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"How Long Does It Take to Stop?" Methodological Analysis of Driver Perception-Brake Times

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Human perception-brake reaction time (RT) studies have reported a wide variety of results. By analyzing a large number of data sets, however, it is possible to estimate times under specific conditions. The most important variable is driver expectation, which affects RTs by a factor of 2. When fully aware of the time and location of the brake signal, drivers can detect a signal and move the foot from accelerator to brake pedal in about 0.70 to 0.75 sec. Response to unexpected, but common signals, such as a lead car's brake lights, is about 1.25 sec, whereas RTs for surprise events, such as an object suddenly moving into the driver's path, is roughly 1.5 sec. These times are modulated somewhat by other factors, including driver age and gender, cognitive load, and urgency.

Driver RT has important consequences for both the design of safe roads and for the assessment of liability in court. Although standards organizations have established norms, 2.5 sec in the United States and 2.0 sec in Europe, these values have sometimes been criticized (e.g., Hooper & McGee, 1983a, 1983b). Many researchers have therefore continued to seek a canonical brake RT value and to investigate the variables that affect it.

The literature have reported braking time estimates that differ by a factor of almost 4. Results vary greatly because investigators have used many different signals, responses, and testing conditions. Because it is impossible to derive a single, all-purpose number, the better strategy is to analyze the studies and to determine expected brake RT for specific situations.

There are several ways to tease out the important variables. One is to blindly code studies by type, to plug them into a mathematical formula and then to perform a factor analysis. This approach is liable to produce rather odd conclusions, such as the notion (Sohn & Stepleman, 1998) that the major RT variable is the country where the RT took place! Moreover, authors (e.g., Sens, Cheng, Weichel, & Guenther, 1989; Sohn & Stepleman, 1998) of previous surveys have tended to accept research results at face value, paying little attention to methodological flaws, limitations, and variations (although see Olson, 1989).

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OVERVIEW

My primary goal is to determine typical brake RT values for different driving conditions. The method is to review a large number of brake RT studies—far more than have been examined in any previous analysis—and to analyze and to critique the methods and variables used. In addition, I will connect the applied braking and basic RT literature. By understanding the factors underlying RT in general, it will be easier to reconcile differences across studies and to generalize results. Last, it is time for an updated review, because the last comprehensive overview is more than 10 years old.

In the ensuing discussion, I first provide a brief background on the basic concepts of RT analysis. In the subsequent section, I describe and critique the methodologies that have been used to measure driver braking times. Next, I examine effects of the principal variables—expectation, urgency, age and gender, and cognitive load—on brake times. I very briefly describe data on steering RTs and then make a few concluding remarks.

Before starting, a few disclaimers are in order. First, I only considered data for good conditions—daylight (with one exception), good weather, clear visibility, and so forth. In fact, data on brake RTs in less favorable conditions are rare. Second, I do not claim that the results included here constitute a complete summary of all brake RT studies. I excluded some commonly cited data due to large methodological flaws (e.g., Grime, 1952, which allowed anticipatory responses), and I was simply unable to obtain others (e.g., Allen Corporation, 1978.) My goal was merely to gather enough data to see the general trends. Third, in the analysis, I focus on expected values and pay cursory attention to population variability. Although important for practical purposes, analyzing variability would add complexity to the already difficult task of combining diverse data sets.

Last, in order to integrate data from such a large number of studies and variables, in the discussion, I gloss over some smaller methodological details. Table 1 summarizes the braking time results. In order to make general trends visible at a glance, I have sometimes collapsed data across less important variables. During the discussion, however, I drill down on these variables.

BACKGROUND

In order to interpret and generalize the brake RT studies following, it is important to understand the fundamental concepts from basic RT and information-processing research. In the following, I very briefly outline the basic theory necessary to analyze brake RTs. For fuller details, see Boff and Lincoln (1988).

