Traffic Sign Reading Distances and Times During Night Driving

HELMUT T. ZWAHLEN

Videotaped eye fixations and saccades (30 frames per second) were analyzed for 32 young, healthy unfamiliar drivers along rural two-lane highways in Ohio under low-beam illumination conditions at night for the approach to a curve/turn warning sign (curve/turn symbol) for two selected curves. The first-look distance (longitudinal distance measured from the sign to a driver's eyes at which a driver foveally fixates the sign for the first time), last-look distance (the distance measured from the sign to a driver's eyes where he or she moves the eyes away from the sign for the last time before reaching the sign), number of looks and durations of looks at the warning sign were of main interest in this study. Cumulative last-look distance, first-look duration, and last-look duration graphs were established. The results of this study and a previous similar study indicate that drivers look on the average about two times at a warning sign during a nighttime low-beam approach. It was found that between the first look (information acquisition) and the last look (confirmation) at a sign there was usually at least one eye fixation on the roadway ahead. Using cumulative eye fixation duration data obtained for straight road driving under low-beam nighttime conditions published in another study and an average saccade duration of about 0.03 sec, a sign reading distance model was developed that determines the distance (minimum required legibility distance, MRLD) at which a simple bold symbol on a warning sign must be recognized. The model provides for a given speed the overall cumulative probability distribution function for the MRLD in terms of distance or in terms of time. The advantage of this model, which is applicable to warning signs with simple symbols under low-beam illumination at night, is that it is totally based on observed, recorded, and analyzed driver eye scanning and information-seeking behavior in the field.

The minimum distance away from the sign at which the message or a symbol on a sign must be legible or recognized by a driver under nighttime low-beam driving conditions is important, if one wants to determine the minimum required sign luminance, or the minimum retroreflective requirements of a sign sheeting material. A recent FHWA report on minimum retroreflectivity requirements for traffic signs (*1*) and a software package called CARTS, discussed in Paniati and Mace (*1*) make use of such a minimum required distance (minimum required visibility distance, MRVD), which has been described by Mace and Gabel (*2*). The MRVD values used in CARTS were found to be unsatisfactory for the following reasons:

1. A total of 95 out of 164 (58 percent MRVD distances used for signs in CARTS have a value of about 61 m (200 ft) for an approach speed of 88 kph (55 mph). This results in a preview time of only 2.5 sec when a driver's sign-reading process starts. According to a number of technical sources such as CIE report 73 (*3*) a minimum preview time of 3 sec is recommended, which would indicate that the sign-reading process would have to be completed when a driver's eyes are 3 seconds away from a warning sign.
2. In the case of side-mounted signs an arbitrary horizontal out-of-view angle of 10 degrees is used; it is not speed dependent and results in a constant out-of-view distance of about 34 m (111 ft) for a typical sign placed on the right side of the road. This results in a minimum preview time of 1.4 sec at a speed of 88 kph (55 mph).
3. There is only one MRVD value given in CARTS for a given sign and speed without reference to a population percentile value or information whether it is an average value, a median value, or a percentile value. Any human factor design in the field of traffic safety should always be based on a selected population percentile value (i.e., 85 or 95 percent. Furthermore, most MRVD values given in CARTS appear to be extremely short, especially for signs with symbols, when compared with actual driver eye-scanning behavior data.
4. There is no transparent mathematical formula or logical structure given in CARTS that would identify, for each sign and speed case, the factors and their values used to arrive at the MRVD distance. Some MRVD distances are also not speed dependent.
5. Some of the MRVD model components are most likely based on average values only, which are based on laboratory studies using young subjects in a nondriving situation under relatively high luminance conditions (*4,5*).

OBJECTIVE

It was the objective of this study to develop a model for driver sign reading behavior for warning signs or similar signs with simple bold symbols and limited information content, which is based on actual observed symbolic sign reading behavior of young drivers at night under low-beam conditions on two-lane rural roads in the real world. Further, the model must be capable of providing minimum required legibility distance (MRLD) values for selected population percentiles (i.e., 50, 85, and 95 percent).

REQUIREMENTS OF THE MRLD MODEL

The following requirements had to be met by the MRLD model:

1. The MRLD model should be based on actual driver eye-scanning behavior recorded under nighttime, low-beam driving conditions on two-lane rural roads;
2. The MRLD model should be valid for a speed range of 48 to 105 kph (30 to 65 mph) and for warning signs, regulatory signs with either bold simple symbols or 1- or 2-word simple text (well-known; large character height; short words, e.g., EXIT, LEFT, RIGHT);
3. The MRLD model should provide not only an average MRLD value for a selected speed but also MRLD values for different driver population percentile values such as 50, 85, and 95 percent;
4. The model should be simple and easy to use.

Human Factors and Ergonomics Laboratory, Department of Industrial and Systems Engineering, Ohio University, Athens, Ohio 45701-2979.

