HUMAN FACTORS

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CHAPTER 3 - Frequently used Symbols

ξ = parameter of log normal distribution ~ standard deviation
λ = parameter of log normal distribution ~ median
σ = standard deviation
Φ = value of standard normal variate
a_{GV} = maximum acceleration on grade
a_{LV} = maximum acceleration on level
A = movement amplitude
C_r = roadway curvature
$C_{(t)}$ = vehicle heading
CV = coefficient of variation
d = braking distance
D = distance from eye to target
$E_{(t)}$ = symptom error function
f = coefficient of friction
F_s = stability factor
g = acceleration of gravity
$g_{(s)}$ = control displacement
G = gradient
H = information (bits)
K = gain (dB)
l = wheel base
L = diameter of target (letter or symbol)
LN = natural log
M = mean
MT = movement time
N = equiprobable alternatives
PRT = perception-response time
$R_{(t)}$ = desired input forcing function
RT = reaction time (sec)
s = Laplace operator
SR = steering ratio (gain)
SSD = stopping sight distance
t = time
T_L = lead term constant
T_ℓ = lag term constant
T_N = neuro-muscular time constant
u = speed
V = initial speed
W = width of control device
Z = standard normal score

3.

HUMAN FACTORS

3.1 Introduction

In this chapter, salient performance aspects of the human in the context of a person-machine control system, the motor vehicle, will be summarized. The driver-vehicle system configuration is ubiquitous. Practically all readers of this chapter are also participants in such a system; yet many questions, as will be seen, remain to be answered in modeling the behavior of the human component alone. Recent publications (IVHS 1992; TRB 1993) in support of Intelligent Transportation Systems (ITS) have identified study of "Plain Old Driving" (POD) as a fundamental research topic in ITS. For the purposes of a transportation engineer interested in developing a molecular model of traffic flow in which the human in the vehicle or an individual human-vehicle comprises a unit of analysis, some important performance characteristics can be identified to aid in the formulation, even if a comprehensive transfer function for the driver has not yet been formulated.

This chapter will proceed to describe first the discrete components of performance, largely centered around neuromuscular and cognitive time lags that are fundamental parameters in human performance. These topics include perception-reaction time, control movement time, responses to the presentation of traffic control devices, responses to the movements of other vehicles, handling of hazards in the roadway, and finally how different segments of the driving population may differ in performance.

Next, the kind of control performance that underlies steering, braking, and speed control (the primary control functions) will be described. Much research has focused on the development of adequate models of the tracking behavior fundamental to steering, much less so for braking or for speed control.

After fundamentals of open-loop and closed-loop vehicle control are covered, applications of these principles to specific maneuvers of interest to traffic flow modelers will be discussed. Lane keeping, car following, overtaking, gap acceptance, lane closures, stopping and intersection sight distances will also be discussed. To round out the chapter, a few other performance aspects of the driver-vehicle system will be covered, such as speed limit changes and distractions on the highway.

3.1.1 The Driving Task

Lunenfeld and Alexander (1990) consider the driving task to be a hierarchical process, with three levels: (1) Control, (2) Guidance, and (3) Navigation. The *control* level of performance comprises all those activities that involve second-to-second exchange of information and control inputs between the driver and the vehicle. This level of performance is at the control interface. Most control activities, it is pointed out, are performed "automatically," with little conscious effort. In short, the control level of performance is *skill based*, in the approach to human performance and errors set forth by Jens Rasmussen as presented in *Human Error* (Reason 1990).

Once a person has learned the rudiments of control of the vehicle, the next level of human performance in the driver-vehicle control hierarchy is the rules-based (Reason 1990) *guidance* level as Rasmussen would say. The driver's main activities "involve the maintenance of a safe speed and proper path relative to roadway and traffic elements ." (Lunenfeld and Alexander 1990) Guidance level inputs to the system are dynamic speed and path responses to roadway geometrics, hazards, traffic, and the physical environment. Information presented to the driver-vehicle system is from traffic control devices, delineation, traffic and other features of the environment, continually changing as the vehicle moves along the highway.

These two levels of vehicle control, control and guidance, are of paramount concern to modeling a corridor or facility. The third (and highest) level in which the driver acts as a supervisor apart, is *navigation*. Route planning and guidance while enroute, for example, correlating directions from a map with guide signage in a corridor, characterize the navigation level of performance. Rasmussen would call this level *knowledge-based behavior*. Knowledge based behavior will become increasingly more important to traffic flow theorists as Intelligent Transportation Systems (ITS) mature. Little is currently known about how enroute diversion and route changes brought about by ITS technology affect traffic flow, but much research is underway. This chapter will discuss driver performance in the conventional highway system context, recognizing that emerging ITS technology in the next ten years may radically change many driver's roles as players in advanced transportation systems.

At the control and guidance levels of operation, the driver of a motor vehicle has gradually moved from a significant prime mover, a supplier of forces to change the path of the vehicle, to an information processor in which strength is of little or no consequence. The advent of power assists and automatic transmissions in the 1940's, and cruise controls in the 1950's moved the driver more to the status of a manager in the system. There are commercially available adaptive controls for severely disabled drivers (Koppa 1990) which reduce the actual movements and strength required of drivers to nearly the vanishing point. The fundamental control tasks, however, remain the same.

These tasks are well captured in a block diagram first developed many years ago by Weir (1976). This diagram, reproduced in Figure 3.1, forms the basis for the discussion of driver performance, both discrete and continuous. Inputs enter the driver-vehicle system from other vehicles, the roadway, and the driver him/herself (acting at the *navigation* level of performance).

The fundamental display for the driver is the visual field as seen through the windshield, and the dynamics of changes to that field generated by the motion of the vehicle. The driver attends to selected parts of this input, as the field is interpreted as the visual world. The driver as system manager as well as active system component "hovers" over the control level of performance. Factors such as his or her experience, state of mind, and stressors (e.g., being on a crowded facility when 30 minutes late for a meeting) all impinge on the supervisory or monitoring level of performance, and directly or indirectly affect the control level of performance. Rules and knowledge govern driver decision making and the second by second psychomotor activity of the driver. The actual control

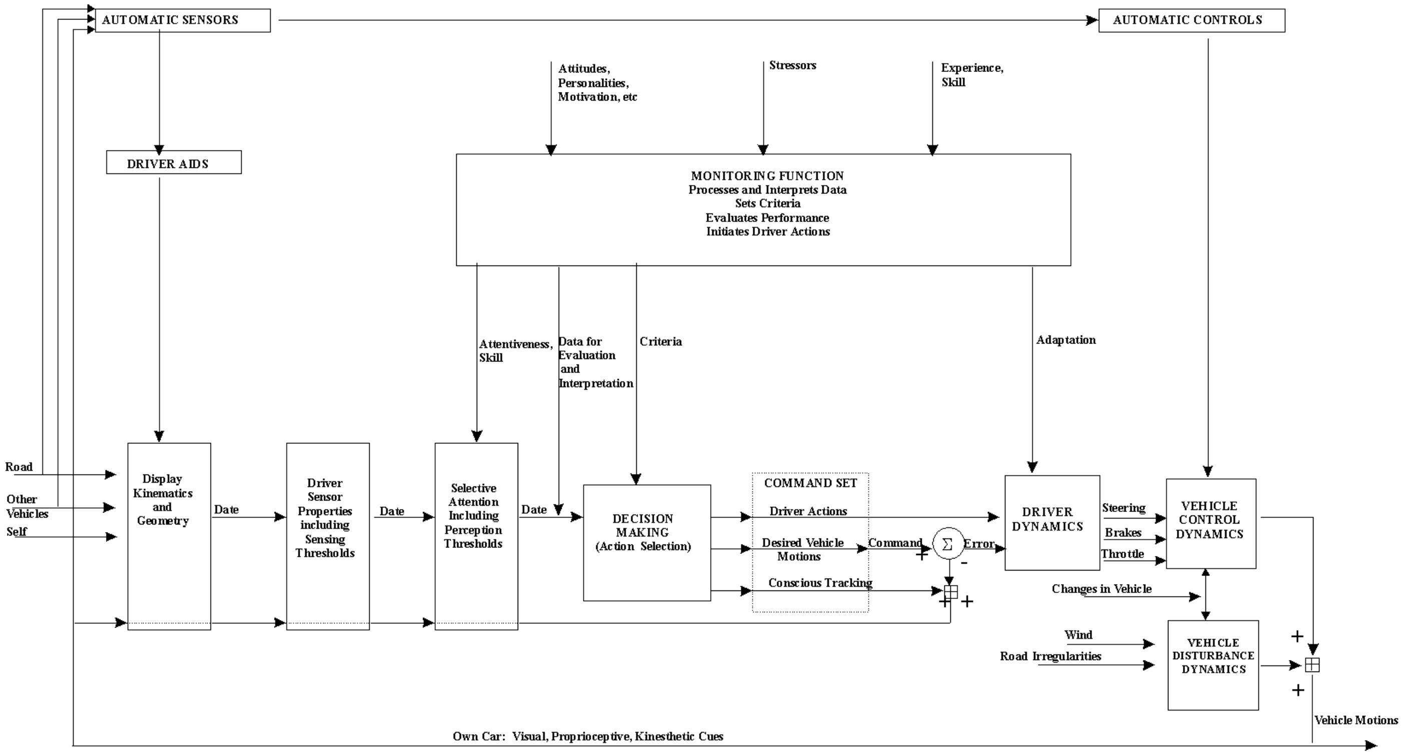

Figure 3.1
Generalized Block Diagram of the Car-Driver-Roadway System.

movements made by the driver couple with the vehicle control at the interface of throttle, brake, and steering. The vehicle, in turn, as a dynamic physical process in its own right, is subject to inputs from the road and the environment. The resolution of control dynamics and vehicle disturbance dynamics is the vehicle path.

As will be discussed, a considerable amount of information is available for some of the lower blocks in this diagram, the ones associated with braking reactions, steering inputs, and vehicle control dynamics. Far less is really known about the higher-order functions that any driver knows are going on while he or she drives.

3.2 Discrete Driver Performance

3.2.1 Perception-Response Time

Nothing in the physical universe happens instantaneously. Compared to some physical or chemical processes, the simplest human reaction to incoming information is very slow indeed. Ever since the Dutch physiologist Donders started to speculate in the mid 19th century about central processes involved in choice and recognition reaction times, there have been numerous models of this process. The early 1950's saw Information Theory take a dominant role in experimental psychology. The linear equation

$$RT = a + bH \qquad (3.1)$$

Where:

RT = Reaction time, seconds
H = Estimate of transmitted information
H = $log_2 N$, if N equiprobable alternatives
a = Minimum reaction time for that modality
b = Empirically derived slope, around 0.13 seconds (sec) for many performance situations

that has come to be known as the Hick-Hyman "Law" expresses a relationship between the number of alternatives that must be sorted out to decide on a response and the total reaction time, that is, that lag in time between detection of an input (stimulus) and the start of initiation of a control or other response. If the time for the response itself is also included, then the total lag is termed "response time." Often, the terms "reaction time" and "response time" are used interchangeably, but one (reaction) is always a part of the other (response).