Response Components

When a human responds to a sensory input, the total RT can be decomposed into a sequence of components:

1. *Mental processing time* is the time it takes for the responder to perceive that a signal has occurred and to decide on a response. For example, it is the time required to detect that a person is running across the roadway directly ahead and that the brakes should be applied. Mental processing time can be further decomposed into subcomponents:

TABLE 1
Brake Reaction Times

Study	Variables	PT	MT	TT	N	Distance to Collision	Speed	Paradigm	Signal	Response
Expected										
Norman (1952)					53	700	High	Road exp	"Brillant light"	Touch brake pedal
				0.73						
Olson and Sivak (1986)	Age Alertness	0.50 y[a] 0.50 o[a]	0.20 y[a] 0.22 o[a]	0.70 y[a]	49	46 m/3–4 sec	27 mph	Road exp	Yellow foam	PT: release accelerator MT = depress brake
Sivak, Post, Olson, and Donohue (1981a)	Light location Speed Distance			0.73	12			Road exp	Brake light	Push button
Dureman and Boden (1972)	Fatigue Shock			0.7	8			Simulator	Tone	Press pedal
Johansson and Rumar (1971)	Alertness			0.66[a]	321			Road exp	Sound-klaxon	Brake light
Korteling (1990)	Age Road difficulty			0.620 y 0.709 o	40	15 m	100/80 kph	Road exp	Brake light	"Brake pedal response"
Nagler and Nagler (1973)	Many				225			Simulator	Stop sign on panel	Move foot from accelerator to brake "depressed"
				0.63						
Lisper, Laurell, and Stening (1973)	Fatigue			0.65	10			Road exp	Tone	Vocal
Olson and Sivak (1986)	Age Alertness	0.40 y[a] 0.48 o[a]	0.19 y[a] 0.20 o[a]	0.59 y[a] 0.68 o[a]	49			Road exp	Red light	PT: release accelerator MT = depress brake
Lings (1991)	Practice Disability Age Gender	0.318[a]	0.27 o[a]	0.588[a]	109			Simulator	Red traffic signal	PT: release accelerator
Schweitzer, Apter, Ben-David, Lieberman, and Parush (1995)	Distance Speed Alertness			0.535[b]	45	6/12 m	60/80 kph	Road exp	Brake lights	Apply brakes
Greenshields (1936)	Age				1461			Simulator	Red on mock traffic signal	From accelerator to "pressure on brake"
				0.496						
Scott, Chandler, and Li (1996)	Seat position Driver height	0.247[b]	0.218[b]	0.465[b]	84			Simulator	Green light turns red	Release accelerator, depress brake
Wright and Shephard (1978)	Age Carbon monoxide Gender	0.25	0.17	0.42	348			Simulator	Light	PT: release accelerator MT = depress brake
Davies and Watts (1969)	Pedal height		0.149 0.309		10			Simulator	Light	From accelerator to "pressure on brake"

(Continued)

TABLE 1
(Continued)

Study	*Variables*	*PT*	*MT*	*TT*	*N*	*Distance to Collision*	*Speed*	*Paradigm*	*Signal*	*Response*
Unexpected										
Triggs (1987)	Day							Naturalistic	Railroad signal–day	Brake light
				1.77						
Sivak et al. (1981a)	Brake light location			1.38	277			Naturalistic	Brake light	Brake light
van Winsum and Brouwer (1997)				1.35	1			Simulator	Brake lights	Press brake pedal
Chang, Messer, and Santiago (1985)	Speed Distance			1.3[b]	1614		25–55 mph	Naturalistic	Yellow light	Brake light
Mortimer (1969)				1.3	80				Brake light	Press brake pedal
Sivak, Olson, and Farmer (1982)	Speed Distance			1.21	1644	1 2/3–5 lengths	32–40 56–72 kph	Naturalistic	Brake light	Radar response
Triggs (1987)	Night Time			1.16[b]				Naturalistic	Railroad signal–night	Brake light
Gazis, Herman, and Maradudin (1960)				1.14				Naturalistic	Yellow traffic signal	Brake light
Alm and Nilsson (1994)	Cell phone Road difficulty			1.13	40		100 kph	Simulator	Red square	Depress brake 10 mm
Triggs (1987)				0.92				Naturalistic	Brake light	Brake light
Nilsson and Alm (1991)	Age Cell phone use			0.92 y 1.32 o	40		105 kph	Simulator	Red square	Depress brake 10 mm
Johansson and Rumar (1971)	Alertness			0.9[a]	5			Road exp	Sound-buzz	Apply brake
Schweitzer et al. (1995)	Distance Speed Alertness			0.606[b]	45	6/12 m	60/80 kph	Road exp	Brake lights	Apply brakes