DESCRIPTION OF MRLD MODEL

The MRLD model is based on the fact that drivers almost always try to confirm the information they have acquired in a first or previous eye fixation on a sign with an additional eye fixation. One could argue that a driver should have a right to be given enough time to make at least two eye fixations on a warning sign or a regulatory sign, which contains text information that is either simple bold symbolic or limited, or has well-known or short words and large character height. It is further observed and generally agreed on that a driver should look at the roadway ahead as frequently as driving conditions permit (almost always at least once or twice every second). In addition, for carrying out the information acquisition and the driving task in an efficient, safe, and comfortable manner a preview time of at least 3 sec or more is usually required (*3*). Therefore, the MRLD is given by the last-look distance plus the last-look duration times speed, plus the saccade duration times speed, plus the road-look duration times speed, plus the saccade duration times speed plus the first-look duration times speed. All of the three durations and the last-look distance are probability distribution functions and are assumed to be independent of each other, with the exception of the two saccade durations (0.03 sec each), which are assumed to be constants. The saccade distance when moving the gaze away from the sign, after the last look, is assumed to be part of the last-look distance.

DEVELOPMENT OF MRLD MODEL KNOWN, SHORT WORD TEXT INFORMATION

The following assumptions were made during the development of the MRLD model for warning signs containing either simple bold symbolic or limited large-character-height well-known short-word text information:

1. Drivers make an average of about two eye fixations on a warning sign (first look, information acquisition and processing; second look or last look, confirmation of information) (*6,7*).
2. Between the first look and last look on the sign there is usually at least one eye fixation on the road or the road environment ahead of the vehicle.
3. The duration of an individual eye fixation on the sign or on the road is long enough that a driver can acquire and process the information available from that fixation, make a decision, and initiate a control action, if any is required.
4. Foveal or near-foveal eye fixations away from the road to the sign are required to recognize the symbol or text, or both, on the sign.
5. The eye fixation times to recognize a simple bold symbol or simple, large-character-height text on a road sign are not constant within a driver, are somewhat different from driver to driver, and can best be described by a probability distribution (cumulative time distribution).
6. During a given approach to a sign, the first-look (eye fixation) duration, the road-look (eye fixation) duration, and the last-look (eye fixation) duration are assumed to be independent of each other.
7. The last-look distance (distance away from sign when the driver no longer looks foveally at the sign, until he or she passes the sign) within a driver is not a constant. The last-look distances are also somewhat different between drivers. They can be best described by a probability distribution (cumulative distance distribution). The last-look distance can also be called the "true" preview distance, because from that distance to the sign the driver looks most often on a roadway section, or a road environment section, that is beyond the sign.
8. The average saccade time between the first look at the sign and the subsequent look at the road or road environment is assumed to be a constant of 0.03 sec (*8*). The saccade involved at the end of the last look moving the gaze away from the sign has been assumed to be part of the last-look distance.
9. The average saccade time between the road look and the subsequent last look at the sign is also assumed to be a constant of 0.03 sec (*8*). The saccade involved at the end of the last look moving the gaze away from the sign has been assumed to be part of the last-look distance.
10. The distance obtained by the sum of the three look durations times the driving speed and the two saccade durations times the driving speed is best represented as a probability distribution. This distance is independent of the last-look distance (which is also a probability distribution).
11. For the MRLD Model 1 it is assumed that the three look durations and the last-look duration (obtained by dividing the last-look distance by the approach speed) within a speed range from 48 to about 105 kph (30 to 65 mph) are constant for all speeds. In this case the sum of the durations (including the two saccades) by a selected speed can be multiplied and the overall distance for that selected speed can be acquired .
12. For the MRLD Model 2 it is assumed that the three look durations are constant and that the last-look distance is constant regardless of the speed within the speed range from 48 to 105 kph (30 to 65 mph). In this case the overall distance is obtained by multiplying the sum of the three durations (including the two saccades) times the selected speed and adding to this distance the constant last-look distance.
13. When a driver looks at a single bold traffic sign symbol, a large character height, well-known short word, a large-number-height two or three-digit number, or at two large-character-height, well-known simple words, it is assumed that the information acquisition and processing time is roughly the same for all these situations.
14. Acquiring and processing the information obtained by an eye fixation on familiar bold symbols or large-character-height short messages on traffic signs, or both, making the correct decision, and initiating the proper action, is assumed to be a highly overlearned task. It is further assumed that this task is completely executed during the duration of that particular eye fixation (usually 0.3 to 0.8 sec).
15. Whether warning signs or regulatory signs are placed on the left or on the right side of the road, the look durations and the last-look distances are assumed to be the same.
16. Because of the much lower sign luminance values found at night, the legibility or recognition of the message on a warning or similar sign such as a regulatory sign during nighttime is more important than the legibility or recognition during daytime.
17. It is assumed that a warning sign, or another similar sign with a limited message content, such as a regulatory sign is always placed in such a way that the action or maneuver, if any is required, can be carried out by the driver in due time (enough distance provided for action or maneuver) from the point of the last-look distance to wherever the action or maneuver needs to be completed. For this to apply, the size of the symbol or the character height of the legend, or both, must be large enough to allow the

reading and processing of the message before the last-look distance is reached.

