Forensic Engineering Analysis of Total Reaction Time

By James M. Green, P.E., DEE

ABSTRACT

This paper develops a method for determining a meaningful reaction time in accident reconstruction and civil engineering design. A method for Total Perception Time (TPT) is explained using literature from the professions of Psychology, Optometry and Engineering. A determination of Total Perception Time (TPT), or Total Perception Distance (TPD), is given where the engineer allows enough time for the actual stimulus to be identified before determining if evasive action can be taken or collision can be avoided. The use of TPT can be calculated in accident reconstruction and Engineering design by using the actual environmental conditions that were present at the site under investigation. The purpose of presenting this analysis is to establish a starting point for discussion and evaluation of Total Perception Time (TPT) or Total Perception Distance (TPD). The reaction time sequence affects every facet of forensic engineering and civil engineering design. It is the writer's intent that a definition of this methodology can be developed in order that the engineering community will have a tool that is accepted.

INTRODUCTION

In reconstructing accidents, confusion exists as to the proper application of total reaction time (TRT) to the entities involved in the accident. The purpose of this paper is to review the existing literature and to analyze the various professions' definition of total reaction time. The psychology and opthamology analysis being made in this paper is to establish total reaction time (TRT) that utilizes the principles of conspicuity, as well as civil and traffic engineering. Confusion is apparent in the reconstruction of accidents, and in engineering design, over the use of conspicuity. The ability to see a stimulus, under ambient conditions present, is the study of conspicuity. The use of factors such as color, lighting, reflectivity and other environmental criteria must be considered to determine reaction time. It is not the intent of this paper to define the method for calibrating lighting at an accident site. For a complete treatment of the gridding procedure, see the references[4, 7].

Basic Human Perception-Reaction Time - Literature Review

In Paul Olson's paper [5], the components of perception-reaction time (PRT) are defined as follows: Detection begins when an object or condition of concern enters the driver's field of vision. The detection step concludes when the driver has developed a conscious awareness that "something" is present. Olson concludes that this stimulus may be in the field of view of the driver for some time before it is consciously detected. The driver then identifies the object, decides on the appropriate action, and commands the muscle groups to carry out the required action. This is what Olson defines as "response distance" or "response time".

Olson's analysis continues in an attempt to summarize the research so that the time required for a driver to respond to an emergency situation can be quantified. The analysis correctly or incorrectly confirms that the action to be taken by the driver is difficult or impossible to accomplish because there were too many variables in the conspicuity of the stimulus. Olson goes on to compare various studies on this issue and concluded that a basic response time of 1.5 seconds would be appropriate in cases of conspicuity. Olson states that an increase in the PRT of 1.5 seconds is a matter of judgment [6,7,8].

Examination of the data in the various studies presented in Olson's paper indicate that the actual human physiological response time is likely to be between .75 and 1.5 seconds dependent on age and the stimulus used in the study. The problem in detailing a finite response time is the other variables that are present in the real world. Foremost of these variables presented in the studies [6, 7, 8] supporting the Olson paper is the ability for the stimulus to be seen. The issue of conspicuity is interwoven throughout the studies referenced in the Olson paper. The PRT values given by the various studies also are developed during ambient daylight hours.

Perception-Reaction and Avoid Time at Night

Olson and Sivak [4] broaden the problem of perception to include nighttime driving. The writer has reconstructed hundreds of pedestrian and cycling accidents at night, whereby he has verified that the variables are complex and are a function of the conspicuity of the clothing worn by the pedestrian or cyclist, reflectivity, ambient light, headlight aim, as well as other factors. Accidents investigated usually include a motor vehicle colliding with pedestrians or cyclists. However, the emphasis in Olson and Sivak's analysis is the conspicuity of the individual within the range of headlights. Since the speed of approaching motor vehicles may vary, Olson and Sivak give response time and response distance to pedestrian targets. They include the use of dark and light targets. The expected response distances in Olson and Sivak's paper are as follows:

Table 1: Expected Response Distances (ft) to Pedestrian Targets

Headlamp Beam	Target Location	Clothing	Average Response Distance	Range
Low	Right	Dark	80	0-160
		Light	160	80-240
	Left	Dark	60	0-120
		Light	120	60-200
High	Right	Dark	120	60-300
		Light	240	160-400
	Left	Dark	120	60-300
		Light	240	160-400