Lieberman et al. (1995)	Distance Speed	0.399	0.24	0.638[b]	45	6/12 m	60/80 kph	Road exp	Brake lights	Apply brakes
Schweitzer et al. (1995)	Distance Speed Alertness			0.606[b]	45	6/12 m	60/80 kph	Road exp	Brake lights	Apply brakes
Unexpected										
Summala and Koivisto (1990)	Time-collision Age			1.75 y 1.95 o		0–6 sec		Naturalistic	Policeman stop	Deceleration (radar)
McGehee, Mazzae, and Bladwin (2000)	Track versus simulator	1.28-t		(1.58-t)[d]	192-t		45 mph[d]	Simulator and	"Intersection incursion"[e]	Release brake
		0.96-s		(1.26-s)[c]	120-s		45-55 mph[e]	Road exp	Blow up foam vehicle[d]	
Hankey (1996)	Time-collision Gender	1.23	0.324	1.55[b]	48	2.85–4.35 sec	55 mph	Road exp	Car	PT: release accelerator MT = depress brake
Lerner (1994)	Age			1.5	116	200 ft	40 mph	Road exp	Trash barrel	Touch brake
Broen and Chang (1996)	Pedal configuration Age Gender	1.16	0.17	1.33	100		25 mph	Simulator	"Obstacle"	No specified
Arbuthnott (1980)	Field dependence Sound	0.904[b]	0.313[b]	1.27[b]	100			Simulator	Car pulling out	PT: release accelerator MT = depress brake
Olson and Sivak (1986)	Age Alertness	0.70 y[a] 0.75 o[a]	0.40 y[a] 0.35 o[a]	1.1 y[a] 1.1 o[a]	49	46 m/3–4 sec	27 mph	Road exp	Yellow foam	PT: release accelerator MT = depress brake
Barrett and Thornton (1968)				1.05	19	76.5 ft	25 mph	Simulator	Dummie from shed	"Began to depress pedal"
Barrett, Kobayashi, and Fox (1968)	Field dependence			1.02	10	82.5 ft	25 mph	Simulator	Dummie from shed	"Began to depress brake"
Triggs (1987)				0.97				Naturalistic	Tire road shoulder	Brake light

Note. PT = Perception time; MT = Motor time; TT = Total time; Exp = Experiment; Y = Young; O = Old.
[a]Value is a median. [b]Data collapsed over several variables. [c]Estimated. [d]Track. [e]Simulator.

a. *Sensation* is the time it takes to detect an object in the roadway. ("There is a shape in the road.") All things being equal, RT decreases with greater signal intensity (brightness, contrast, size, loudness, etc.), foveal viewing, and better visibility conditions. Best RTs are also faster for auditory signals than for visual ones.

b. *Perception* is the time needed to recognize the meaning of the sensation. ("The shape is a person.") Time increases with low signal probability, uncertainty (signal location, time or form), and surprise. "Choice" RT, when there are multiple possible signals and responses, is generally much slower than simple RTs, which occurs when there is only one possible signal or response pair, or both.

c. *Response selection and programming* is the time necessary to decide which, if any, response to make and to mentally program the movement. ("I should steer left instead of braking.") Response selection slows under choice RT when there are multiple possible responses. Conversely, practice decreases the required time. Strictly speaking, mental processing time should not be called *perception time* because it reflects mental response preparation as well as perception.

2. *Movement time* is the time it takes the responder's muscles to perform the programmed movement. For example, it is the time required to lift the foot from the accelerator and then to touch the brake pedal. In general, the more complex the movement, the longer the movement time. Increased arousal level and practice decreased movement time.

3. *Device response time* is the time it takes the physical device to perform its response. For example, it may be measured as the time it takes to bring a car to a halt after brake engagement.

In the truest sense of the term, *RT* should refer only to the first component—the mental processing time. However, this quantity is internal and cannot be directly and objectively measured without a physical response. Most basic RT studies use finger responses, such as the release of a spring-loaded telegraph key, which minimize the movement and device response components. However, movement times cannot be completely eliminated and always affect reaction time measurement.

Unfortunately, terms are used inconsistently in the literature. *RT*, for example, has been used to mean mental processing time alone and has sometimes combined with movement time. A few authors even included the device response time.

To avoid confusion, I follow the technically incorrect convention of referring to mental processing time as *perception time*. The combined perception and movement time will be called *brake reaction time*. *Stopping time* is brake RT plus device response time.