STUDY DESCRIPTION

A rural two-lane highway was used to conduct the nighttime eye-scanning study under low-beam conditions. Two warning sign approaches (curve sign, with and without advisory speed plate, turn sign with and without advisory speed plate) were used. The speeds ranged from 69 to 78 kph (43 to 48 mph). A total of 32 young, healthy subjects were used. These previously collected video eye-scanning records were further analyzed with respect to first-look (not used in MRLD model), last-look distances, and first-look and last-look durations to obtain cumulative time duration and distance distribution functions.

Figure 1 shows the different stages of the detection and legibility/recognition process for a driver approaching a traffic sign on a long, straight, level highway at night with low beams. Figure 2 shows the cumulative frequency of first-look durations, the cumulative frequency of last-look durations, both at night for an average speed of 73 kph (45.44 mph), and the cumulative frequency of road-look durations at night (*8*) for an average speed of 84.2 kph (52.3 mph). Figure 3 shows the cumulative frequency of last-look distances at night for an average speed of 73 kph (45.44 mph). The data from a tunnel approach driver eye-scanning behavior study by Zwahlen (*9*) was used to determine the average saccade duration between two successive eye fixations and was found to be 0.03 sec. Since the saccade durations are short, they were assumed to be constant. Research has shown that drivers on the average look about two times at a warning sign (*6,7*). The MRLD is considered the sum of four independent distance random variables (three eye fixation durations multiplied by selected speed): first look, road look, last look, and the last-look distance or the last-look duration times speed, plus two constant saccade durations times speed (0.03 sec each, small overall effect). Because the driver eye scan data were collected over a fairly narrow speed range, no reliable data are available at this point to determine whether the last-look distance is speed dependent within the range of 48 to 105 kph (30 to 65 mph), or whether the last-look distance expressed as a time duration is speed dependent over the speed range mentioned earlier. Therefore, two MRLD models are proposed. Figure 4 shows MRLD Model 1 and Figure 5 shows MRLD Model 2. In Figures 4 and 5 the saccade distance when moving the gaze away from the sign after the last look is assumed to be part of the last-look distance.

The sum of four independent distance random variables is also a random variable and the distribution of the sum can be obtained by applying the techniques of probability modeling. In the first approach it was assumed that all four independent variables are distributed normally each with a specific mean and a specific standard deviation. Using a transform such as the moment generating function (*10*) defined next and the convolution property (*11*) it can be shown that the sum of the four independent normal random variables will also be normally distributed with a mean equal to the sum of the individual means and with a variance that is the sum of the four variances. The moment generating function is defined as

$$M(s) = E(e^{st}) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\infty} e^{st}\cdot e^{1/2\left[\frac{x-\mu}{\sigma}\right]^2} dx \quad (1)$$

$$M(s) = e^{\left(s\mu+\frac{\sigma^2 s^2}{2}\right)} \quad (2)$$

If four independent normals are added using transform notation and the convolution property (*11*)

$$\begin{aligned} T(f*g*h*i) &= T(f)\cdot T(g)\cdot T(h)\cdot T(i) \quad (3)\\ &= e^{\left(\frac{s\mu_1+\sigma_1^2 s^2}{2}\right)}\cdot e^{\left(\frac{s\mu_2+\sigma_2^2 s^2}{2}\right)}\cdot\\ &\quad e^{\left(\frac{s\mu_3+\sigma_3^2 s^2}{2}\right)}\cdot e^{\left(\frac{s\mu_4+\sigma_4^2 s^2}{2}\right)}\\ &= e^{(s[\mu_1+\mu_2+\mu_3+\mu_4]+\frac{s^2}{2}(\sigma_1^2+\sigma_2^2+\sigma_3^2+\sigma_4^2))} \end{aligned}$$

$$\text{Sum} = \text{Normal}\,(\mu_1+\mu_2+\mu_3+\mu_4, \sigma_1^2+\sigma_2^2+\sigma_3^2+\sigma_4^2) \quad (4)$$

