despite their best efforts, the results have limitations. One key problem is the challenge of testing sufficiently large and representative populations needed to obtain statistically valid results. A more-basic problem is that researchers cannot expose test subjects to risk of serious harm.

Due to these practical and ethical considerations, researchers cannot produce experimental results that can assign precise reaction times to a given real-world driving situation (Olson 172). Reported results may represent minimum reaction response times for subjects and conditions tested, but these results typically fall short of providing a basis for precise prediction of the full range of reaction times that can be expected in actual traffic conditions. As a result, the human factors engineer must exercise best judgment when using test results to predict perception-response time in specific circumstances.

VISUAL INFORMATION RELATED TO TIME-TO-COLLISION

The next question is, "How can closure rate and time-to-collision be derived from the optical variables that a driver may observe?" For those situations where closing speed between two objects is constant, the time remaining before collision is calculated mathematically by dividing the current distance (Z) by the instantaneous speed of approach (-dZ/dt). This relationship, Z/(dZ/dt), is denoted as the "tau-margin" in human factors literature.

In the case of head-on approach at a constant rate of closure, closing rate is perceived by observing the angular size of an observed object (as viewed at any moment) relative to the rate of increase in angular size or "how fast the object is growing in size." Mathematically, the optical angle ϕ divided by the angular rate of dilation $d\phi/dt$ specifies the tau-margin as follows:

$$\text{tau-margin} = (\phi)/(d\phi/dt) = \text{time-to-collision}$$

HUMAN PERCEPTION THRESHOLD FOR OPTICAL DILATION

For a person to perceive that s/he is approaching an object within his/her field of view, the object's size must grow at a certain threshold rate. Olson's *Forensic Aspects of Driver Perception and Response* examines this topic.

> Plotkin (1976) has reported research on the ability of subjects to discern closing speed. In a controlled study he found that the limit of human perception was 25 to 30 milliradians per second. In equation form, the results can be expressed as follows:
>
> $V \geq (0.0275s^2)/w$
>
> Where:
>
> V = velocity in ft. per second
>
> 0.0275 = perception limit in radians per second

FIGURE 1

Time from Instant at which Perception of Closing Rate Becomes Possible Until Instant of Collision

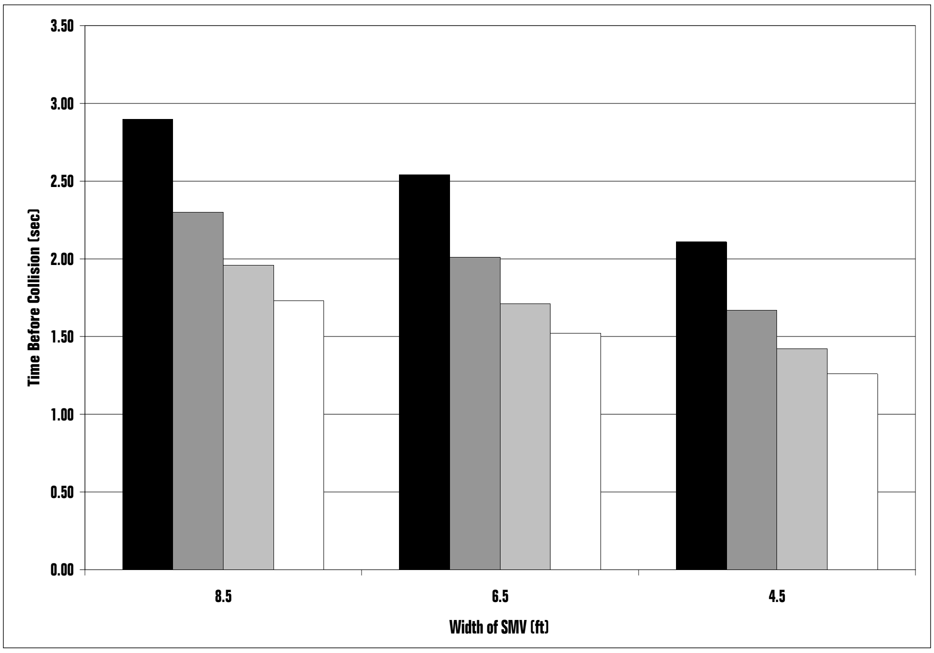


TABLE 1

Threshold Time Before Collisions

(Seconds)

Closing Speed	Slow Moving Vehicle Width		
	8.5 ft.	**6.5 ft.**	**4.5 ft.**
25 mph	2.90	2.54	2.11
40 mph	2.30	2.01	1.67
55 mph	1.96	1.71	1.42
70 mph	1.73	1.52	1.26