Underlying the Hick-Hyman Law is the two-component concept: part of the total time depends upon choice variables, and part is common to all reactions (the intercept). Other components can be postulated to intervene in the choice variable component, other than just the information content. Most of these models have then been *chaining* individual components that are presumably orthogonal or uncorrelated with one another. Hooper and McGee (1983) postulate a very typical and plausible model with such components for braking response time, illustrated in Table 3.1.

Each of these elements is derived from empirical data, and is in the 85th percentile estimate for that aspect of time lag. Because it is doubtful that any driver would produce 85th percentile values for each of the individual elements, 1.50 seconds probably represents an extreme upper limit for a driver's perception-reaction time. This is an estimate for the simplest kind of reaction time, with little or no decision making. The driver reacts to the input by lifting his or her foot from the accelerator and placing it on the brake pedal. But a number of writers, for example Neuman (1989), have proposed perception-reaction times (PRT) for different types of roadways, ranging from 1.5 seconds for low-volume roadways to 3.0 seconds for urban freeways. There are more things happening, and more decisions to be made per unit block of time on a busy urban facility than on a rural county road. Each of those added factors increase the PRT. McGee (1989) has similarly proposed different values of PRT as a function of design speed. These estimates, like those in Table 3.1, typically include the time for the driver to move his or her foot from the accelerator to the brake pedal for brake application.

Table 3.1
Hooper-McGee Chaining Model of Perception-Response Time

Component	Time (sec)	Cumulative Time (sec)
1) Perception		
Latency	0.31	0.31
Eye Movement	0.09	0.4
Fixation	0.2	1
Recognition	0.5	1.5
2) Initiating Brake Application	1.24	2.74

Any statistical treatment of empirically obtained PRT's should take into account a fundamental if not always vitally important fact: the times cannot be distributed according to the normal or gaussian probability course. Figure 3.2 illustrates the actual shape of the distribution. The distribution has a marked positive skew, because there cannot be such a thing as a negative reaction time, if the time starts with onset of the signal with no anticipation by the driver. Taoka (1989) has suggested an adjustment to be applied to PRT data to correct for the non-normality, when sample sizes are "large" --50 or greater.

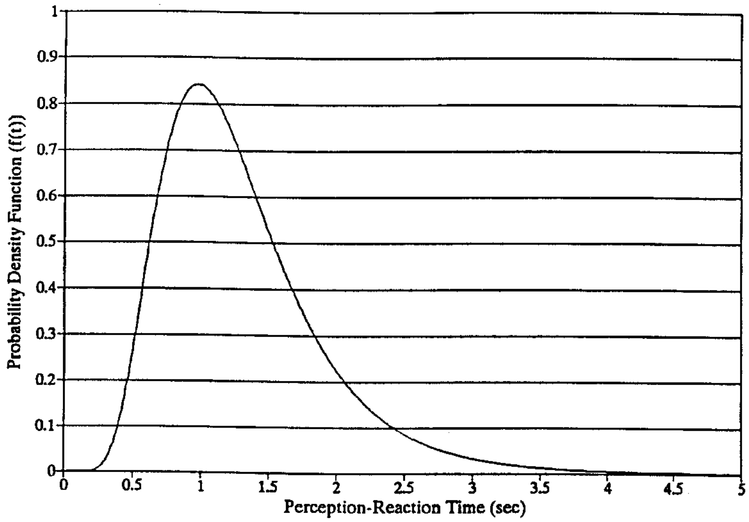

Figure 3.2
Lognormal Distribution of Perception-Reaction Time.

The log-normal probability density function is widely used in quality control engineering and other applications in which values of the observed variable, *t*, are constrained to values equal to or greater than zero, but may take on extreme positive values, exactly the situation that obtains in considering PRT. In such situations, the natural logarithm of such data may be assumed to approach the normal or gaussian distribution. Probabilities associated with the log-normal distribution can thus be determined by the use of standard-score tables. Ang and Tang (1975) express the log-normal probability density function *f(t)* as follows:

$$f(t) = \frac{1}{\sqrt{2\Pi}\ \xi t} \exp\left[\left(\frac{LN(t) - \lambda}{\xi}\right)^2\right] \qquad (3.2)$$

where the two parameters that define the shape of the distribution are λ and ξ. It can be shown that these two parameters are related to the mean and the standard deviation of a sample of data such as PRT as follows:

$$\xi^2 = LN\left(1 + \frac{\sigma^2}{\mu^2}\right) \qquad (3.3)$$

The parameter λ is related to the median of the distribution being described by the simple relationship of the natural logarithm of the median. It can also be shown that the value of the standard normal variate (equal to probability) is related to these parameters as shown in the following equation:

$$\lambda = LN\left(\frac{\mu}{\sqrt{1 + \sigma^2/\mu^2}}\right) \qquad (3.4)$$

$$\Phi\left(\frac{LN(t) - \lambda}{\xi}\right) = 0.5,\ 0.85,\ etc. \qquad (3.5)$$

and the standard score associated with that value is given by:

$$\frac{LN(t) - \lambda}{\xi} = Z \qquad (3.6)$$

Therefore, the value of *LN(t)* for such percentile levels as 0.50 (the median), the 85th, 95th, and 99th can be obtained by substituting in Equation 3.6 the appropriate *Z* score of 0.00, 1.04, 1.65, and 2.33 for *Z* and then solving for *t*. Converting data to log-normal approximations of percentile values should be considered when the number of observations is reasonably large, over 50 or more, to obtain a better fit. Smaller data sets will benefit more from a tolerance interval approach to approximate percentiles (Odeh 1980).

A very recent literature review by Lerner and his associates (1995) includes a summary of brake PRT (including brake onset) from a wide variety of studies. Two types of response situation were summarized: (1) The driver does not know when or even if the stimulus for braking will occur, i.e., he or she is surprised, something like a real-world occurrence on the highway; and (2) the driver is aware that the signal to brake will occur, and the only question is when. The Lerner et al. (1995) composite data were converted by this writer to a log-normal transformation to produce the accompanying Table 3.2.

Sixteen studies of braking PRT form the basis for Table 3.2. Note that the 95th percentile value for a "surprise" PRT (2.45 seconds) is very close to the AASHTO estimate of 2.5 seconds which is used for all highway situations in estimating both stopping sight distance and other kinds of sight distance (Lerner et al. 1995).

In a very widely quoted study by Johansson and Rumar (1971), drivers were waylaid and asked to brake very briefly if they heard a horn at the side of the highway in the next 10 kilometers. Mean PRT for 322 drivers in this situation was 0.75 seconds with an SD of 0.28 seconds. Applying the Taoka conversion to the log normal distribution yields:

50th percentile PRT = 0.84 sec
85th percentile PRT = 1.02 sec
95th percentile PRT = 1.27 sec
99th percentile PRT = 1.71 sec

Table 3.2
Brake PRT - Log Normal Transformation

	"Surprise"	**"Expected"**
Mean	1.31 (sec)	0.54
Standard Dev	0.61	0.1
λ	0.17 (no unit)	-0.63 (no unit)
ξ	0.44 (no unit)	0.18 (no unit)
50th percentile	1.18	0.53
85th percentile	1.87	0.64
95th percentile	2.45	0.72
99th percentile	3.31	0.82

In very recent work by Fambro et al. (1994) volunteer drivers in two age groups (Older: 55 and up; and Young: 18 to 25) were suddenly presented with a barrier that sprang up from a slot in the pavement in their path, with no previous instruction. They were driving a test vehicle on a closed course. Not all 26 drivers hit the brakes in response to this breakaway barrier. The PRT's of the 22 who did are summarized in Table 3.3 (Case 1). None of the age differences were statistically significant. Additional runs were made with other drivers in their own cars equipped with the same instrumentation. Nine of the 12 drivers made stopping maneuvers in response to the emergence of the barrier. The results are given in Table 3.3 as Case 2. In an attempt (Case 3) to approximate real-world driving conditions, Fambro et al. (1994) equipped 12 driver's own vehicles with instrumentation. They were asked to drive a two-lane undivided secondary road ostensibly to evaluate the drivability of the road.

Table 3.3
Summary of PRT to Emergence of Barrier or Obstacle

Case 1. Closed Course, Test Vehicle			
12	Older:	Mean = 0.82 sec;	SD = 0.16 sec
10	Young:	Mean = 0.82 sec;	SD = 0.20 sec
Case 2. Closed Course, Own Vehicle			
7	Older:	Mean = 1.14 sec;	SD = 0.35 sec
3	Young:	Mean = 0.93 sec;	SD = 0.19 sec
Case 3. Open Road, Own Vehicle			
5	Older:	Mean = 1.06 sec;	SD = 0.22 sec
6	Young:	Mean = 1.14 sec;	SD = 0.20 sec

A braking incident was staged at some point during this test drive. A barrel suddenly rolled out of the back of a pickup parked at the side of the road as he or she drove by. The barrel was snubbed to prevent it from actually intersecting the driver's path, but the driver did not know this. The PRT's obtained by this ruse are summarized in Table 3.4. One driver failed to notice the barrel, or at least made no attempt to stop or avoid it.

Since the sample sizes in these last two studies were small, it was considered prudent to apply statistical tolerance intervals to these data in order to estimate proportions of the driving population that might exhibit such performance, rather than using the Taoka conversion. One-sided tolerance tables published by Odeh (1980) were used to estimate the percentage of drivers who would respond in a given time or shorter, based on these findings. These estimates are given in Table 3.4 (95 percent confidence level), with PRT for older and younger drivers combined.

The same researchers also conducted studies of driver response to expected obstacles. The ratio of PRT to a totally unexpected event to an expected event ranges from 1.35 to 1.80 sec, consistent with Johansson and Rumar (1971). Note, however, that one out of 12 of the drivers in the open road barrel study (Case 3) *did not appear to notice the hazard at all.* Thirty percent of the drivers confronted by the artificial barrier under closed-course conditions also did not respond appropriately. How generalizable these percentages are to the driver population remains an open question that requires more research. For analysis purposes, the values in Table 3.4 can be used to approximate the driver PRT envelope for an unexpected event. PRT's for expected events, e.g., braking in a queue in heavy traffic, would range from 1.06 to 1.41 second, according to the ratios given above (99th percentile).

These estimates may not adequately characterize PRT under conditions of complete surprise, i.e., when expectancies are greatly violated (Lunenfeld and Alexander 1990). Detection times may be greatly increased if, for example, an unlighted vehicle is suddenly encountered in a traffic lane in the dark, to say nothing of a cow or a refrigerator.

Table 3.4
Percentile Estimates of PRT to an Unexpected Object

Percentile	**Case 1 Test Vehicle Closed Course**	**Case 2 Own Vehicle Closed Course**	**Case 3 Own Vehicle Open Road**
50th	0.82 sec	1.09 sec	1.11 sec
75th	1.02 sec	1.54 sec	1.40 sec
90th	1.15 sec	1.81 sec	1.57 sec
95th	1.23 sec	1.98 sec	1.68 sec
99th	1.39 sec	2.31 sec	1.90 sec
Adapted from Fambro et al. (1994).			

3.3 Control Movement Time

Once the lag associated with perception and then reaction has ensued and the driver just begins to move his or her foot (or hand, depending upon the control input to be effected), the amount of time required to make that movement may be of interest. Such control inputs are overt motions of an appendage of the human body, with attendant inertia and muscle fiber latencies that come into play once the efferent nervous impulses arrives from the central nervous system.