Human Information Processing and Speed of Response

Humans operate under two information-processing modes. The first, often called *automatic response* (Schneider & Schiffrin, 1977), occurs under two conditions. One is when there is a strong, innate stimulus–response compatibility. For example, humans will tend to move in the direction opposite that of an object on a collision trajectory. The second situation occurs when making highly practiced responses to common signals. Automatic mode is fast because there is no requirement for conscious decision making. The response seems almost a reflex, as if signal processing goes straight from sensation to movement without the need for perception or for response selection and programming. The visual search and attention literature (e.g., Green, 1991, 1992; Green & Senders, 1998) sometimes calls this *preattentive mode* because it doesn't appear to require focal attention and seems often to have no capacity limitation.

Hitting the brake pedal in response to the flashed brake lights of the car ahead is an example of learned, automatic response. This seemingly occurs automatically and without volition. Drivers often have the feeling that they responded before they became consciously aware of the brake light, especially if their attention was directed elsewhere when it flashed.

The second mode of processing mode is termed *attentive* or *controlled* and requires thought. It generally occurs when there are novel events that require extra processing time both in perception (more sensory input and more memory retrieval to interpret) and decision (more time required to assess significance and to decide what, if any, response is warranted.) Attentive processing occurs, for example, when a driver sees an unexpected shape in the road, especially at night and other situations where visibility is poor.

In sum, understanding the driver's dominant information processing mode is important for predicting and analyzing RTs. Attention is a graded function, so the two modes represent a graded continuum rather than a dichotomy (e.g., Schneider and Detweiler, 1988). Drivers operating in the more automatic mode will response faster, whereas drivers forced to move toward the controlled end of the continuum will respond more slowly and likely with greater error (Kay, 1971).

BRAKE RT STUDIES

Table 1 shows total brake RT from a wide range of studies. Where available, I provide separate columns for perception and movement times. In several cases, studies failed to report means or medians, so I read data off of graphs. (Several authors showed only analysis of variance, correlations, and so forth, but not actual data. For example, van Winsum and Brouwer, 1997, only showed actual data for a single driver.) Means for young (y) and old (o) drivers are noted separately.

Each line also shows other significant properties: method, number of subjects, signal, response, distance from hazard at trial onset, and traveling speed. Blank cells indicate that the variable did not apply to the study or that it was not stated.

Before discussing research results in detail, however, I outline common methodological techniques. It is important to keep methodology in mind in order to assess ecological validity to uncover factors that might bias results up or down and to aid in reconciling different brake RT results.

Methodology

Paradigms

Studies have employed one of three basic paradigms: simulator studies, controlled road studies, or naturalistic observation.

Simulator studies. Off-road (in the lab or at a public gathering such as a fair) studies were performed in a car mock-up or in the cabin of a real vehicle. In older studies, "drivers" typically braked in response to an actual traffic light placed in front of the simulator, although a few studies used film loops for more authenticity. Modern studies used computer graphics to produce more realistic visual scenes.

Controlled road studies. The participant drove public or private roads or a track while a researcher sat in the passenger seat. The participant usually knew that she or he was being tested, but the investigator may or may not have revealed the real purpose of the study. Investigators often measured RT to "unexpected" events.

Naturalistic observation. The researchers set up recording equipment and measured the response of drivers who were unaware of being monitored. The typical study recorded the interval between a yellow traffic signal, brake lights of a leading car (possibly driven by a researcher), and so forth, and onset of the naive driver's brake lights.

Paradigm Comparison and Evaluation

Each paradigm has significant limitations in *ecological validity*, the degree to which results generalize to normal driving conditions. For example, there are obviously large differences between simulators and the roadway. Compared to the roadway, simulators present simplified visuals, loss of small texture cues, smaller field of view, no depth from stereopsis, and so forth. There are usually no nonvisual cues, which may play an important role in motion perception (e.g., Ohita & Komatsu, 1991). Moreover, there are fewer distractions, cognitive load is small, and the driver likely makes fewer eye movements to investigate objects in the peripheral field. There is no rear-view mirror to check. McGehee, Mazzae, and Bladwin (2000) attempted a direct comparison and concluded that simulators produce brake RTs that are 0.3 sec faster. However, they found steering times similar.