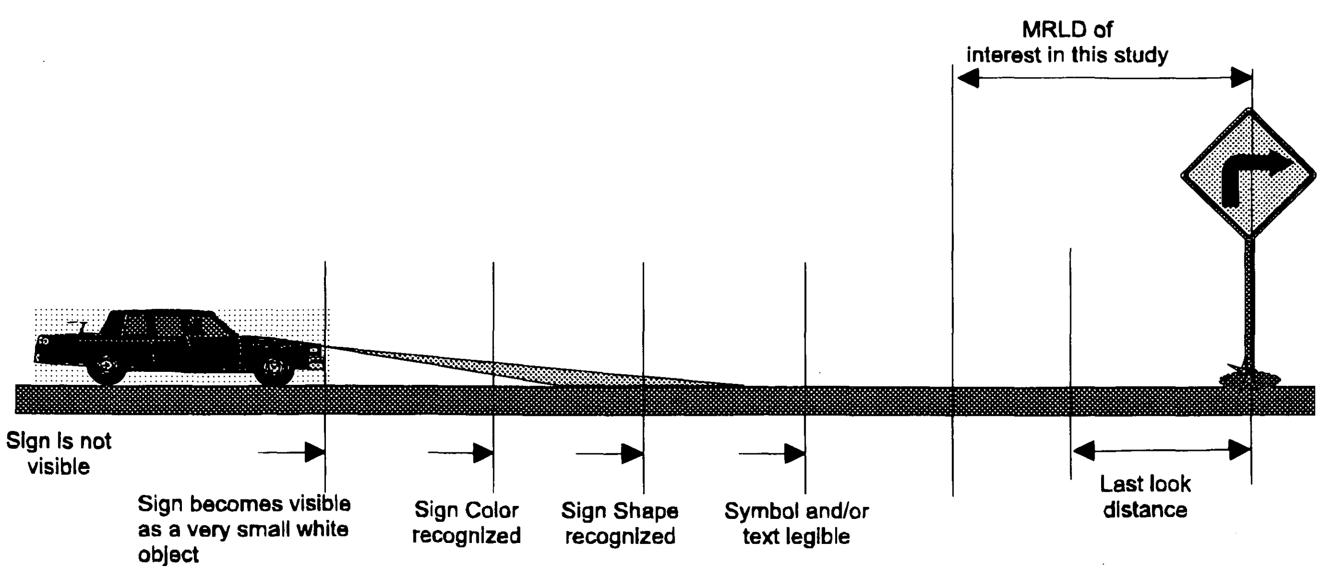


FIGURE 1 Approach to a traffic sign on a long, straight, level highway at night with low beams.

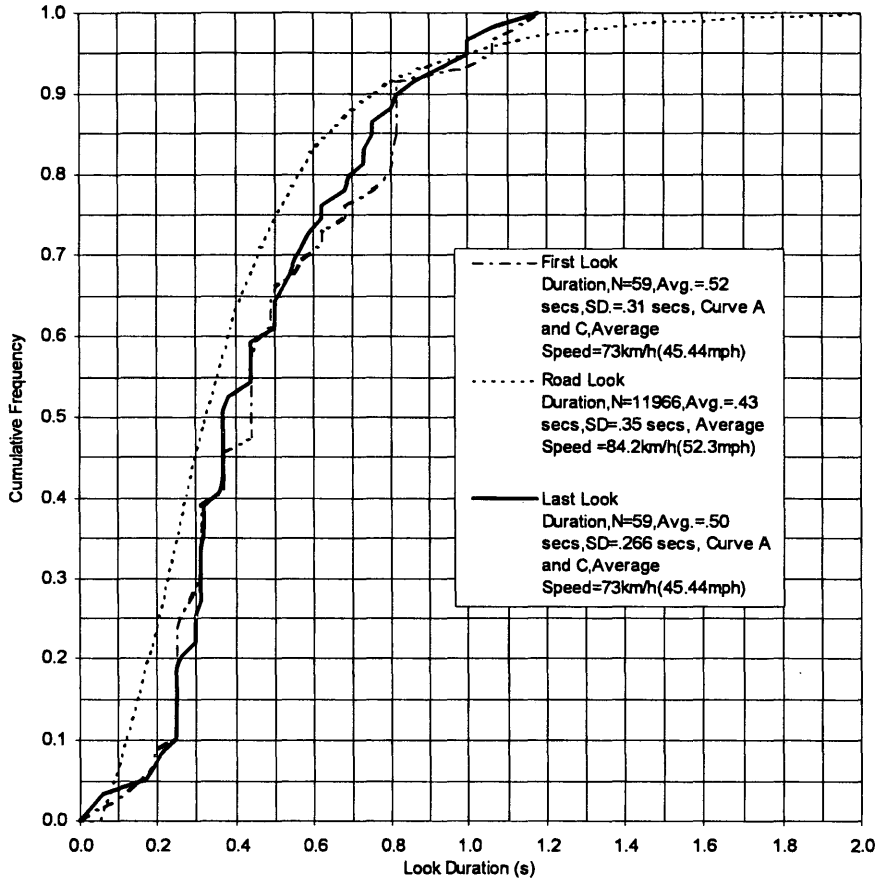


FIGURE 2 Cumulative frequency of first-look duration, road look duration, last-look duration, and nighttime.