Table 1 Note: Vehicle widths and closing speeds were selected to cover a range of values corresponding to many situations likely to be encountered on the highway. The following procedure was used to calculate the table values. First, threshold distance at which human perception of closing could occur was calculated using Plotkin's rearranged equation $s \leq (Vw/0.0275)^{1/2}$. Next, time until collision was calculated by dividing threshold distance by closing speed. For example, at a closing speed of 55 mph and a vehicle width of 6.5 ft., calculated threshold distance for recognition of closing is 138 ft. Time until collision is calculated by dividing threshold distance by closing speed as follows: t = 138ft./80.67ft./sec. = 1.71 seconds.

s = the distance between vehicles in ft.
w = the width of stopped vehicle in ft.

This equation can be used to illustrate people's maximum capability to judge closing speed. Bearing in mind that the subjects were fully informed of the purpose of the investigation, their expectancy was different from that of a driver who has no reason to believe that the vehicle ahead is stopped or going slower than normal. This says that the constant 0.0275 radians/second would be significantly greater when applied to real-world situations. How much greater is, unfortunately, a matter of conjecture.

In sum, the ability of persons to judge the speed of another vehicle, whether traveling in the same or opposite direction, is limited under controlled test conditions. In the real world, when the situation is counter to what the individual expects from that other vehicle, it will certainly be much worse.

EFFECT OF CLOSING SPEED & VEHICLE WIDTH ON PERCEPTION OF CLOSING RATE

As noted, the threshold rate necessary to perceive closure is an optical dilation rate of about 0.0275 radians per second (1.58 degrees per second). In some real-world situations, such as on a dark highway, optical dilation is the principal mechanism by which a driver may judge closing rate. Table 1, which includes a range of closing speeds and SMV widths, lists calculated elapsed times from the instant at which closing rate can be perceived until closing speed results in collision. Figure 1 offers a graphical presentation of this data. Table 2 lists calculated values of distance, time, visual angle and angular rate of change for a closing rate of 54.5 mph (80 ft. per second) and an SMV width of 8 ft.

AN ACTUAL ACCIDENT INVESTIGATION

A subcompact passenger car and a highway tractor/closed-van semi-trailer collided on a rural, unlit two-lane highway; the accident occurred in clear weather, after dark.

The truck driver had slowed to enter the parking lot of a roadside convenience store. Before turning, however, he discovered the store was closed and was beginning to resume speed. At the time of the collision, the truck was in the right-hand lane, traveling an estimated 10 mph. There was no indication that the truck's brake lights, turn signals or hazard warning flashers were activated.

The driver of the subcompact was following the truck when his vehicle collided with the rear of the semi-trailer. The rear of the truck offered little resistance to "run-under" by the subcompact. As a result, the lower half of the small car was wedged beneath the semi-trailer and remained entangled while the truck driver pulled off the highway.

No skid marks were present prior to the collision. Had the motorist been traveling at the posted speed limit (which was 65 mph), estimated closing rate would have been 55 mph. The fatally injured driver had a clean driving record. Post-mortem blood analysis showed no trace of alcohol or drugs.

The investigating police officer cited "motorist failure to control speed" as the accident cause; he also indicated that the motorist might have been distracted, fatigued or asleep, yet offered no criticism of the truck driver.

Application of Optical Dilation Detection Threshold

Rearranging the original equation to solve for "s" (distance between vehicles in ft.) gives: $s \leq (Vw/0.0275)^{1/2}$

Assuming that the closing rate was 55 mph (80.7 ft. per second) and that the width of the semi-trailer was 8 ft., the calculated value of "s" is 153.2 ft. Based on Plotkin's test results as reported by Olson, the earliest opportunity under test conditions for a fully informed and alert driver to detect that his/her vehicle was closing on the truck would occur at a distance of 153.2 ft.

At a distance of 153.2 ft. with a closing speed of 80.7 ft. per second, the maximum time available before collision is determined by dividing 153.2 ft. by 80.7 ft. per second=1.9 seconds. Actual distance and time available for an unsuspecting driver would be significantly less. Figure 2 depicts visual angle and angular change versus time before collision for a closing speed of 55 mph with an 8-ft.-wide target.