In controlled road studies, drivers are also more alert than they would be during normal driving. Moreover, some road experiments, as well as naturalistic observation studies, also suffer from the problem that not all drivers perform the expected response. Studies often found that some drivers avoided the obstacle by steering rather than by braking or performed both responses. The obtained braking RT estimate is then a biased sample. It might be hypothesized, for example, that people who are the slowest brakers have learned to avoid the obstacle by steering when possible. If so, then their times were unmeasured, and the results underestimate brake RT for the general population. On the other hand, the data might overestimate brake RT because the drivers were considering alternative responses, and choice RT is slower than simple RT. There is no evidence whether either of these hypotheses is true, but they demonstrate the potential bias sources introduced by allowing participants to make alternate responses.

In addition, most simulator and controlled road studies created large practice effects. With a few exceptions, the researchers collected data for many trials on each driver. Participants became highly practiced, which would reduce times compared to those likely in actual driving conditions. Lings (1991), for example, found that the first brake response in a series was always slower.

Naturalistic observation has the merit of high ecological validity. Normal driving is largely an automatic information-processing task, but simulator and controlled road studies put drivers on alert and probably switch them to a more conscious and controlled mode. It has been hypothesized (Kay, 1971) that accidents most commonly occur when a person is forced to suddenly switch from automatic to controlled processing. Only naturalistic observation can capture this switch. In addition, naturalistic studies generally measured times for a very large number of drivers.

However, the naturalistic method is limited because the researchers cannot easily test effects of independent variables, place drivers in emergency or even urgent situations, or measure perception and movement times separately. Last, they are unable to record data about driver demographics, so sample bias is always possible.

A quick glance at Table 1 reveals some paradigm trends in overall speed estimates. The table organizes studies first by driver expectation (which is the most important variable—see the following) and then by mean brake RT. Although not an overwhelming trend, simulator times are generally faster than those found on the road, at least in expected and unexpected conditions. Although there are few relevant studies, the data show no clear difference between road and naturalistic studies for the unexpected condition, the only category they share. (As discussed following, I discount the anomalous Schweitzer, Apter, Ben-David, Liebermann, & Parush, 1995, and Liebermann, Ben-David, Schweitzer, Apter, & Parush, 1995, studies.)

Signals and Responses

Braking signals. Studies have used a wide range of signals to induce braking. The most common are brake lights of a leading car and traffic signals (either in the simulator or on the road). Other studies have used unexpected incursions by another vehicle, an object such as a trash can, or even a dummy pedestrian. A few studies used auditory signals, and one simulator study used an arbitrary computer graphic—a red square. Finally, there are several studies that used the slowing of a lead car with an inoperative brake light. The test driver responded to change in velocity, which is much more difficult to detect than the onset of a light or the sudden appearance of an object. I have excluded these studies from the table because they produce a much higher range of RTs than those found using other signals. However, I will mention some of the results where relevant.

There are several sources of potential variability inherent in the sensory detection of this wide variety of signals. First, RT will be faster when the signal is foveally viewed than when it is seen in the visual periphery. Response times to incursions from the side of the road should be slower than from objects viewed immediately ahead. Some incorrectly believe that motion is more salient in the visual periphery so that objects approaching from the side will more readily grab attention. In fact, research (e.g., Green, 1983) demonstrates that viewers are much poorer at detecting motion in the periphery. Brake and traffic lights have their slow rise time, effects which, in part, cancel out the slower detection of peripheral objects.

Last, auditory signals generally produce faster RTs. Humans, like other animals, probably have an innate tendency to interpret sounds as warnings. Moreover, auditory transduction is mechanical, whereas visual transduction requires a relatively slow, biochemical process.

Response. Some studies recorded only a single total braking RT, some measured perception and movement time separately, and some examined only movement time. In almost all cases, perception time was measured from the onset of the signal to the release of the accelerator and movement time was the period from release of the accelerator until brake application.

Researchers measured response times either by directly recording brake depression with a microswitch attached to the pedal or by observing onset of the driver's brake lights. However, standard brake lights have a slow rise time and do not become visible until 0.05 to 0.1 sec or more after activation. RT estimates obtained by viewing brake light onset should therefore be slightly slower than times obtained from pedal microswitches. In fact, the finding (Sivak, Flannagan, Sato, Traube, & Aoki, 1994) that special fast-rise brake lights could decrease reaction times by over 0.15 sec suggests a significant difference between the two measurement methods. Last, braking responses have also been measured by means of radar, which detects deceleration. These RTs should also be faster than times measured from brake lights.