3.3.1 Braking Inputs

As discussed in Section 3.3.1 above, a driver's braking response is composed of two parts, prior to the actual braking of the vehicle: the perception-reaction time (PRT) and immediately following, movement time (MT).

Movement time for any sort of response was first modeled by Fitts in 1954. The simple relationship among the range or amplitude of movement, size of the control at which the control movement terminates, and basic information about the minimum "twitch" possible for a control movement has long been known as "Fitts' Law."

$$MT = a + b\ Log_2\left(\frac{2A}{W}\right) \tag{3.7}$$

where,

a = minimum response time lag, no movement
b = slope, empirically determined, different for each limb
A = amplitude of movement, i.e., the distance from starting point to end point
W = width of control device (in direction of movement)

The term

$$Log_2\left(\frac{2A}{W}\right) \tag{3.8}$$

is the "Index of Difficulty" of the movement, in binary units, thus linking this simple relationship with the Hick-Hyman equation discussed previously in Section 3.3.1.

Other researchers, as summarized by Berman (1994), soon found that certain control movements could not be easily modeled by Fitts' Law. Accurate tapping responses less than 180 msec were not included. Movements which are short and quick also appear to be preplanned, or "programmed," and are open-loop. Such movements, usually not involving visual feedback, came to be modeled by a variant of Fitts' Law:

$$MT = a + b\ \sqrt{A} \tag{3.9}$$

in which the width of the target control (W) plays no part.

Almost all such research was devoted to hand or arm responses. In 1975, Drury was one of the first researchers to test the applicability of Fitts' Law and its variants to foot and leg movements. He found a remarkably high association for fitting foot tapping performance to Fitts' Law. Apparently, all appendages of the human body can be modeled by Fitts' Law or one of its variants, with an appropriate adjustment of a and b, the empirically derived parameters. Parameters a and b are sensitive to age, condition of the driver, and circumstances such as degree of workload, perceived hazard or time stress, and pre-programming by the driver.

In a study of pedal separation and vertical spacing between the planes of the accelerator and brake pedals, Brackett and Koppa (1988) found separations of 10 to 15 centimeters (cm), with little or no difference in vertical spacing, produced control movement in the range of 0.15 to 0.17 sec. Raising the brake pedal more than 5 cm above the accelerator lengthened this time significantly. If pedal separation (= A in Fitts' Law) was varied, holding pedal size constant, the mean MT was 0.22 sec, with a standard deviation of 0.20 sec.

In 1991, Hoffman put together much of the extant literature and conducted studies of his own. He found that the Index of Difficulty was sufficiently low (<1.5) for all pedal placements found on passenger motor vehicles that visual control was unnecessary for accurate movement, i.e., movements were ballistic in nature. *MT* was found to be greatly influenced by vertical separation of the pedals, but comparatively little by changes in *A*, presumably because the movements were ballistic or open-loop and thus not correctable during the course of the movement. *MT* was lowest at 0.20 sec with no vertical separation, and rose to 0.26 sec if the vertical separation (brake pedal higher than accelerator) was as much as 7 cm. A very recent study by Berman (1994) tends to confirm these general *MT* evaluations, but adds some additional support for a ballistic model in which amplitude A does make a difference.

Her *MT* findings for a displacement of (original) 16.5 cm and (extended) 24.0 cm, or change of 7.5 cm can be summarized as follows:

	Original pedal	Extended pedal
Mean	0.20 sec	0.29 sec
Standard Deviation	0.05 sec	0.07 sec
95 percent tolerance level	0.32 sec	0.45 sec
99 percent tolerance level	0.36 sec	0.51 sec

The relationship between perception-reaction time and *MT* has been shown to be very weak to nonexistent. That is, a long reaction time does not necessarily predict a long *MT*, or any other relationship between these two times. A recent analysis by the writer yielded a Pearson Product-Moment Correlation Coefficient (r) value of 0.17 between these two quantities in a braking maneuver to a completely unexpected object in the path of the vehicle (based on 21 subjects). Total PRT's as presented in Section 3.3.1 should be used for discrete braking control movement time estimates; for other situations, the modeler could use the tolerance levels in Table 3.5 for *MT*, chaining them after an estimate of perception (including decision) and reaction time for the situation under study (95 percent confidence level). See Section 3.14 for a discussion on how to combine these estimates.

3.3.2 Steering Response Times

Summala (1981) covertly studied driver responses to the sudden opening of a car door in their path of travel. By "covert" is meant the drivers had no idea they were being observed or were participating in the study. This researcher found that neither the latency nor the amount of deviation from the pre-event pathway was dependent upon the car's prior position with respect to the opening car door. Drivers responded with a ballistic "jerk" of the steering wheel. The mean response latency for these Finnish drivers was 1.5 sec, and reached the half-way point of maximum displacement from the original path in about 2.5 sec. The

Table 3.5
Movement Time Estimates

Source	N	Mean (Std)	75th Sec	90th Sec	95th Sec	99th Sec
Brackett (Brackett and Koppa 1988)	24	0.22 (0.20)	0.44	0.59	0.68	0.86
Hoffman (1991)	18	0.26 (0.20)	0.50	0.66	0.84	1.06
Berman (1994)	24	0.20 (0.05)	0.26	0.29	0.32	0.36

3.4 Response Distances and Times to Traffic Control Devices

The driving task is overwhelmingly visual in nature; external information coming through the windshield constitutes nearly all the information processed. A major input to the driver which influences his or her path and thus is important to traffic flow theorists is traffic information imparted by traffic control devices (TCD). The major issues concerned with TCD are all related to distances at which they may be (1) detected as objects in the visual field; (2) recognized as traffic control devices: signs, signals, delineators, and barricades; (3) legible or identifiable so that they may be comprehended and acted upon. Figure 3.3 depicts a conceptual model for TCD information processing, and the many variables which affect it. The research literature is very rich with data related to target detection in complex visual environments, and a TCD's target value also depends upon the driver's predilection to look for and use such devices.

3.4.1 Traffic Signal Change

From the standpoint of traffic flow theory and modeling, a major concern is at the stage of legibility or identification and a combination of "read" and "understand" in the diagram in Figure 3.3. One of the most basic concerns is driver response or lag to

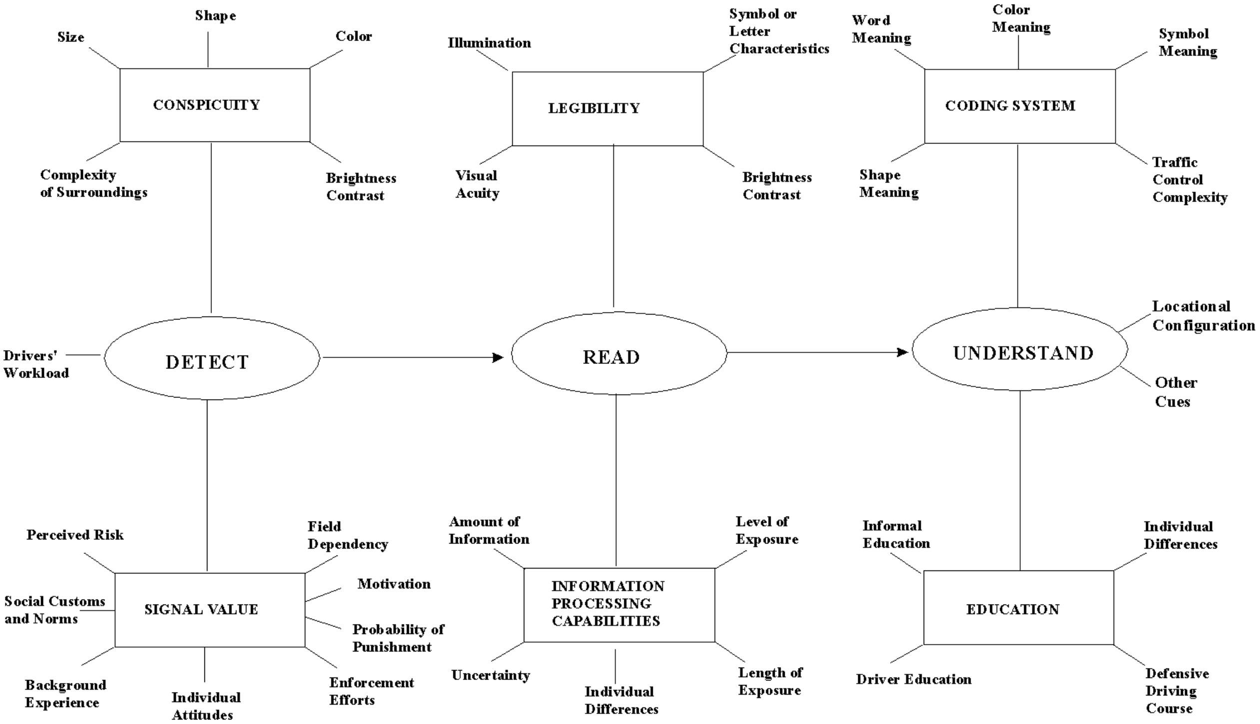

Figure 3.3
A Model of Traffic Control Device Information Processing.

changing traffic signals. Chang et al. (1985) found through covert observations at signalized intersections that drivers response lag to signal change (time of change to onset of brake lamps) averaged 1.3 sec, with the 85th percentile PRT estimated at 1.9 sec and the 95th percentile at 2.5 sec. This PRT to signal change is somewhat inelastic with respect to distance from the traffic signal at which the signal state changed. The mean PRT (at 64 kilometers per hour (km/h)) varied by only 0.20 sec within a distance of 15 meters (m) and by only 0.40 sec within 46 m.

Wortman and Matthias (1983) found similar results to Chang et al. (1985) with a mean PRT of 1.30 sec, and a 85th percentile PRT of 1.5 sec. Using tolerance estimates based on their sample size, (95 percent confidence level) the 95th percentile PRT was 2.34 sec, and the 99th percentile PRT was 2.77 sec. They found very little relationship between the distance from the intersection and either PRT or approach speed ($r^2 = 0.08$). So the two study findings are in generally good agreement, and the following estimates may be used for driver response to signal change:

Mean PRT to signal change =	1.30 sec
85th percentile PRT =	1.50 sec
95th percentile PRT =	2.50 sec
99th percentile PRT =	2.80 sec

If the driver is stopped at a signal, and a straight-ahead maneuver is planned, PRT would be consistent with those values given in Section 3.3.1. If complex maneuvers occur after signal change (e.g., left turn yield to oncoming traffic), the Hick-Hyman Law (Section 3.2.1) could be used with the *y* intercept being the basic PRT to onset of the traffic signal change. Considerations related to intersection sight distances and gap acceptance make such predictions rather difficult to make without empirical validation. These considerations will be discussed in Section 3.15.

3.4.2 Sign Visibility and Legibility

The psychophysical limits to legibility (alpha-numeric) and identification (symbolic) sign legends are the resolving power of

Table 3.6
Visual Acuity and Letter Sizes

Snellen Acuity	Visual angle of letter or symbol		Legibility Index
SI (English)	'of arc	radians	m/cm
6/3 (20/10)	2.5	0.00073	13.7
6/6 (20/20)	5	0.00145	6.9
6/9 (20/30)	7.5	0.00218	4.6
6/12 (20/40)	10	0.00291	3.4
6/15 (20/50)	12.5	0.00364	2.7
6/18 (20/60)	15	0.00436	2.3

the visual perception system, the effects of the optical train leading to presentation of an image on the retina of the eye, neural processing of that image, and further processing by the brain. Table 3.6 summarizes visual acuity in terms of visual angles and legibility indices.