Test Results of Driver Perception-Reaction Time

Several tests have been conducted to measure response-reaction time to actual driving situations. The results provide what is perhaps the best basis on which to estimate expected response to a closing rate hazard. In two series of tests, ordinary unalerted motorists were "trapped" between two test vehicles (Olson 180). The lead vehicle would depress the brake pedal enough to activate the brake lights and the following vehicle would record the elapsed time until the trapped driver's reaction was indicated by activation of the vehicle's brake light.

Average response-reaction times for different groups of motorists and different brake light configurations in this study ranged from 1.25 seconds to 1.45 seconds. The 85th percentile response was reported for two series of tests conducted; it was about 1.9 seconds.

While these tests measured the reactions of unsuspecting motorists driving real vehicles, the situation studied was one familiar to all motorists—something they had experienced many times. Therefore, these results should be considered measures of *simple reaction time.* One must significantly increase any estimate of perception-reaction time to an unfamiliar situation.

Summala conducted a series of tests on perception-response time to a driving situation that required a steering response (Sanders and McCormick 588). In one series, the door of a car parked along a roadside was opened to cause approaching cars to veer to the left. In another series, a light was turned on at roadside causing a similar response.

In both tests, the average time to initiate a steering response was about 1.5 seconds. Further, it was found that the steering response reached the 50 percent point at about 2.5 seconds while thea maximum steering response was reached between 3 and 4 seconds. Based on these findings, Summala recommended that at least 3 seconds should be allowed to perform steering avoidance maneuvers in the roadway environment.

Expected Driver Reactions in the Investigated Accident

Several factors must be considered to estimate the driver's expected reactions and his ability to avoid collision with the slow-moving truck.

1) Based on documented human limitations associated with detection of visual angular dilation, the driver of the car would not have been able to perceive that he was closing on the truck until less than 1.9 seconds (likely much less) remained prior to impact.

2) Based on documented human limitations related to reaction to relatively familiar driving situations, the driver would have needed more than 1.5 seconds to react to the closing rate hazard presented by the slow-moving truck.

3) Based on the mechanics of automotive braking and steering systems, system (vehicle) reaction time is required before a selected maneuver (slowing or turning the vehicle) begins to take effect. Brake pedal pressure or steering wheel movement must be translated through mechanical systems to create frictional forces between tire treads and the road surface. Even if the driver had begun an attempt to maneuver his vehicle prior to impact, no time was available in which to accomplish the maneuver.

4) In light of these considerations, it is clear that, given a closing speed of 55 mph, a normal driver could not be expected to perceive the closing rate hazard and respond by controlling his vehicle to avoid colliding with the slow-moving truck.

CONCLUSIONS REGARDING ACCIDENT CAUSE

Given the circumstances described, most drivers would not be able to react in

TABLE 2

Calculated Visual Angle & Angular Rate of Change

Based on Closing Rate ~55 mph (80 fps) and an SMV Width of 8 ft.

Distance (feet)	Time (seconds)	Visual Angle (degrees)	Angular Change (degrees/second)
1600	20	.286	.014
1520	19	.302	.016
1440	18	.318	.018
1360	17	.337	.020
1320*	16.5	.347	.021
1280	16	.358	.022
1200	15	.382	.025
1120	14	.409	.029
1040	13	.441	.034
960	12	.477	.040
880	11	.521	.047
800	10	.573	.057
720	9	.637	.071
640	8	.716	.086
560	7	.818	.115
480	6	.955	.160
400	5	1.15	.229
320	4	1.43	.355
240	3	1.91	.636
160	2	2.86	1.43
80	1	5.72	5.72

Table 2 Note: 1320 ft. = 1/4 mile. The times-to-impact listed in column 2 were calculated by dividing each distance shown in column 1 by the assumed closing speed of 80 ft. per second. Visual angles listed in column 3 were calculated according to:

$a = 2[\tan^{-1}(.5d/s)]$

where:

a = **the visual angle in radians (converted to degrees)**

d = **the diameter of the visual target (8 ft.)**

s = **the distance between observer and target in ft. (column 1)**

Instantaneous rates of change in the visual angles listed in column 4 were calculated according to:

$da/dt = [-d/(s^2+.25d^2)]ds/dt$

where:

da/dt = **the instantaneous rate of angular change in radians per second (converted to degrees per second)**