Olson and Sivak note that the use of headlight high beams at night increase visibility, but not as much as "one might think". Their rough rule of thumb gives high beam headlights improving detection and the identification distance to objects on the right side of the road an increase of approximately 50 percent. The improvement of detection and identification to objects on the left side of the road increases by approximately 100 percent. This difference is due to the fact that low beams direct most of their intensity to the right. Olson and Sivak also note that proper reflective clothing will increase the response distance "substantially", but they do not quantify the increased visibility of the subject.

In order to determine a total reaction time (TRT), the review of literature indicates that the stimulus must be recognized as actually being present. Olson's use of the 1.5 seconds as a basic response time is a reasonable first step. Civil and transportation engineers [1] when designing intersections use a line of sight reaction time of 2.5 seconds for design speeds for the minimum PRT-time necessary to respond to emergency situations.

Regardless of the reaction time used, it is essential that the stimulus confronting the driver must be recognized in order to invoke a driver response.

To date, the Blomberg Studies [2, 3] are the leading methodology currently employed in field studies used to define the effect color and retroreflectivity have on initial recognition distance. During nighttime hours, Blomberg found that the use of lighting, reflective clothing and bike retroreflectors increased the recognition distance from as low as 75 feet to as much as 1200 feet. Blomberg's analysis has been found to be correct and the increased recognition distances have been found to be reliable [4].

The salient points in Blomberg's studies that have a direct bearing on the development of a TRT are as follows:

- Nighttime recognition distances for an object in dark clothing with no other means of conspicuity are approximately 75 feet on low beams. High beams do not appreciably increase recognition distance (See Table 1).
- Nighttime visibility is increased to as much as 560 feet with fluorescent clothing [2, 3, 4]. The visibility is further increased by lighting systems that meet the DOT requirement of 600 feet. Beyond the 600 feet of car beam headlights for both high and low beams, recognition distance of an object should be determined by using unbiased observers as was done in the Blomberg studies.
- Daytime visibility is increased from 400 feet to 2200 feet with fluorescent clothing [2,3,4]. The other types of clothing evaluated in the Blomberg studies, as well as other researchers [2, 3, 4], show visibility and recognition distances will vary with the type of clothing worn.

The Use of TRT in Forensic Engineering Applications

From the literature, and several hundred field studies and reconstructions, the application of the reaction sequence is recommended in the following equations:

Total Reaction Time (TRT) is equal to Perception-Reaction Time (PRT) + Avoid Time (AT) or

TRT = PRT+ AT.

In order to avoid an impact, perception-reaction time (PRT) plus avoid time (AT) must be less than Total Time for Avoidance (TAT) or

PRT + AT < TAT

If braking distances are being used, then the total reaction distance (TRD) is equal to perception-reaction distance (PRD) plus avoid distance (AD). Avoid distance is the braking distance required to avoid impact. In terms of distance, the equation becomes;

TRD = PRD + AD

In order to avoid an impact, reaction distance (RD) plus avoid distance (AD) must be less than Total Distance for Avoidance (TAD) or;

RD + AD < TAD

Case Study 1: Cyclist's Being Struck at Night

Two bicyclists' were riding one bicycle at night. One cyclist was on the seat peddling and one cyclist was seated on the handlebars. Both cyclists were dressed in black. The bicycle was equipped with neither a light nor a set of retroreflectors. However, the pedals were equipped with retroreflectors.

Both cyclists were legally intoxicated and were driving in the middle of the road on a dark secondary road at 9 PM at night. The cyclist's were hit from behind by a Tractor Trailer combination at approximately 40 MPH.

The Plaintiffs and plaintiff families alleged that the truck driver was negligent by failing to perceive, react and avoid the cyclists.

Case Study 1 Analysis - The major objective of the analysis was to determine the distance at which the truck driver was able to perceive the two cyclists. Analysis of the accident scene revealed that the background lighting was 2 LUX. The amount of light from a source striking a surface is defined as illumination and is measured in LUX. 1 LUX is 1 lumen/M^2 or 1 FT-candle. There were no light poles (luminaries) providing artificial light. The ability to perceive the cyclist's was solely dependent on the light being reflected back from the bodies of the cyclist's and the subject bicycle.