The exact formula for calculating visual angle is

$$\measuredangle = 2\ \arctan\left(\frac{L}{2D}\right) \tag{3.10}$$

where, L = diameter of the target (letter or symbol)
D = distance from eye to target in the same units

All things being equal, two objects that subtend the same visual angle will elicit the same response from a human observer, regardless of their actual sizes and distances. In Table 3.6 the Snellen eye chart visual acuity ratings are related to the size of objects in terms of visual arc, radians (equivalent for small sizes to the tangent of the visual arc) and legibility indices. Standard transportation engineering resources such as the *Traffic Control Devices Handbook* (FHWA 1983) are based upon these fundamental facts about visual performance, but it should be clearly recognized that it is very misleading to extrapolate directly from letter or symbol legibility/recognition sizes to *sign* perceptual distances, especially for word signs. There are other expectancy cues available to the driver, word length, layout, etc. that can lead to performance better than straight visual angle computations would suggest. Jacobs, Johnston, and Cole (1975) also point out an elementary fact that 27 to 30 percent of the driving population cannot meet a 6/6 (20/20) criterion. Most states in the U.S. have a 6/12 (20/40) static acuity criterion for unrestricted licensure, and accept 6/18 (20/60) for restricted (daytime, usually) licensure. Such tests in driver license offices are subject to error, and examiners tend to be very lenient. Night-time static visual acuity tends to be at least one Snellen line worse than daytime, and much worse for older drivers (to be discussed in Section 3.8).

Jacobs, et al. also point out that the sign size for 95th percentile recognition or legibility is 1.7 times the size for 50th percentile performance. There is also a pervasive notion in the research that *letter* sign legibility distances are half *symbol* sign recognition distances, when drivers are very familiar with the symbol (Greene 1994). Greene (1994), in a very recent study, confirmed these earlier findings, and also notes that extreme variability exists from trial to trial *for the same observer* on a given sign's recognition distance. Presumably, word signs would manifest as much or even more variability. Complex, fine detail signs such as Bicycle Crossing (MUTCD W11-1) were observed to have coefficients of variation <u>between</u> subjects of 43 percent. Coefficient of Variation (*CV*) is simply:

$$CV = 100 \cdot (Std\ Deviation/Mean) \tag{3.11}$$

In contrast, very simple symbol signs such as T-Junction (MUTCD W2-4) had a CV of 28 percent. <u>Within</u> subject variation (from trial to trial) on the same symbol sign is summarized in Table 3.7.

Before any reliable predictions can be made about legibility or recognition distances of a given sign, Greene (1994) found that six or more trials under controlled conditions must be made, either in the laboratory or under field conditions. Greene (1994) found percent differences between high-fidelity laboratory and field recognition distances to range from 3 to 21 percent, depending upon sign complexity. These differences consistent with most researchers, were all in the direction of laboratory distances being greater than actual distances; the laboratory tends to overestimate field legibility distances. Variability in legibility distances, however, is as great in the laboratory as it is under field trials.

With respect to visual angle required for recognition, Greene found, for example, that the Deer Crossing at the mean recognition distance had a mean visual angle of 0.00193 radian, or 6.6 minutes of arc. A more complex, fine detail sign such as Bicycle Crossing required a mean visual angle of 0.00345 radian or 11.8 minutes of arc to become recognizable.

With these considerations in mind, here is the best recommendation that this writer can make. For the purposes of predicting driver comprehension of signs and other devices that require interpretation of words or symbols use the data in Table 3.6 as "best case," with actual performance expected to be somewhat to much worse (i.e., requiring closer distances for a given size of character or symbol). The best visual acuity that can be expected of drivers under optimum contrast conditions so far as static acuity is concerned would be 6/15 (20/50) when the sizable numbers of older drivers is considered [13 percent in 1990 were 65 or older (O'Leary and Atkins 1993)].

Table 3.7
Within Subject Variation for Sign Legibility

Sign	Young Drivers		Older Drivers	
	Min CV	Max CV	Min CV	Max CV
WG-3 2 Way Traffic	3.9	21.9	8.9	26.7
W11-1 Bicycle Cross	6.7	37.0	5.5	39.4
W2-1 Crossroad	5.2	16.3	2.0	28.6
W11-3 Deer Cross	5.4	21.3	5.4	49.2
W8-5 Slippery	7.7	33.4	15.9	44.1
W2-5 T-Junction	5.6	24.6	4.9	28.7

3.4.3 Real-Time Displays and Signs

With the advent of Intelligent Transportation Systems (ITS), traffic flow modelers must consider the effects of changeable message signs on driver performance in traffic streams. Depending on the design of such signs, visual performance to them may not differ significantly from conventional signage. Signs with active (lamp or fiber optic) elements may not yield the legibility distances associated with static signage, because Federal Highway Administration, notably the definitive manual by Dudek (1990).

3.4.4 Reading Time Allowance

For signs that cannot be comprehended in one glance, i.e., word message signs, allowance must be made for reading the information and then deciding what to do, before a driver in traffic will begin to maneuver in response to the information. Reading speed is affected by a host of factors (Boff and Lincoln 1988) such as the type of text, number of words, sentence structure, information order, whatever else the driver is doing, the purpose of reading, and the method of presentation. The USAF resource (Boff and Lincoln 1988) has a great deal of general information on various aspects of reading sign material. For purposes of traffic flow modeling, however, a general rule of thumb may suffice. This can be found in Dudek (1990): "Research...has indicated that a minimum exposure time of one second per short word (four to eight characters) (*exclusive of prepositions and other similar connectors*) or two seconds per unit of information, whichever is largest, should be used for unfamiliar drivers. On a sign having 12 to 16 characters per line, this minimum exposure time will be two seconds per line." "Exposure time" can also be interpreted as "reading time" and so used in estimating how long drivers will take to read and comprehend a sign with a given message.

Suppose a sign reads:

Traffic Conditions
Next 2 Miles
Disabled Vehicle on I-77
Use I-77 Bypass Next Exit

Drivers not familiar with such a sign ("worst case," but able to read the sign) could take at least 8 seconds and according to the Dudek formula above up to 12 seconds to process this information and begin to respond. In Dudek's 1990 study, 85 percent of drivers familiar with similar signs read this 13-word message (excluding prepositions) with 6 message units in 6.7 seconds. The formulas in the literature properly tend to be conservative.

3.5 Response to Other Vehicle Dynamics

Vehicles in a traffic stream are discrete elements with motion characteristics loosely coupled with each other via the driver's processing of information and making control inputs. Effects of changes in speed or acceleration of other elements as perceived and acted on by the driver of any given element are of interest. Two situations appear relevant: (1) the vehicle ahead and (2) the vehicle alongside (in the periphery).

3.5.1 The Vehicle Ahead

Consideration of the vehicle ahead has its basis in thresholds for detection of radial motion (Schiff 1980). Radial motion is change in the apparent size of a target. The minimum condition for perceiving radial motion of an object (such as a vehicle ahead) is the symmetrical magnification of a form or texture in the field of view. Visual angle transitions from a near-linear to a geometric change in magnitude as an object approaches at constant velocity, as Figure 3.4 depicts for a motor vehicle approaching at a delta speed of 88 km/h. As the rate of change of visual angle becomes geometric, the perceptual system triggers a warning that an object is going to collide with the observer, or, conversely, that the object is pulling away from the observer. This phenomenon is called *looming*. If the rate of change of visual angle is irregular, that is information to the perceptual system that the object in motion is moving at a changing velocity (Schiff 1980). Sekuler and Blake (1990) report evidence that actual looming detectors exist in the human visual system. The relative change in visual angle is roughly equal to the reciprocal of "time-to-go" (time to impact), a special

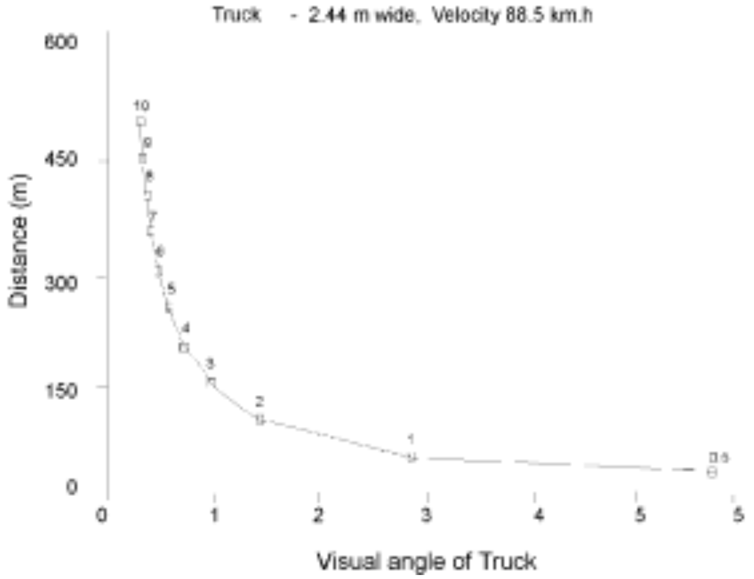

Figure 3.4
Looming as a Function of Distance from Object.

case of the well-known Weber fraction, $S = \Delta I/I$, the magnitude of a stimulus is directly related to a change in physical energy but inversely related to the initial level of energy in the stimulus.

Human visual perception of acceleration (as such) of an object in motion is very gross and inaccurate; it is very difficult for a driver to discriminate acceleration from constant velocity unless the object is observed for a relatively long period of time - 10 or 15 sec (Boff and Lincoln 1988).

The delta speed threshold for detection of oncoming collision or pull-away has been studied in collision-avoidance research. Mortimer (1988) estimates that drivers can detect a change in distance between the vehicle they are driving and the one in front when it has varied by approximately 12 percent. If a driver were following a car ahead at a distance of 30 m, at a change of 3.7 m the driver would become aware that distance is decreasing or increasing, i.e., a change in relative velocity. Mortimer notes that the major cue is rate of change in visual angle. This threshold was estimated in one study as 0.0035 radians/sec.

This would suggest that a change of distance of 12 percent in 5.6 seconds or less would trigger a perception of approach or pulling away. Mortimer concludes that "...unless the relative velocity between two vehicles becomes quite high, the drivers will respond to changes in their headway, or the change in angular size of the vehicle ahead, and use that as a cue to determine the speed that they should adopt when following another vehicle."

3.5.2 The Vehicle Alongside

Motion detection in peripheral vision is generally less acute than in foveal (straight-ahead) vision (Boff and Lincoln 1988), in that a greater relative velocity is necessary for a driver "looking out of the corner of his eye" to detect that speed change than if he or she is looking to the side at the subject vehicle in the next lane. On the other hand, peripheral vision is very blurred and motion is a much more salient cue than a stationary target is. A stationary object in the periphery (such as a neighboring vehicle exactly keeping pace with the driver's vehicle) tends to disappear for all intents and purposes *unless it moves with respect to the viewer* against a patterned background. Then that movement will be detected. Relative motion in the periphery also tends to look slower than the same movement as seen using fovea vision. Radial motion (car alongside swerving toward or away from the driver) detection presumably would follow the same pattern as the vehicle ahead case, but no study concerned with measuring this threshold directly was found.