However, use of microswitches also has problems because it takes appreciable time to fully depress a brake pedal. Studies using a microswitch, unfortunately, are often vague as to what was actually recorded. Many authors simply have said that they stopped the reaction timer when there was pressure on the brake (Davies & Watts, 1969) or there was brake pedal response, (Korteling, 1990), and so forth. This is probably one reason that brake RT data are so variable—the more depression required to close the microswitch, the longer the resulting RT. Different studies may have used different pedal depression criteria.

A few studies measured the complete braking response, from initial pedal activation to complete depression. Because estimates (Barrett, Kobayashi, & Fox, 1968; Hankey, 1996; van Winsum & Brouwer, 1997; McGehee et al., 2000), range upward from 0.5 sec, it is important for studies to be precise in explaining exactly how much pedal depression constituted a response. Moreover, Barrett et al. found a relation between speed of initial and full brake pedal depression. The fastest responders (about 0.8 sec) slammed on the brakes, going from initial to full depression in approximately 0.5 sec. Slower responders, however, took much longer to fully depress the pedal. Those with perception times of 1 sec, for example, took 0.8 to 1.0 sec for full depression, and the slowest responders never reached full depression at all.

This result is important for estimating stopping distances. At 55 mph, a driver is traveling 81 ft/sec, so the difference in stopping distance for a 0.2 sec delay would be calculated as 16 ft. Because slower initial brake RTs mean slower pedal depression, the deceleration is slower, and stopping time and distance are greater. Most studies only measure initial brake response. Therefore, taking their brake RTs at face value may underestimate stopping distances and times for the slower responders.

Data Analysis

Most brake RT studies report means, which produce high expected RTs. When values of a random variable approximate a normal distribution, then mean, median, and mode produce similar estimates of expected value. However, RT data are almost always skewed toward longer values (Figure 1). A relatively very few long RTs in the distribution tail usually inflate mean values. For example, Chang, Messer, and Santiago (1985), one of the few studies that reported both, found that medians were 0.2 sec lower than means.

Similarly, standard deviations will be misleading because they combine the smaller variance of the fast responders with the larger variance of the slowpokes. (See Summala & Koivisto, 1990, for a graphic depiction of the slow brakers' greater variance.) As a result, there will be more slow responders than the data variance suggest.

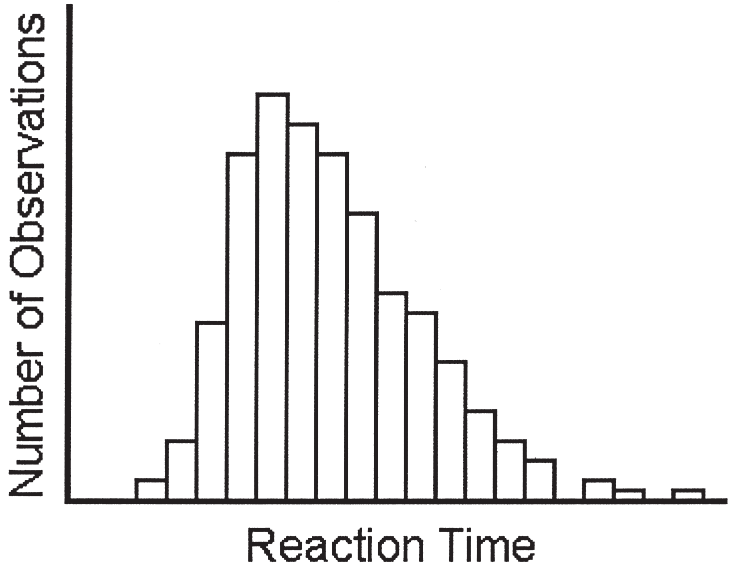

FIGURE 1 Hypothetical reaction time distribution.

Some investigators (e.g., Schweitzer et al., 1995) seemed aware of these problems and cut off the RT distribution's tail at longish RTs. The mean and median then moved closer together, but the question remains whether arbitrarily dropping the long values biases the outcome and misrepresents the population. It may be supposed that these very long times represent driver errors or gross lack of attention, but there is no way to ensure that tail cutting does not compromise ecological validity.