Inspection of the subject clothing revealed that the individuals were wearing high heeled work boots, that more probably than not, covered up the pedal retroreflectors. The analyses was based on the perception distance of the two cyclist's on low beams. The issue of why the driver had low beams on a dark road was argued throughout the trial.

Current literature indicates that under low beams with this type of clothing, the perception distance was approximately 75 feet according to Blomberg, and approximately 60 feet with a range of 0 to 120 feet according to Olson and Sivak (See Table 1).

The literature gave a reasonable starting point in the analysis. Five unbiased subjects were obtained in the age group of the driver. An exemplar rider was placed on an exemplar cycle as a test target. The rider was an android dressed in the same type of clothing. An exemplar truck approached the test target at 40 MPH and perception distances were recorded on low beams with the test target in the center of the road. Perception distances were defined as the distance at which the unbiased subjects first recognized that a cyclist was in front of the truck and avoidance was necesary. These values were as follows:

Table 2:

Perception Distances at 40 MPH Using Unbiased Subjects

Subject	Perception Distance (ft)
1	78
2	91
3	62
4	74
5	83
Average Perception Distance	78 Feet

All 5 subjects either hit the test target or swerved and barely missed the test target during the test runs. The braking distance (AD) was found to be 140 Feet at 40 MPH.

Determination of Total Reaction Distance Case Study 1

Using the actual field test data, the Total Reaction Time was calculated as follows:

$$\text{Perception-Reaction Time} = \frac{78 \text{ feet}}{58.8 \text{ ft/sec}} = 1.33 \text{ seconds}$$

Perception-Reaction Distance = 78 Feet

where 40 MPH = 40 MPH x 1.467 ft/sec/mph = 58.7 ft/sec

Total Reaction Time = PRT + AT

Total Reaction Distance = PRD + AD

Low Range TRD = (0.75 sec)(58.7 ft/sec) + 140 ft

Low Range TRD = 184 FT

High Range TRD = (1.50 sec)(58.7 ft/sec) + 140 ft

High Range TRD = 228 FT.

In this case study, the following conclusions were made:

1. The avoid time in this case is the time the truck would take to stop or avoid the cyclists. Testing of the actual truck, which had a gross vehicle weight of 28,000 pounds, revealed the actual stopping distance to be 140 feet after brake application. It was decided to use Total Reaction Distance in the analysis.

2. As stated earlier, perception-reaction distance plus avoid distance must be less than total distance for avoidance. (PRD + AD < TAD).

   a. For low range reaction time available for the driver of 0.75 seconds;

      TRD = PRD + AD = 184 FT

   b. For the high range reaction time available for the driver of 1.5 seconds

      TRD = RD + AD = 228 FT

   c. Both 184 FT and 228 FT are more than 78 FT (PRD + AD < TAD). The accident could not be avoided.

Case Study No. 2: Transit Bus Struck at Night at an Intersection

A transit authority bus proceeded through an intersection and stop sign onto a high speed highway. The bus was struck in the side by a 2 axle truck-tractor at 67 MPH with gross vehicle weight of more than 27,000 pounds. The truck was hauling another 3 axle single unit truck. The transit authority bus driver claimed that the sun was still in the sky and that he was not required to have on headlights or running lights until after Civil Twilight.

Case Study 2 Analysis - Evaluation of the meteorological data from the U.S. Naval Observatory for the accident site revealed that Civil Twilight had passed. Under the state code, for the State in which the accident had occurred, the end of Civil Twilight requires that lights be turned on for motor vehicles. Evaluation of the accident site on the meteorological anniversary date revealed that background illumination was 3.0 LUX. Therefore, the primary stimulus for TRT or TRD was the visibility of the bus under the lighting conditions.

The actual bus involved in the accident was utilized for luminance measurements. The side opposite the impact point was undamaged and suitable for analysis. The bus was placed perpendicular to the path of the truck on a deserted road. An exemplar truck was placed at various distances to determine perceive distances.