3.6 Obstacle and Hazard Detection, Recognition, and Identification

Drivers on a highway can be confronted by a number of different situations which dictate either evasive maneuvers or stopping maneuvers. Perception-response time (PRT) to such encounters have already been discussed in Section 3.3.1. But before a maneuver can be initiated, the object or hazard must first be detected and then recognized as a hazard. The basic considerations are not greatly different than those discussed under driver responses to traffic control devices (Section 3.5), but some specific findings on roadway obstacles and hazards will also be discussed.

3.6.1 Obstacle and Hazard Detection

Picha (1992) conducted an object detection study in which representative obstacles or objects that might be found on a roadway were unexpectedly encountered by drivers on a closed course. Six objects, a 1 x 4 board, a black toy dog, a white toy dog, a tire tread, a tree limb with leaves, and a hay bale were placed in the driver's way. Both detection and recognition distances were recorded. Average visual angles of detection for these various objects varied from the black dog at 1.8 minimum of arc to 4.9 min of arc for the tree limb. Table 3.8 summarizes the detection findings of this study.

At the 95 percent level of confidence, it can be said from these findings that an object subtending a little less than 5 minutes of arc will be detected by all but 1 percent of drivers under daylight conditions provided they are looking in the object's direction. Since visual acuity declines by as much as two Snellen lines after nightfall, to be dtected such targets with similar contrast would

Table 3.8
Object Detection Visual Angles (Daytime)
(Minutes of Arc)

Object	Mean	Tolerance, 95th confidence		
		STD	95th	99th
1" x 4" Board, 24" x 1"*	2.47	1.21	5.22	6.26
Black toy dog, 6" x 6"	1.81	0.37	2.61	2.91
White toy dog, 6" x 6"	2.13	0.87	4.10	4.84
Tire tread, 8" x 18"	2.15	0.38	2.95	3.26
Tree Branch, 18" x 12"	4.91	1.27	7.63	8.67
Hay bale, 48" x 18"	4.50	1.28	7.22	8.26
All Targets	3.10	0.57	4.30	4.76
***frontal viewing plan dimensions**				

have to subtend somewhere around 2.5 times the visual angle that they would at detection under daylight conditions.

3.6.2 Obstacle and Hazard Recognition and Identification

Once the driver has detected an object in his or her path, the next job is to: (1) decide if the object, whatever it is, is a potential hazard, this is the recognition stage, followed by (2) the identification stage, even closer, at which a driver actually can tell what the object is. If an object (assume it is stationary) is small enough to pass under the vehicle and between the wheels, it doesn't matter very much what it is. So the first estimate is primarily of size of the object. If the decision is made that the object is too large to pass under the vehicle, then either evasive action or a braking maneuver must be decided upon. Objects 15 cm or less in height very seldom are causal factors in accidents (Kroemer et al. 1994).

The majority of objects encountered on the highway that constitute hazard and thus trigger avoidance maneuvers are larger than 60 cm in height. Where it may be of interest to establish a visual angle for an object to be discriminated as a hazard or non-hazard, such decisions require visual angles on the order of at least the visual angles identified in Section 3.4.2 for letter or symbol recognition, i.e., about 15 minutes of arc to take in 99 percent of the driver population. It would be useful to reflect that the full moon subtends 30 minutes of arc, to give the reader an intuitive feel for what the minimum visual angle might be for object recognition. At a distance somewhat greater than this, the driver decides if an object is sizable enough to constitute a hazard, largely based upon roadway lane width size comparisons and the size of the object with respect to other familiar roadside objects (such as mailboxes, bridge rails). Such judgements improve if the object is identified.

3.7 Individual Differences in Driver Performance

In psychological circles, variability among people, especially that associated with variables such as gender, age, socio-economic levels, education, state of health, ethnicity, etc., goes by the name "individual differences." Only a few such variables are of interest to traffic flow modeling. These are the variables which directly affect the path and velocity the driven vehicle follows in a given time in the operational environment. Other driver characteristics which may be of interest to the reader may be found in the *NHTSA Driver Performance Data* book (1987, 1994).

3.7.1 Gender

Kroemer, Kroemer, and Kroemer-Ebert (1994) summarize relevant gender differences as minimal to none. Fine finger dexterity and color perception are areas in which women perform better than men, but men have an advantage in speed. Reaction time tends to be slightly longer for women than for men the recent popular book and PBS series, *Brain Sex* (Moir and Jessel 1991) has some fascinating insights into why this might be so. This difference is statistically but not practically significant. For the purpose of traffic flow analysis, performance differences between men and women may be ignored.

3.7.2 Age

Research on the older driver has been increasing at an exponential rate, as was noted in the recent state-of-the-art summary by the Transportation Research Board (TRB 1988). Although a number of aspects of human performance related to driving change with the passage of years, such as response time, channel capacity and processing time needed for decision making, movement ranges and times, most of these are extremely variable, i.e., age is a poor predictor of performance. This was not so for visual perception. Although there are exceptions, for the most part visual performance becomes progressively poorer with age, a process which accelerates somewhere in the fifth decade of life.

Some of these changes are attributable to optical and physiological conditions in the aging eye, while others relate to changes in neural processing of the image formed on the retina. There are other cognitive changes which are also central to understanding performance differences as drivers age. Both visual and cognitive changes affecting driver performance will be discussed in the following paragraphs.

CHANGES IN VISUAL PERCEPTION

Loss of Visual Acuity (static) - Fifteen to 25 percent of the population 65 and older manifest visual acuities (Snellen) of less than 20/50 corrected, owing to senile macular degeneration (Marmor 1982). Peripheral vision is relatively unaffected, although a gradual narrowing of the visual field from 170 degrees to 140 degrees or less is attributable to anatomical changes (eyes become more sunk in the head). Static visual acuity among drivers is not highly associated with accident experience and is probably not a very significant factor in discerning path guidance devices and markings.

Light Losses and Scattering in Optic Train - There is some evidence (Ordy et al. 1982) that the scotopic (night) vision system ages faster than the photopic (daylight) system does. In addition, scatter and absorption by the stiff, yellowed, and possibly cateracted crystalline lens of the eye accounts for much less light hitting the degraded retina. The pupil also becomes stiffer with age, and dilates less for a given amount of light impingement (which considering that the mechanism of pupillary size is in part driven by the amount of light falling on the retina suggests actual physical atrophy of the pupil--senile myosis). There is also more matter in suspension in the vitreous humor of the aged eye than exists in the younger eye. The upshot is that only 30 percent of the light under daytime conditions that gets to the retina in a 20 year old gets to the retina of a 60 year old. This becomes *much worse at night* (as little as 1/16), and is exacerbated by the scattering effect of the optic train. Points of bright light are surrounded by halos that effectively obscure less bright objects in their near proximity. Blackwell and Blackwell (1971) estimated that, because of these changes, a given level of contrast of an object has to be increased by a factor of anywhere from 1.17 to 2.51 for a 70 year old person to see it, as compared to a 30 year old.

Glare Recovery - It is worth noting that a 55 year old person requires more than 8 times the period of time to recover from glare if dark adapted than a 16 year old does (Fox 1989). An older driver who does not use the strategy to look to the right and shield his or her macular vision from oncoming headlamp glare is literally driving blind for many seconds after exposure. As described above, scatter in the optic train makes discerning *any* marking or traffic control device difficult to impossible. The slow re-adaptation to mesopic levels of lighting is well-documented.

Figure/Ground Discrimination **-** Perceptual style changes with age, and many older drivers miss important cues, especially under higher workloads (Fox 1989). This means drivers may miss a significant guideline or marker under unfamiliar driving conditions, because they fail to discriminate the object from its background, either during the day or at night.

CHANGES IN COGNITIVE PERFORMANCE

Information Filtering Mechanisms **-** Older drivers reportedly experience problems in ignoring irrelevant information and correctly identifying meaningful cues (McPherson et al. 1988). Drivers may not be able to discriminate actual delineation or signage from roadside advertising or faraway lights, for example. Work zone traffic control devices and markings that are meant to override the pre-work TCD's may be missed.

Forced Pacing under Highway Conditions **-** In tasks that require fine control, steadiness, and rapid decisions, forced paced tasks under stressful conditions may disrupt the performance of older drivers. They attempt to compensate for this by slowing down. Older people drive better when they can control their own pace (McPherson et al. 1988). To the traffic flow theorist, a sizable proportion of older drivers in a traffic stream may result in vehicles that lag behind and obstruct the flow.

Central vs. Peripheral Processes **-** Older driver safety problems relate to tasks that are heavily dependent on central processing. These tasks involve responses to traffic or to *roadway conditions* (emphasis added) (McPherson et al. 1988).

The Elderly Driver of the Past or Even of Today is Not the Older Driver of the Future **-** The cohort of drivers who will be 65 in the year 2000, which is less than five years from now, were born in the 1930's. Unlike the subjects of gerontology studies done just a few years ago featuring people who came of driving age in the 1920's or even before, when far fewer people had cars and traffic was sparse, the old of tomorrow started driving in the 1940's and after. They are and will be more affluent, better educated, in better health, resident in the same communities they lived in before becoming "older drivers," and they have driven under modern conditions and the urban environment since their teens. Most of them have had classes in driver education and defensive driving. They will likely continue driving on a routine basis until almost the end of their natural lives, which will be happening at an ever advancing age. The cognitive trends briefly discussed above are very variable in incidence and in their actual effect on driving performance. The future older driver may well exhibit much less decline in many of these performance areas in which central processes are dominant.

3.7.3 Driver Impairment

Drugs **-** Alcohol abuse in isolation and combination with other drugs, legal or otherwise, has a generally deleterious effect on performance (Hulbert 1988; Smiley 1974). Performance differences are in greater variability for any given driver, and in generally lengthened reaction times and cognitive processing times. Paradoxically, some drug combinations can improve such performance on certain individuals at certain times. The only drug incidence which is sufficiently large to merit consideration in traffic flow theory is alcohol.

Although incidence of alcohol involvement in *accidents* has been researched for many years, and has been found to be substantial, very little is known about incidence and levels of impairment in the driving population, other than it must also be substantial. Because these drivers are impaired, they are over-represented in accidents. Price (1988) cites estimates that 92 percent of the adult population of the U.S. use alcohol, and perhaps 11 percent of the total adult population (20-70 years of age) have alcohol abuse problems. Of the 11 percent who are problem drinkers, seven percent are men, four percent women. The incidence of problem drinking drops with age, as might be expected. Effects on performance as a function of blood alcohol concentration (BAC) are well-summarized in Price, but are too voluminous to be reproduced here. Price also summarizes effects of other drugs such as cocaine, marijuana, etc. Excellent sources for more information on alcohol and driving can be found in a Transportation Research Board Special Report (216).

Medical Conditions **-** Disabled people who drive represent a small but growing portion of the population as technology advances in the field of adaptive equipment. Performance studies and insurance claim experience over the years (Koppa et al. 1980) suggest that such driver's performance is indistinguishable from the general driving population. Although there are doubtless a number of people on the highways with illnesses or conditions for which driving is contraindicated, they are probably not enough of these to account for them in any traffic flow models.