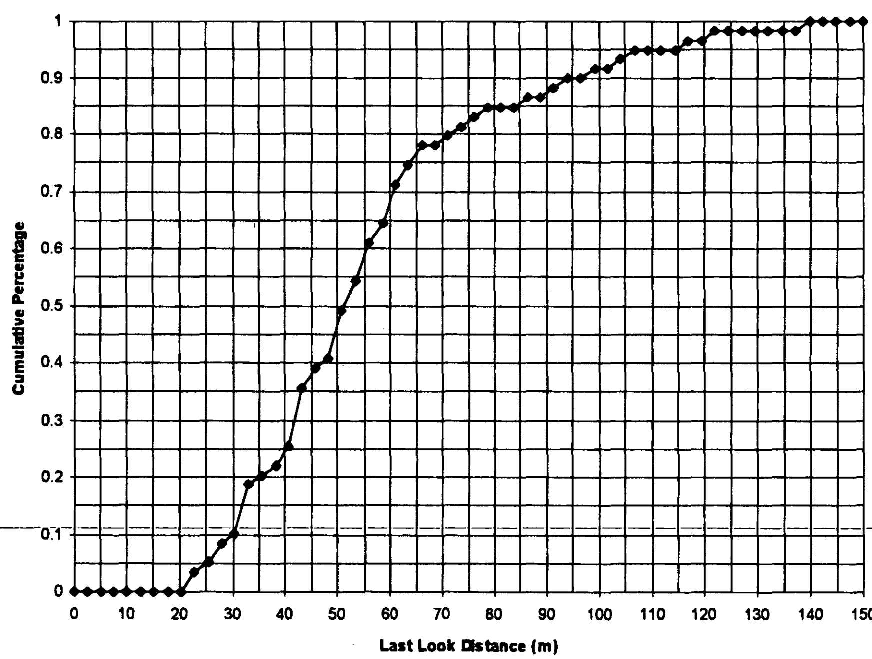
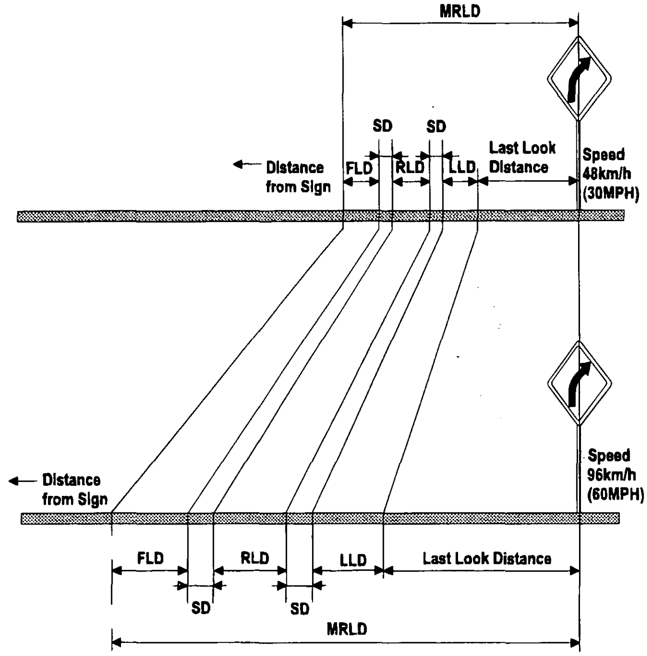
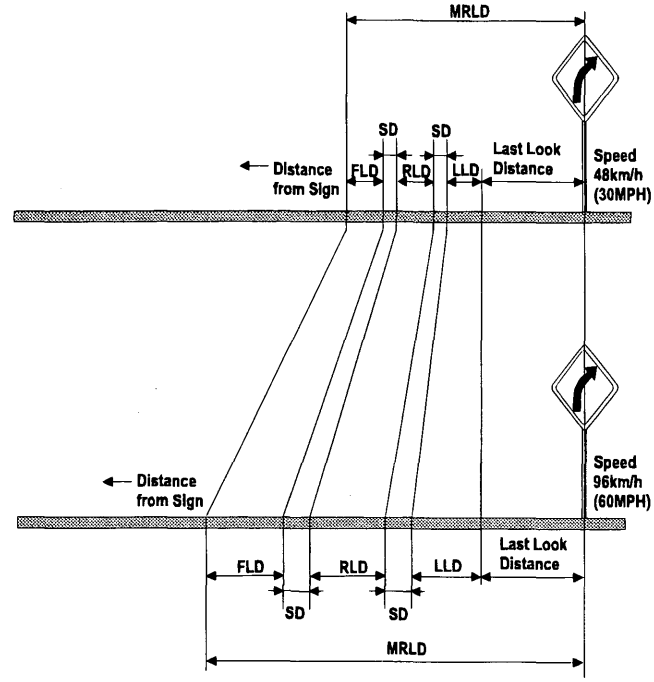


FIGURE 3 Cumulative frequency of last-look distance, nighttime, curves *A* and *C*, average speed 73 kph (45.44 mph).