Table 3:

Perception Distances and Luminance Values with Low Beams

Distance	Luminance (ft Lambert)[a]	Subject[b]
50	212	yes
100	193	yes
150	184	yes
200	60	yes
250	37	yes
300	21	no
350	6	no
400	4	no
450	2	no
500	0	no
550	0	no
600	0	no

a - A 1 degree spot photometer was used for a narrow angle reflected- light measurement. This instrument may be special ordered from Spectra Cine, Inc., 3607 West Magnolia Blvd., Burbank, CA 91505.
b - A biased subject was used here to determine where the bus could no longer be seen. Costs associated with the project prohibited unbiased subjects being used.

Determination of Total Reaction Distance Case Study No. 2

Using the developed field data, the total reaction time (TRT) or total reaction distance (TRD), was calculated as follows:

The truck was traveling 67 MPH (98.27 ft/sec)

Braking Tests revealed the truck could stop in 240 feet at 67 MPH.

Therefore;

Low Range Total Reaction Distance = (0.75 sec)(98.27 ft/sec) + 240 ft

Low Range TRD = 314 ft

High Range Total Reaction Distance = (1.5 sec)(98.27 ft/sec) + 240 ft

High Range TRD = 387 ft

PRD + AD must be less than TAD. Using the maximum TRD values,

- Low Range TRD = PRD + AD = 314 FT

  PRD + AD must be less than TAD

  314 > 300 FT

- High Range TRD = PRD + AD = 388 FT

  PRD + AD must be less than TAD

  388 FT > 300 FT

Therefore, the accident could not be avoided once the bus pulled into the intersection.

Case Study 3: Motorcyclist Striking a Truck at Night

While under pursuit by the police, a motorcyclist struck the trailer portion of a tractor trailer at 90 MPH in 25 MPH speed zone. The motorcyclist was killed and his estate sued the tractor trailer owner for backing into a driveway on the rural road at the accident site.

Case Study 3 Analysis - Investigation of the tractor and trailer indicated that both entities met the DOT requirements for retroreflectivity. Unbiased observers were utilized to determine perception distances. The tractor trailer was placed on the roadway in the same location as the accident. The perception distances were 1400 feet for motorcycle high beam and 1150 feet for low beam. Motorcycle stopping distances at 90 MPH were 390 ft and at 25 MPH were 33 ft. The pertinent data generated yielded the following:

High Range TRD = PRD + AD

= (1.5 sec)(90 MPH)(1.47 ft/sec/MPH) + 390 ft

High Range TRD = 198 ft + 390 ft = 588 ft

To avoid the impact,

PRD + AD < TAD

198 ft + 390 ft = 588ft

588 ft is less than 1400 ft

Even at 90 MPH, the motorcyclist had plenty of time and distance to avoid the impact.

Conclusion

The literature discussed in this paper indicated that certain points are agreed upon among the Psychology, Optometry and Engineering Professions regarding TRT and TRD. These points are as follows:

1. The human body typically reacts physiologically from 0.75 to 1.5 seconds in expected stimulus response situations. An example of this scenario is the measuring of response time for someone to react to a sudden flash of light in the laboratory.
2. The human body takes varying periods of time to recognize that a response to a stimulus may be necessary. An example of this would be a driver in a motor vehicle attempting to discern and identify an object in the road ahead at night. For example, assume a driver comes upon a cyclist in the road ahead at night. The cyclist is dressed in black and has no lights or retroreflectors on the cycle. In this instance, the driver will not discern movement sufficient enough to alert him or her of the need to avoid until close to 75 feet treshold to the eventual point of impact.
3. A definition of TRT is the total time a subject will take to react and avoid a stimulus after perceiving the danger. When the Forensic Engineer is determining the causal factor of an accident, the perception time which the first part of the TRT, must take into account the environmental and ambient conditions that are present. This can only be done from a properly calibrated accident site. The calibrated site must utilize the accepted methods for accurately defining, with a high degree of engineering and scientific certainty, the conditions at the scene when the accident occurred[1].
4. The Engineer should attempt to reproduce the conditions utilizing unbiased subjects to accurately define the perception distance. If an accident occurred at night on low beams with an accident victim dressed in a certain manner then that is the situation that should be reproduced using unbiased subjects. From that simulation, the perception time can be determined.