3.8 Continuous Driver Performance

The previous sections of this chapter have sketched the relevant discrete performance characteristics of the driver in a traffic stream. Driving, however, is primarily a continuous dynamic process of managing the present heading and thus the future path of the vehicle through the steering function. The first and second derivatives of location on the roadway in time, velocity and acceleration, are also continuous control processes through modulated input using the accelerator (really the throttle) and the brake controls.

3.8.1 Steering Performance

The driver is tightly coupled into the steering subsystem of the human-machine system we call the motor vehicle. It was only during the years of World War II that researchers and engineers first began to model the human operator in a tracking situation by means of differential equations, i.e., a transfer function. The first paper on record to explore the human transfer function was by Tustin in 1944 (Garner 1967), and the subject was antiaircraft gun control. The human operator in such tracking situations can be described in the same terms as if he or she is a linear feedback control system, even though the human operator is noisy, non-linear, and sometimes not even closed-loop.

3.8.1.1 Human Transfer Function for Steering

Steering can be classified as a special case of the general pursuit tracking model, in which the two inputs to the driver (which are somehow combined to produce the correction signal) are (1) the desired path as perceived by the driver from cues provided by the roadway features, the streaming of the visual field, and higher order information; and (2) the perceived present course of the vehicle as inferred from relationship of the hood to roadway features. The exact form of either of these two inputs are still subjects of investigation and some uncertainty, even though nothing can be more commonplace than steering a motor vehicle. Figure 3.5 illustrates the conceptual model first proposed by Sheridan (1962). The human operator looks at both inputs, *R(t)* the desired input forcing function (the road and where it seems to be taking the driver), and *E(t)* the system error function, the difference between where the road is going and what *C(t)* the vehicle seems to be doing. The human operator can look ahead (*lead*), the prediction function, and also can correct for perceived errors in the path. If the driver were trying to drive by viewing the road through a hole in the floor of the car, then the prediction function would be lost, which is usually the state of affairs for servomechanisms. The two human functions of prediction and compensation are combined to make a control input to the vehicle via the steering wheel which (for power steering) is also a servo in its own right. The control output from this human-steering process combination is fed back (by the perception of the path of the vehicle) to close the loop. Mathematically, the setup in Figure 3.5 is expressed as follows, if the operator is reasonably linear:

$$g_{(s)} = \frac{Ke^{-ts}(1+T_L s)}{(1+T_L s)(1+T_N s)} + R \qquad (3.12)$$

Sheridan (1962) reported some parameters for this Laplace transform transfer function of the first order. *K*, the gain or sensitivity term, varies (at least) between +35 *db* to -12 *db*. Gain, how much response the human will make to a given input, is the parameter perhaps most easily varied, and tends to settle at some point comfortably short of instability (a phase margin of 60 degrees or more). The exponential term e^{-ts} ranges from 0.12 to 0.3 sec and is best interpreted as reaction time. This delay is the dominant limit to the human's ability to adapt to fast-changing conditions. The *T* factors are all time constants, which however may not stay constant at all. They must usually be empirically derived for a given control situation.

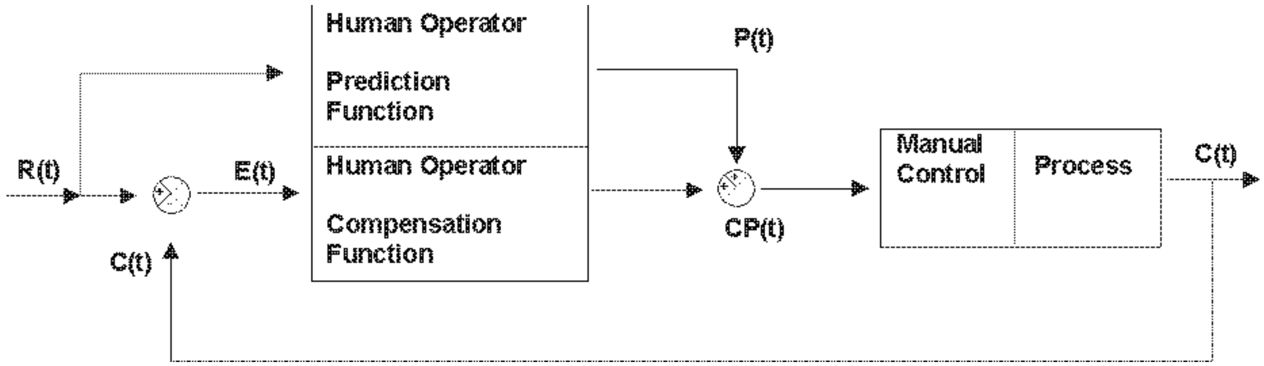

Figure 3.5
Pursuit Tracking Configuration (after Sheridan 1962).

Sheridan reported some experimental results which show T_L (lead) varying between 0 and 2, T_I (lag) from 0.0005 to 25, and T_N (neuromuscular lag) from 0 to 0.67. R, the remnant term, is usually introduced to make up for nonlinearities between input and output. Its value is whatever it takes to make output track input in a predictable manner. In various forms, and sometimes with different and more parameters, Equation 3.10 expresses the basic approach to modeling the driver's steering behavior. Novice drivers tend to behave primarily in the *compensatory* tracking mode, in which they primarily attend to the difference, say, between the center of the hood and the edge line of the pavement, and attempt to keep that difference at some constant visual angle. As they become more expert, they move more to pursuit tracking as described above. There is also evidence that there are "precognitive" open-loop steering commands to particular situations such as swinging into an accustomed parking place in a vehicle the driver is familiar with. McRuer and Klein (1975) classify maneuvers of interest to traffic flow modelers as is shown in Table 3.9.

In Table 3.9, the entries under driver control mode denote the order in which the three kinds of tracking transition from one to the other as the maneuver transpires. For example, for a turning movement, the driver follows the dotted lines in an intersection and aims for the appropriate lane in the crossroad in a pursuit mode, but then makes adjustments for lane position during the latter portion of the maneuver in a compensatory mode. In an emergency, the driver "jerks" the wheel in a precognitive (open-loop) response, and then straightens out the vehicle in the new lane using compensatory tracking.

Table 3.9
Maneuver Classification

	Driver Control Mode		
Maneuver	**Compen-satory**	**Pursuit**	**Precognitive**
Highway Lane Regulation	1		
Precision Course Control	2	1	
Turning; Ramp Entry/Exit	2	1	
Lane Change	2		1
Overtake/Pass	2	1	
Evasive Lane Change	2		1

3.8.1.2 Performance Characteristics Based on Models

The amplitude of the output from this transfer function has been found to rapidly approach zero as the frequency of the forcing function becomes greater than 0.5 *Hz* (Knight 1987). The driver makes smaller and smaller corrections as the highway or wind gusts or other inputs start coming in more frequently than one complete cycle every two seconds.

The time lag between input and output also increases with frequency. Lags approach 100 msec at an input of 0.5 Hz and increase almost twofold to 180 msec at frequencies of 2.4 Hz. The human tracking bandwidth is of the order of 1 to 2 Hz. Drivers can go to a precognitive rhythm for steering input to better this performance, if the input is very predictable, e.g., a "slalom" course. Basic lane maintenance under very restrictive conditions (driver was instructed to keep the left wheels of a vehicle on a painted line rather than just lane keep) was studied very recently by Dulas (1994) as part of his investigation of changes in driving performance associated with in-vehicle displays and input tasks. Speed was 57 km/h. Dulas found average deviations of 15 cm, with a standard deviation of 3.2 cm. Using a tolerance estimation based on the nearly 1000 observations of deviation, the 95th percentile deviation would be 21 cm, the 99th would be 23 cm. Thus drivers can be expected to weave back and forth in a lane in straightaway driving in an envelope of +/- 23 cm or 46 cm across. Steering accuracy with degrade and oscillation will be considerably more in curves. since such driving is mixed mode, with rather large errors at the beginning of the maneuver, with compensatory corrections toward the end of the maneuver. Godthelp (1986) described this process as follows. The driver starts the maneuver with a lead term before the curve actually begins. This precognitive control action finishes shortly after the curve is entered.

Then a stage of steady-state curve driving follows, with the driver now making compensatory steering corrections. The steering wheel is then restored to straight-ahead in a period that covers the endpoint of the curve. Road curvature (perceived) and vehicle speed predetermines what the initial steering input will be, in the following relationship:

$$g_s = \frac{SRl\ (1+F_s u^2)C_r}{1000} \tag{3.13}$$

where,

C_r = roadway curvature
SR = steering ratio
F_s = stability factor
l = wheelbase
u = speed
g_s = steering wheel angle (radians)

Godthelp found that the standard deviation of anticipatory steering inputs is about 9 percent of steering wheel angle g_s. Since sharper curves require more steering wheel input, inaccuracies will be proportionately greater, and will also induce more oscillation from side to side in the curve during the compensatory phase of the maneuver.

3.9 Braking Performance

The steering performance of the driver is integrated with either braking or accelerator positioning in primary control input. Human performance aspects of braking as a continuous control input will be discussed in this section. After the perception-response time lag has elapsed, the actual process of applying the brakes to slow or stop the motor vehicle begins.

3.9.1 Open-Loop Braking Performance

The simplest type of braking performance is "jamming on the brakes." The driver exerts as much force as he or she can muster, and thus approximates an instantaneous step input to the motor vehicle. Response of the vehicle to such an input is out of scope for this chapter, but it can be remarked that it can result in one or more wheels locking and consequent loss of control at speeds higher than 32 km/h, unless the vehicle is equipped with antiskid brakes (ABS, or Antilock Brake System). Such a model of human braking performance is assumed in the time-hallowed AASHTO braking distance formula (AASHTO 1990):

$$d = \frac{V^2}{257.9f} \tag{3.14}$$

where,

d = braking distance - meters
V = Initial speed - km/h
f = Coefficient of friction, tires to pavement surface, approximately equal to deceleration in g units

Figure 3.6 shows what such a braking control input really looks like in terms of the deceleration profile. This maneuver was on a dry tangent section at 64 km/h, under "unplanned" conditions (the driver does not know when or if the signal to brake will be given) with a full-size passenger vehicle not equipped with ABS. Note the typical steep rise in deceleration to a peak of over 0.9 g, then steady state at approximately 0.7 g for a brakes locked stop. The distance data is also on this plot: the braking distance on this run was 23 m feet. Note also that the suspension bounce produces a characteristic oscillation after the point at which the vehicle is completely stopped, just a little less than five seconds into the run.

Figure 3.7 shows a braking maneuver on a tangent with the same driver and vehicle, this time on a wet surface. Note the characteristic "lockup" footprint, with a steady-state deceleration after lockup of 0.4 g.

From the standpoint of modeling driver input to the vehicle, the open-loop approximation is a step input to maximum braking effort, with the driver exhibiting a simple to complex PRT delay prior to the step. A similar delay term would be introduced prior to release of the brake pedal, thus braking under stop-and-go conditions would be a sawtooth.