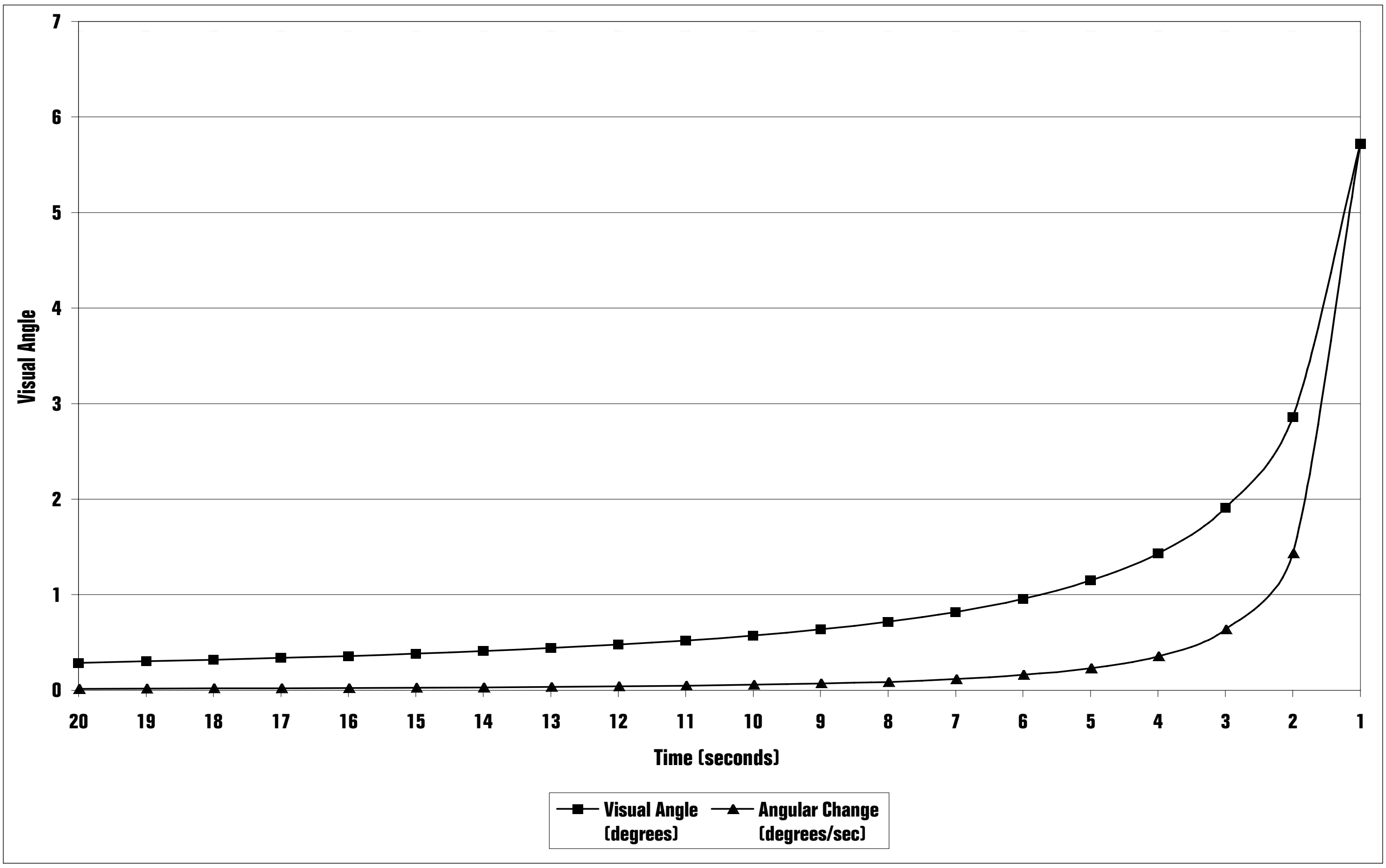
d = **the diameter of the visual target (8 ft.)**

s = **the distance between observer and target in ft. (column 1)**

ds/dt = **closing speed (-80 ft. per second) Note: when "s" is decreasing, ds/dt is negative.**

FIGURE 2

Visual Angle vs. Time Before Impact
Approaching 8-ft.-wide Target at 55 mph



time to avoid colliding with the rear of the semi-trailer.

Because human error is a factor in many motor vehicle accidents, investigators often "rush to judgment" in assigning human error as the accident cause. Although people do make errors, they also have limitations.

The accident described was actually caused by a situation where basic human limitations in perception of closing rate prevented the driver from avoiding a collision even though he was alert, attentive and driving within the posted speed limit. In this case, the best opportunity to avoid the fatal collision was missed when the truck driver failed to turn on the hazard warning lights (flashers) while regaining highway speed. It is ironic that he would have been required by law to display hazard warning lights had he been operating a farm tractor instead of an 18-wheeler. ■

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