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1. Green, James M., "Bicycle Accident Reconstruction for the Forensic Engineer", Trafford Publishing, www.Trafford.com/robots/01-0366html, 2001, pp. 73-78.

5. When using distances, perception-reaction distance plus avoid distance must be less than total avoid distance to avoid impact. (PRD + AD < TAD)

Summary

The review of published literature revealed that perception is a function of the conspicuity of the subject under the ambient environmental conditions in place at the time of an accident. The definition of perception time should be determined from simulation of the actual environmental conditions and the conspicuity of the accident subject at the time of the accident. This should occur using the speeds of the individual components of the accident. If a motor vehicle is approaching a subject at 30 MPH, then that is the speed that should be used to determine perception time [a]. The relationships for analyzing collisions with objects both at night and during the day are as follows:

- Total Reaction Time (TRT) = Perception-Reaction Time (PRT) + Avoid Time (AT)
- Perception-Reaction Time (PRT) + Avoid Time (AT) must be less than Total Time for Avoidance (TAT) for collision not to occur.
- Total Reaction Distance (TRD) = Perception-Reaction Distance (PRD) + Avoid Distance (AD)
- TRD, or PRD + AD, must be less than Total Avoid Distance (TAD) for the collision not to occur.

[a] The writer actually witnessed a “accident reconstructionist,” simulate on video a cyclist leaving the pool of low beam light in front of a truck at night, which wasalleged to represent the lighting conditions while a truck was approaching the cyclist at 35 MPH. The “ accident reconstructionist,” then swore under oath that the 22 seconds it took for the cyclist to disappear from this pool of low beam light represented the lighting conditions, and the ability of the truck driver to see the cyclist at the time of the accident. The error in this analysis was that the truck was approaching the cyclist at 35 MPH. However, the test truck was actually doing zero and the test bicycle was doing 2 MPH as calculated from the video. This in no way simulated the actual accident and mislead the Court.

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REFERENCES

1. AASHTO. A Policy on Geometric Design of Highways and Streets. *American Association of State Highway and Transportation Officials*, 1990, pp. 45-49.

2. Blomberg, R. D., A. Hale, and D. F, Preusser. Conspicuity for Pedestrians and Bicyclists: Definition of the Problem, Development and Test of Countermeasures. *U.S. Dept. of Transportation, National Highway Traffic Safety Administration*, DOT HS-806-563, April 1984, pp. i-xii, 1-78, Appendix A-1-K-5.

3. Blomberg, R. D., A. Hale, and D. F. Preusser. Experimental Evaluation of Alternative Conspicuity – Enhancement Techniques for Pedestrians and Bicyclists. *Journal of Safety Research*, 1986, Vol. 17, pp. 1-12.

4. Green, J. M. *Bicycle Accident Reconstruction for the Forensic Engineer*, Trafford Publishing, www.trafford.com, 2001, pp. 55-67, 73-78, 81-83. This is the procedure I routinely use. The writer has worked this method out through the years with engineers that specialize in showing lighting by animation.

5. Olson, P. L., Ph.D. and M. Sivak, Ph.D. Visibility Problems in Nighttime Driving. *Human Factors and Biodynamics*, 1981, Chapter 15, pp. 383-401.

6. Olson, P. L. *Driver Perception Response Time*. The University of Michigan Transportation Research Institute, SAE paper No. 890731, 1989.

7. Owens, A. D., E. L. Francis, and H. W. Lebowitz. *Visibility Distance with Headlights: A Functional Approach*. SAE paper No. 890684, 1989.

8. Sens, M. J., P. H. Cheng, J. F. Wiechel, and D. A. Guenther. *Perception/Reaction Time Values for Accident Reconstruction*. SAE paper No. 890732, 1989.

Additional References

1. Dixon, Harry, “Night Auto Pedestrian Accidents Driver View: Whence Pedestrian,” *Journal of the National Academy of Forensic Engineers,* Vol. IV, No. 2, December 1987.

2. Dixon, Harry, “Night Auto Pedestrian Accidents: Pedestrian View, Part I, *Journal of the National Academy of Forensic Engineers*, Vol. VII, No. 1, June 1970.