FLD : First Look Duration Distance
RLD : Road Look Duration Distance
LLD : Last Look Duration Distance
SD : Saccade Duration Distance
The saccade distance when moving the gaze away from the sign after the last look is assumed to be part of the last look distance.

FIGURE 4 MRLD Model 1 for a speed of 48 kph and for a speed of 96 kph.



FLD : First Look Duration Distance
RLD : Road Look Duration Distance
LLD : Last Look Duration Distance
SD : Saccade Duration Distance
The saccade distance when moving the gaze away from the sign after the last look is assumed to be part of the last look distance.

FIGURE 5 MRLD Model 2 for a speed of 48 kph and for a speed of 96 kph.

The resulting MRLD distance is at the most an approximation because each individual distance probability distribution was approximated with a normal distribution. In the second approach it is again assumed that all four random distance variables are independent of each other but a Monte Carlo simulation program for a personal computer (PC) was written and used along with the actual obtained cumulative distance distributions to obtain the MRLD distribution function. Using a sample size of 10,000 cases in the simulation this approach provides a slightly more accurate MRLD probability distribution function when compared with the transform and convolution approach using normals. Both approaches have been used in this study, although the latter approach was preferred and finally selected because of the increased accuracy.

RESULTS

Figure 6*a* shows the cumulative frequency of MRLD values for a speed of 73 kph (45.44 mph) for Model 1, the basis of transform and convolution calculations and simulation. Figure 6*b* shows the cumulative frequency of MRLD values for a speed of 73 kph (45.44 mph) for Model 2 on the basis of transform and convolution calculations and simulation. Figure 7 shows the cumulative frequencies of MRLD values obtained by simulation for 48, 88.5, and 104.6 kph for Models 1 and 2. Figure 8 shows the comparison of average, 50 percent (median), 85 and 95 percent MRLD values obtained by simulation (based on the GPSS/PC simulation, $N = 10{,}000$) for MRLD Models 1 and 2. The figure also shows the average MRVD values for 95 out of 164 (58 percent) signs used in CARTS.

DISCUSSION AND CONCLUSIONS

The average MRLD distances obtained with the Monte Carlo simulations, on the basis of the symbol signs investigated using either Model 1 or Model 2 and for a speed range of 48 to 105 kph (30 to 65 mph) are given in Figure 8. One can see that the obtained MRLD values are considerably higher than the corresponding MRVD values used in CARTS for at least 58 percent of all signs in the CARTS sign inventory. The MRLD value is one of the major factors in determining the minimum retroreflectivity requirements. On the basis of typical headlamp candlepower distributions, the geometry of car headlamp, driver, and sign, and retroreflective material characteristics, the short MRVD values will invariably result in low minimum retroreflectivity requirements, whereas the longer MRLD values will result in substantially higher, minimum retroreflectivity requirements. If a symbol is neither bold nor simple, or if the character height of a legend is small, the recognition or legibility distances and the last-look distances observed in the field as well as the

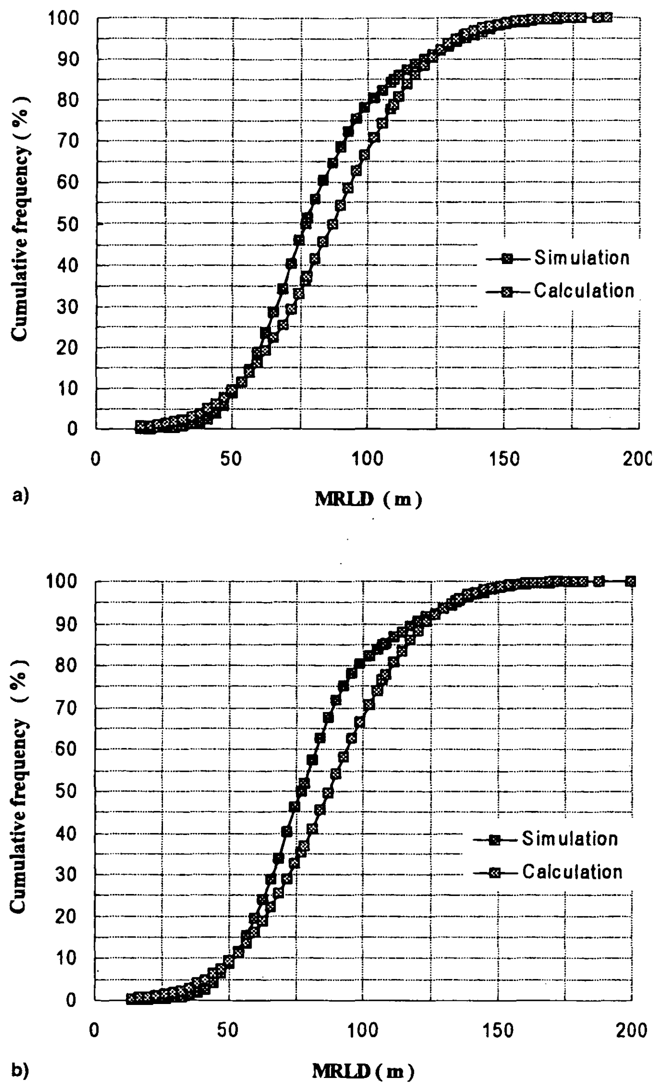


FIGURE 6 Cumulative frequency of MRLD for a speed of 73 kph (45.44 mph): (a) Model 1 and (b) Model 2.