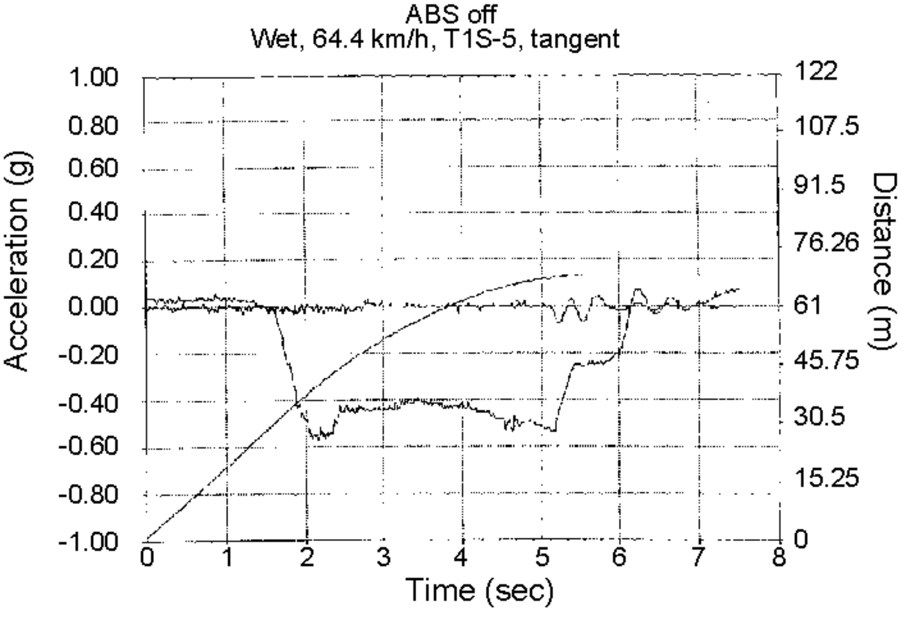

Figure 3.6
Typical Deceleration Profile for a Driver without Antiskid Braking System on a Dry Surface.

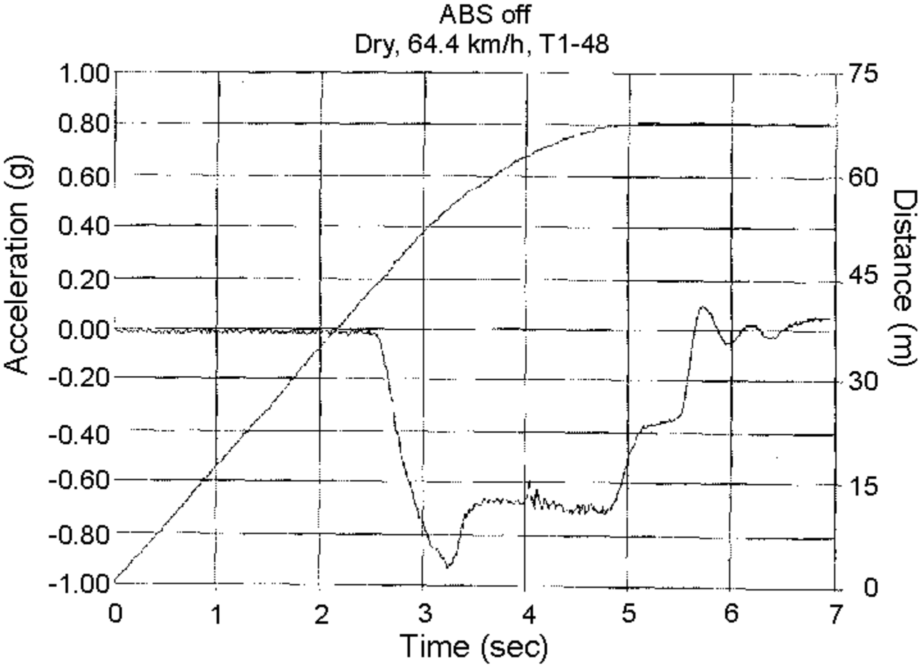

Figure 3.7
Typical Deceleration Profile for a Driver without Antiskid Braking System on a Wet Surface.

3.9.2 Closed-Loop Braking Performance

Recent research in which the writer has been involved provide some controlled braking performance data of direct application to performance modeling (Fambro et al. 1994). "Steady state" approximations or fits to these data show wide variations among drivers, ranging from -0.46 g to -0.70 g.

Table 3.10 provides some steady-state derivations from empirical data collected by Fambro et al. (1994). These were all responses to an unexpected obstacle or object encountered on a closed course, in the driver's own (but instrumented) car.

Table 3.11 provides the same derivations from data collected on drivers in their own vehicle in which the braking maneuver was anticipated; the driver knows that he or she would be braking, but during the run were unsure when the signal (a red light inside the car) would come.

The ratio of unexpected to expected closed-loop braking effort was estimated by Fambro et al. to be about 1.22 under the same pavement conditions. Pavement friction (short of ice) played very little part in driver's setting of these effort levels. About 0.05 to 0.10 g difference between wet pavement and dry pavement steady-state *g* was found.

Table 3.10
Percentile Estimates of Steady State Unexpected Deceleration

Mean	-0.55g
Standard Deviation	0.07
75th Percentile	-0.43
90th	-0.37
95th	-0.32
99th	-0.24

Table 3.11
Percentile Estimates of Steady-State Expected Deceleration

Mean	-0.45g
Standard Deviation	0.09
75th Percentile	-0.36
90th	-0.31
95th	-0.27
99th	-0.21

3.9.3 Less-Than-Maximum Braking Performance

The flow theorist may require an estimate of “comfortable” braking performance, in which the driver makes a stop for intersections or traffic control devices which are discerned considerably in advance of the location at which the vehicle is to come to rest. Driver input to such a planned braking situation approximates a "ramp" (straight line increasing with time from zero) function with the slope determined by the distance to the desired stop location or steady-state speed in the case of a platoon being overtaken. The driver squeezes on pedal pressure to the brakes until a desired deceleration is obtained. The maximum "comfortable" braking deceleration is generally accepted to be in the neighborhood of -0.30 g, or around 3 m/sec^2 (ITE 1992).

The AASHTO Green Book (AASHTO 1990) provides a graphic for speed changes in vehicles, in response to approaching an intersection. When a linear computation of decelerations from this graphic is made, these data suggest decelerations in the neighborhood of -2 to -2.6 m/sec^2 or -0.20 to -0.27 g. More recent research by Chang et al. (1985) found values in response to traffic signals approaching -0.39 g, and Wortman and Matthias (1983) observed a range of -0.22 to -0.43 g, with a mean level of -0.36 g. Hence controlled braking performance that yields a *g* force of about -0.2 g would be a reasonable lower level for a modeler, i.e., almost any driver could be expected to change the velocity of a passenger car by at least that amount, but a more average or "typical" level would be around -0.35 g.

3.10 Speed and Acceleration Performance

The third component to the primary control input of the driver to the vehicle is that of manual (as opposed to cruise control) control of vehicle velocity and changes in velocity by means of the accelerator or other device to control engine RPM.

3.10.1 Steady-State Traffic Speed Control

The driver's primary task under steady-state traffic conditions is to perform a tracking task with the speedometer as the display, and the accelerator position as the control input. Driver response to the error between the present indicated speed and the desired speed (the control signal) is to change the pedal position in the direction opposite to the trend in the error indication. How much of such an error must be present depends upon a host of factors: workload, relationship of desired speed to posted speed, location and design of the speedometer, and personal considerations affecting the performance of the driver at the moment, etc. Drivers in heavy traffic use relative perceived position with respect to other vehicles in the stream as a primary tracking cue (Triggs, 1988). A recent study (Godthelp and Shumann 1994) found errors between speed desired and maintained to vary from -0.3 to -0.8 m/sec in a lane change maneuver; drivers tended to lose velocity when they made such a maneuver. Under steady-stage conditions in a traffic stream, the range of speed error might be estimated to be no more than +/- 1.5 m/sec (Evans and Rothery 1973), basically modeled by a sinusoid. The growing prevalence of cruise controls undoubtedly will reduce the amplitude of this speed error pattern in a traffic stream by half or more.

3.10.2 Acceleration Control

The performance characteristics of the vehicle driver are the limiting constraints on how fast the driver can accelerate the vehicle. The actual acceleration rates, particularly in a traffic stream as opposed to a standing start, are typically much lower than the performance capabilities of the vehicle, particularly a passenger car. A nominal range for "comfortable" acceleration at speeds of 48 km/h and above is 0.6 m/sec^2 to 0.7 m/sec^2 (AASHTO 1990). Another source places the nominal acceleration rate drivers tend to use under "unhurried" circumstances at approximately 65 percent of maximum acceleration for the vehicle, somewhere around 1 m/sec^2 (ITE 1992). If the driver removes his or her foot from the accelerator pedal (or equivalent control input) drag and rolling resistance produce deceleration at about the same level as "unhurried" acceleration, approximately 1 m/sec^2 at speeds of 100 km/h or higher. In contrast to operation of a passenger car or light truck, heavy truck driving is much more limited by the performance capabilities of the vehicle. The best source for such information is the *Traffic Engineering Handbook* (ITE 1992).

3.11 Specific Maneuvers at the Guidance Level

The discussion above has briefly outlined most of the more fundamental aspects of driver performance relevant to modeling the individual driver-vehicle human-machine system in a traffic stream. A few additional topics will now be offered to further refine this picture of the driver as an active controller at the guidance level of operation in traffic.

3.11.1 Overtaking and Passing in the Traffic Stream

3.11.1.1 Overtaking and Passing Vehicles (4-Lane or 1-Way)

Drivers overtake and pass at accelerations in the sub-maximal range in most situations. Acceleration to pass another vehicle (passenger cars) is about 1 m/sec^2 at highway speeds (ITE 1992). The same source provides an approximate equation for acceleration on a grade:

$$a_{GV} \doteq a_{LV} - \frac{G_g}{100} \tag{3.15}$$

where,

a_{GV} = max acceleration rate on grade
a_{LV} = max acceleration rate on level
G = gradient (5/8)
g = acceleration of gravity (9.8 m/sec^2)

The maximum acceleration capabilities of passenger vehicles range from almost 3 m/sec^2 from standing to less than 2 m/sec^2 from 0 to highway speed.

Acceleration is still less when the maneuver begins at higher speeds, as low as 1 m/sec^2 on some small subcompacts. In Equation 3.15, overtaking acceleration should be taken as 65 percent of maximum (ITE 1992). Large trucks or tractor-trailer combinations have maximum acceleration capabilities on a level roadway of no more than 0.4 m/sec^2 at a standing start, and decrease to 0.1 m/sec^2 at speeds of 100 km/h. Truck drivers "floorboard" in passing maneuvers under these circumstances, and maximum vehicle performance is also typical driver input.

3.11.1.2 Overtaking and Passing Vehicles (Opposing Traffic)

The current AASHTO *Policy on Geometric Design* (AASHTO 1990) provides for an acceleration rate of 0.63 m/sec^2 for an initial 56 km/h, 0.64 m/sec^2 for 70 km/h, and 0.66 m/sec^2 for speeds of 100 km/h. Based upon the above considerations, these design guidelines appear very conservative, and the theorist may wish to use the higher numbers in Section 3.11.1.1 in a sensitivity analysis.