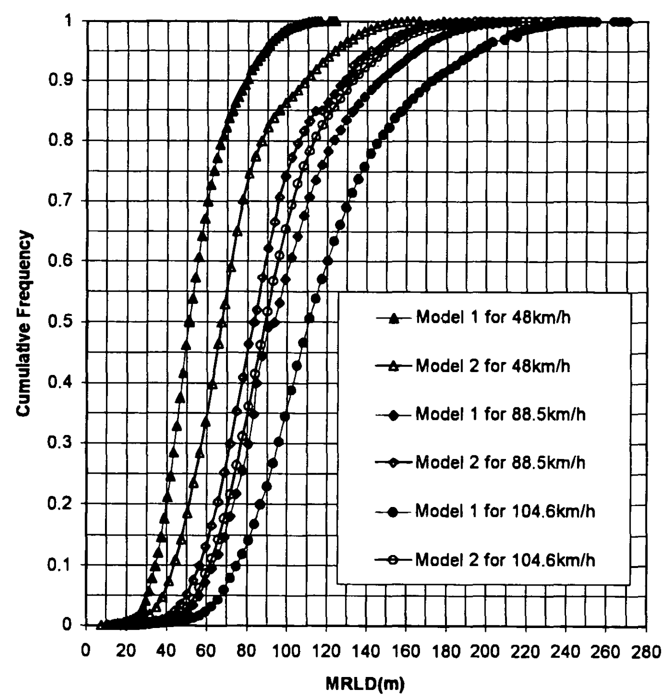


FIGURE 7 Cumulative frequency of MRLD for a speed of 48, 88.5, and 104.6 kph for Models 1 and 2.

derived MRLD distances could be so short and the minimum retroreflectivity values so low that inadequate preview and driver safety conditions may exist. The advantage of the MRLD model is that it is based on actual driver eye-scanning behavior data, collected in the field at night when driving with low beams and that the MRLD values are available not only as moments (average, variance, standard deviation), but also for any population percentile value a user might want to select. The MRLD model has a number of limitations:

1. Limited sign population (curve/turn signs, bold symbols only, with and without advisory speed plates);
2. Limited vehicle population (only one low-beam pattern);
3. Limited approach speed range (only one average approach speed);
4. Two-lane rural dark road environment only;
5. Practically no other traffic; and
6. Relatively young and healthy, nonimpaired driver population.

It is not known how well the obtained time durations and distances would apply to older drivers. More driver eye-scanning behavior research, using wider ranges of the variables mentioned earlier or factors, or both, would be desirable. Also, more complex and less bold sign symbols and smaller legend character heights and multiword messages may require two or more first-look eye fixations (information acquisition) to acquire the desired information and may possibly also require more than one confirmation look. Driver eye-scanning behavior studies would also be beneficial to determine whether a number of the stated assumptions, on which the MRLD model is based can be supported and justified. Further eye-scanning behavior studies also would likely provide information about which one of the two MRLD models more closely matches the real-world data. In the meantime, although not knowing which one of the MRLD models more closely matches the real-world data, and to simplify matters, one could always use an average MRLD value based on the two MRLD models and express such a value as a function of the speed using a simple linear relationship, that is, MRLD (m) = constant + slope * speed. It is also conceivable that a set of MRLD models, either of Type 1 or Type 2, could be applicable and used, which would be more sensitive and apply specifically to certain maximum symbol recognition or character legibility distances. It is reasonable to assume that depending on the character height of the message or text or the size, complexity, and stroke widths used in a symbol, different first-look and last-look distances and durations may be required (i.e., small character heights or small, thin-stroke width symbols on a sign may result in somewhat shorter MRLDs than were found in this study, which are based on fairly large and bold symbols and large advisory speed numerals). Additional driver eye-scanning behavior studies investigating the sensitivity of the MRLD models and distance values with regard to the

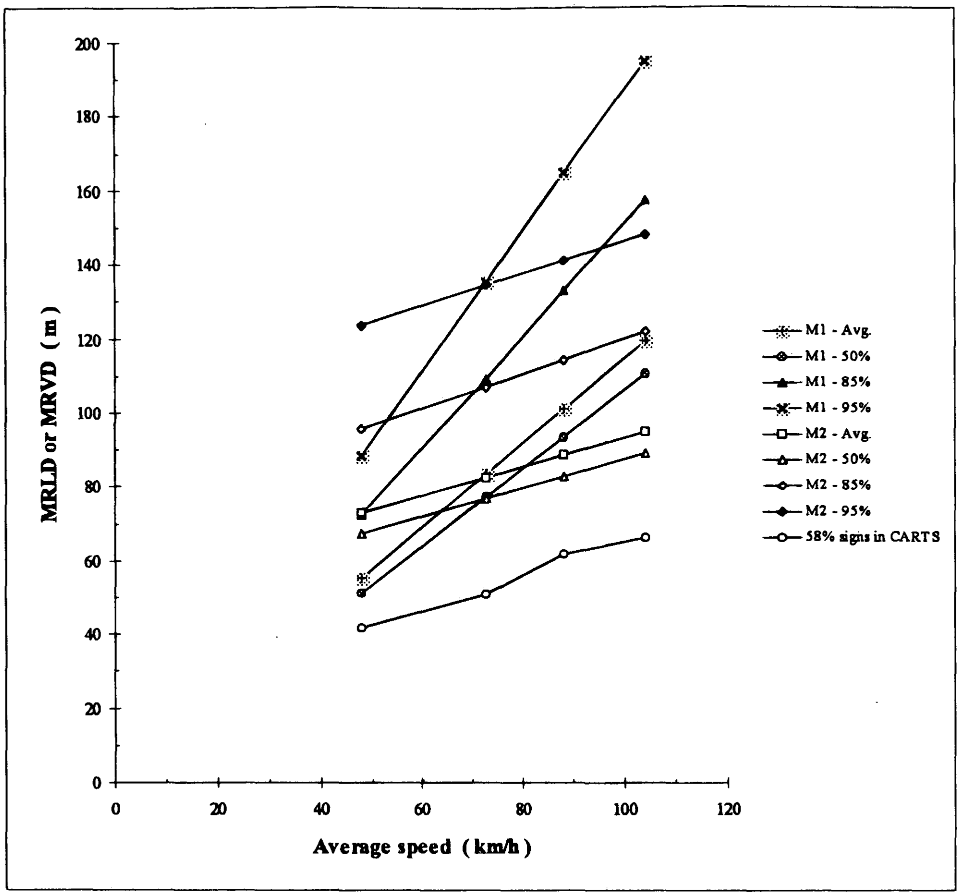


FIGURE 8 Comparison of average, 50, 85, and 95 percent MRLD values based on GPSS/PC simulation, N = 10,000 for MRLD Models 1 and 2 and average MRVD value for 95 out of 164 (58 percent sign in CARTS.

maximum recognition and legibility distances would, therefore, also be helpful.

REFERENCES

1. Paniati, J. F., and D. J. Mace. *Minimum Retroreflectivity Requirements For Traffic Signs.* Report FHWA-RD-93-077, U.S. Department of Transportation, Oct. 1993.
2. Mace, D. J., and R. Gabel. *Modeling Highway Visibility Minimum Required Visibility Distance.* Paper Presented at 71st Annual Meeting of the Transportation Research Board, Washington, D.C., 1992.
3. *Visual Aspects of Road Markings.* Joint Technical Report CIE/PIARC. Publication CIE 73, CIE, 1988.
4. Cole, B. L., and R. L. Jacobs. A Resolution Limited Model for the Prediction of Information Retrieval from Extended Alphanumeric Message. *Proc., 9th Conference of the Australian Research Review Board,* No. 5, 1978.
5. Cole, B. L., and R. L. Jacobs. Acquisition of Information from Alphanumeric Road Signs. *Proc., 9th Conference of the Australian Research Review Board,* No. 5, 1978, pp. 390–395.
6. Zwahlen, H. T. Driver Eye Scanning Of Warning Signs On Rural Highway. *Proc., 25th Annual Meeting of the Human Factors Society,* 1981, pp. 33–37.
7. Zwahlen, H. T. Advisory Speed Signs and Curve Signs and Their Effect on Driver Eye Scanning and Driving Performance. In *Transportation Research Record 1111,* TRB, National Research Council, Washington, D.C., 1987, pp. 110–120.
8. Zwahlen, H. T. Eye Scanning Rules For Drivers—How Do They Compare With Actual Observed Eye Scanning Behavior? In *Transportation Research Record 1403,* TRB, National Research Council, Washington, D.C., 1993, pp. 14–22.
9. Zwahlen, H. T. *Driver Eye Scanning Behavior at Tunnel Approaches.* Final Report, Franklin Institute Research Laboratories, Feb. 1979.
10. Meyer, P. L. *Introductory Probability and Statistical Applications.* Addison-Wesley, Reading, Mass., 1965.
11. Giffin, W. C. *Transform Techniques for Probability Modeling.* Academic Press, New York, 1975.

Publication of this paper sponsored by Committee on Visibility.