3.12 Gap Acceptance and Merging

3.12.1 Gap Acceptance

The driver entering or crossing a traffic stream must evaluate the space between a potentially conflicting vehicle and himself or herself and make a decision whether to cross or enter or not. The time between the arrival of successive vehicles at a point is the time gap, and the critical time gap is the least amount of successive vehicle arrival time in which a driver will attempt a merging or crossing maneuver. There are five different gap acceptance situations. These are:

(1) Left turn across opposing traffic, no traffic control
(2) Left turn across opposing traffic, with traffic control (permissive green)
(3) Left turn onto two-way facility from stop or yield controlled intersection
(4) Crossing two-way facility from stop or yield controlled intersection
(5) Turning right onto two-way facility from stop or yield controlled intersection

Table 3.12 provides very recent design data on these situations from the Highway Capacity Manual (TRB 1985). The range of gap times under the various scenarios presented in Table 3.12 is from a minimum of 4 sec to 8.5 sec. In a stream traveling at 50 km/h (14 m/sec) the gap distance thus ranges from 56 to 119 m; at 90 km/h (25 m/sec) the corresponding distances are 100 to 213 m.

3.12.2 Merging

In merging into traffic on an acceleration ramp on a freeway or similar facility, the Situation (5) data for a four lane facility at 90 km/h with a one second allowance for the ramp provides a baseline estimate of gap acceptance: 4.5 seconds. Theoretically as short a gap as three car lengths (14 meters) can be accepted if vehicles are at or about the same speed, as they would be in merging from one lane to another. This is the minimum, however, and at least twice that gap length should be used as a nominal value for such lane merging maneuvers.

3.13 Stopping Sight Distance

The minimum sight distance on a roadway should be sufficient to enable a vehicle traveling at or near the design speed to stop before reaching a "stationary object" in its path, according to the AASHTO *Policy on Geometric Design* (AASHTO 1990). It goes on to say that sight distance should be at least that required for a "below-average" driver or vehicle to stop in this distance.

Previous sections in this chapter on perception-response time (Section 3.3.1) and braking performance (Section 3.2) provide the raw materials for estimating stopping sight distance. The time-honored estimates used in the AASHTO Green Book (AASHTO 1990) and therefore many other engineering resources give a flat 2.5 sec for PRT, and then the linear deceleration equation (Equation 3.13) as an additive model. This approach generates standard tables that are used to estimate stopping sight distance (SSD) as a function of coefficients of friction and initial speed at inception of the maneuver. The empirically derived estimates now available in Fambro et al. (1994) for both these parts of the SSD equation are expressed in percentile levels of drivers who could be expected to (1) respond and (2) brake in the respective distance or shorter. Since PRT and braking distance that a driver may achieve in a given vehicle are not highly correlated, i.e., drivers that may be very fast to initiate braking may be very conservative in the actual braking maneuver, or may be strong brakers. PRT does not predict braking performance, in other words.

Very often, the engineer will use "worst case" considerations in a design analysis situation. What is the "reasonable" worst case for achieving the AASHTO "below average" driver and vehicle? Clearly, a 99th percentile PRT and a 99th percentile braking distance gives an overly conservative 99.99 combined percentile

Table 3.12
Critical Gap Values for Unsignalized Intersections

Maneuver	Control	Average Speed of Traffic			
		50 km/h		90 km/h	
		Number of Traffic Lanes, Major Roadway			
		2	4	2	4
1	None	5.0	5.5	5.5	6.0
2	Permissive Green[1]	5.0	5.5	5.5	6.0
3	Stop	6.5	7.0	8.0	8.5
3	Yield	6.0	6.5	7.0	7.5
4	Stop	6.0	6.5	7.5	8.0
4	Yield	5.5	6.0	6.5	7.0
5[2]	Stop	5.5	5.5	6.5	6.5
5[2]	Yield	5.0	5.0	5.5	5.5

[1] During Green Interval

[2] If curve radius >15 m or turn angle <60° subtract 0.5 seconds.
If acceleration lane provided, subtract 1.0 seconds.

All times are given in seconds.

All Maneuvers: if population >250,000, subtract 0.5 seconds
if restricted sight distance, add 1.0 seconds
Maximum subtraction is 1.0 seconds
Maximum critical gap ≤ 8.5 seconds

level--*everybody* will have an SSD equal to or shorter than this somewhat absurd combination. The combination of 90th percentile level of performance for each segment yields a combined percentile estimate of 99 percent (i.e., 0.10 of each distribution is outside the envelope, and their product is 0.01, therefore 1.00 - 0.01 = 0.99). A realistic worst case (99th percentile) combination to give SSD would, from previous sections of this chapter be:

PRT:	1.57 sec (Table 3.4)
Braking deceleration:	-0.37 g (Section 3.10.2)

For example, on a dry level roadway, using Equation 3.12, at a velocity of 88 km/h, the SSD components would be:

PRT:	1.57 x 24.44 = 38.4 m
Braking Distance:	82.6 m
SSD:	38 + 83 = 121 m

For comparison, the standard AASHTO SSD for a dry level roadway, using a nominal 0.65 for *f*, the coefficient of friction, would be:

PRT: 2.50 x 24.44 = 61.1 m

Braking Distance: 47.3 m

SSD: 61 + 47 = 108 m

These two estimates are comparable, but the first estimate has an empirical basis for it. The analyst can assume other combinations of percentiles (for example, 75th percentile performance in combination yields an estimate of the 94th percentile). It is always possible, of course, to assume different levels of percentile representation for a hypothetical driver, e.g., 50th percentile PRT with 95th percentile braking performance.

3.14 Intersection Sight Distance

The AASHTO *Policy on Geometric Design* (AASHTO 1990) identifies four differences cases for intersection sight distance considerations. From the viewpoint of traffic flow theory, the question may be posed, "How long is a driver going to linger at an intersection before he or she begins to move?" Only the first three cases will be discussed here, since signalized intersections (Case IV) have been discussed in Section 3.5.1.

3.14.1 Case I: No Traffic Control

The driver initiates either acceleration or deceleration based upon his or her perceived gap in intersecting traffic flow. The principles given in Section 3.13 apply here. PRT for this situation should be the same as for conditions of no surprise outlined in Section 3.3.1. AASHTO (1990) gives an allowance of three seconds for PRT, which appears to be very conservative under these circumstances.

3.14.2 Case II: Yield Control for Secondary Roadway

This is a complex situation. McGee et al. (1983) could not find reliable data to estimate the PRT. A later, follow-up study by Hostetter et al. (1986) considered the PRT to stretch from the time that the YIELD sign first could be recognized as such to the time that the driver either began a deceleration maneuver or speeded up to clear the intersection in advance of cross traffic. But decelerations often started 300 m or more from the intersection, a clear response to the sign and not to the traffic ahead. PRTs were thus in the range of 20 to over 30 sec. with much variability and reflect driving style rather than psychophysical performance.

3.14.3 Case III: Stop Control on Secondary Roadway

Hostetter et al. (1986) note that "for a large percentage of trials at intersections with reasonable sign distance triangles, drivers completed monitoring of the crossing roadway before coming to a stop." Their solution to this dilemma was to include three measures of PRT. They start at different points but terminate with the initiation of an accelerator input. One of the PRT's starts with the vehicle at rest. The second begins with the first head movement at the stop. The third begins with the last head movement in the opposite direction of the intended turn or toward the shorter sight distance leg (for a through maneuver). None of the three takes into account any processing the driver might be doing prior to the stop at the intersection.

Their findings were as follows (Table 3.13):

Table 3.13
PRTs at Intersections

	4-way		T-Intersection	
	Mean	**85th**	**Mean**	**85th**
PRT 1	2.2 sec	2.7	2.8	3.1
PRT 2	1.8	2.6	1.9	2.8
PRT 3	1.6	2.5	1.8	2.5

Thus a conservative estimate of PRT, i.e., time lag at an intersection before initiating a maneuver, would be somewhat in excess of three seconds for most drivers.

3.15 Other Driver Performance Characteristics

3.15.1 Speed Limit Changes

Gstalter and Hoyos (1988) point out the well-known phenomenon that drivers tend to adapt to sustained speed over a period of time, such that the perceived velocity (not looking at the speedometer) lessens. In one study cited by these authors, drivers drove 32 km at speeds of 112 km/h. Subjects were then instructed to drop to 64 km/h. The average speed error turned out to be more than 20 percent *higher* than the requested speed. A similar effect undoubtedly occurs when posted speed limits change along a corridor. In the studies cited, drivers were aware of the "speed creep" and attempted (they said) to accommodate for it. When drivers go from a lower speed to a higher one, they also adapt, such that the higher speed seems higher than in fact it is, hence errors of 10 to 20 percent *slower* than commanded speed occur. It takes several minutes to re-adapt. Hence speed adjustments on a corridor should not be modeled by a simple step function, but rather resemble an over damped first-order response with a time constant of two minutes or more.

3.15.2 Distractors On/Near Roadway

One of the problems that militates against smooth traffic flow on congested facilities is the "rubber neck" problem. Drivers passing by accident scenes, unusual businesses or activities on the road side, construction or maintenance work, or other occurrences irrelevant to the driving task tend to shift sufficient attention to degrade their driving performance. In *Positive Guidance* terms (Lunenfeld and Alexander 1990) such a situation on or near the roadway is a temporary violation of expectancy. How to model the driver response to such distractions? In the absence of specific driver performance data on distractors, the individual driver response could be estimated by injecting a sudden accelerator release with consequent deceleration from speed discussed in Section 3.11.2. This response begins as the distraction comes within a cone of 30 degrees centered around the straight-ahead direction on a tangent, and the outer delineation of the curve on a horizontal curve. A possible increase in the amplitude of lane excursions could also occur, similar to the task-loaded condition in the Dulas (1994) study discussed in Section 3.9.1.2.

3.15.3 Real-Time Driver Information Input

With the advent of Intelligent Transportation Systems (ITS), driver performance changes associated with increased information processing work load becomes a real possibility. ITS may place message screens, collision avoidance displays and much more in the vehicle of the future. Preliminary studies of the effects of using such technology in a traffic stream are just now appearing in the literature. There is clearly much more to come. For a review of some of the human factors implications of ITS, see Hancock and Pansuraman (1992) and any recent publications by Peter Hancock of The University of Minnesota.

Drivers as human beings have a very finite attentional resource capacity, as summarized in Dulas (1994). Resources can be allocated to additional information processing tasks only at the cost of decreasing the efficiency and accuracy of those tasks. When the competing tasks use the same sensory modality and similar resources in the brain, increases in errors becomes dramatic. To the extent that driving is primarily a psychomotor task at the skill-based level of behavior, it is relatively immune to higher-level information processing, if visual perception is not a dominant factor.

But as task complexity increases, say, under highly congested urban freeway conditions, any additional task becomes very disruptive of performance. This is especially true of older drivers. Even the use of cellular telephones in traffic has been found to be a potent disrupter of driving performance (McKnight and McKnight 1993). A study described by Dulas (1994) found that drivers using a touch screen CRT at speeds of 64 km tended to increase lane deviations such that the probability of lane excursion was 0.15. Early and very preliminary studies indicate that close attention to established human engineering principles for information display selection and design should result in real-time information systems that do not adversely affect driver performance.

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Back to the main publication page.

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