Results

In the following, I discuss brake reaction as a function of several driving-related variables. In the first section I focus on expectancy, because it is the most important determinant. I then examine demographics (age and gender), urgency (time to collision) and cognitive load (distraction). In the final section I compare responses for braking and for steering.

Expectancy

Brake RT studies can be divided into those that investigate RT with the driver alerted and expecting a signal to brake and those that use unexpected signals. The first group is interested determining the upper bound for behavior under ideal circumstances, whereas the second aims to measure RTs under more natural conditions.

However, the terms *expected* and *unexpected* are used inconsistently across studies. For example, most authors term a condition as *expected* when the driver is explicitly told that a brake response must be made. Johansson and Rumar (1971), however, had a condition in which the driver is told to respond to a buzzer, yet the authors called this *unexpected*. Moreover, a simple dichotomy does not fully capture the full gamut of driver readiness gradations. Some signals are truly unexpected, whereas others are fairly common and only have some temporal uncertainty. For didactic purposes, I crudely decompose expectation level into three categories: expected, unexpected, and surprise.

Expected. RT studies must always employ a degree of signal uncertainty in order to prevent anticipatory responses. However, RT increases with uncertainty of signal onset (Boff & Lincoln, 1988). In some cases, investigators have minimized uncertainty in order to determine best possible braking performance or to conveniently study the effects of some variable (drugs, brake pedal separation, etc.). Participants knew that they were to make the brake response, and temporal uncertainty was usually no more than fractions of a second or a few seconds at most. Moreover, there was little spatial uncertainty, because the signal was fixed in position. This is an important type of study, because it constrains the universe of possible brake RTs by determining the boundary condition.

Norman (1952) performed perhaps the clearest road study of braking under low uncertainty. Drivers traveled an aircraft taxiway at "high speeds" and braked on seeing an expected "brilliant light" 700 ft ahead. The mean brake RT was 0.73 sec and the 95th percentile was at 0.89 sec. Norman's values are consistent with data from the expected conditions of several other road studies (Olson & Sivak, 1986, for obstacle; Sivak, Post, Olson, & Donohue, 1981b), although their variability was much higher. Olson and Sivak (1986) also found a slightly lower RT for a light signal attached to the hood of the car. The value is likely lower because of lessened spatial uncertainty, and because the table value is for the median rather than the mean. Finally, Summala, Lamble, and Laakso (1998) reported RTs of roughly 0.5 sec to brake lights of a leading car. However, drivers started with the foot already on the brake, which would likely subtract 0.2+ sec movement time from the normally measured total brake RT.

Although Norman's (1952) conditions might seem designed to produce the fastest RTs possible on the roadway, Table 1 shows that several studies report even faster total brake RTs. The oft-cited Johansson and Rumar (1971) study found median RTs of 0.66 sec under expected conditions. The lower estimate is not surprising for several reasons. First, Norman used only one run per driver, so there was no practice effect. As another study has shown (Lings, 1991), brake RTs decreased markedly from the first to subsequent trials even under conditions of minimal uncertainty.

Johansson and Rumar (1971) also used an auditory signal (a Klaxon™), which produces faster optimal RTs than those obtained with a visual signal. The use of an auditory signal likely also explains the slightly lower RTs reported by two other studies, Dureman and Boden (1972) and Lisper, Laurell, and Stening (1973), which also had large practice effects. Last, Johansson and Rumar also reported medians rather than means. Korteling (1990) found his younger participants responding in 0.620 sec, whereas older drivers required a mean of 0.709 sec. (I averaged his low and high cognitive load conditions.) However, he discarded RTs greater than 2.0 sec. All things considered, there are many studies that agree that a mean brake RT of about 0.70 to 0.75 sec is the best that can be expected on the road.

Companion papers by Schweitzer et al. (1995) and Liebermann et al. (1995), however, reported anomalously fast RTs compared to those of other studies using similar methodology. There are several possible reasons for their fast estimates. First, they also truncated the data, throwing away RTs greater than 1.7 sec. Second, their participants were in an unusually heightened state of arousal. The lead car performed a series of "alternative misleading emergency maneuvers." Surely, the participants must have been highly alert and primed for fast response.

Third, there were likely large practice effects. The investigators collected times in three successive conditions: (a) naive, drivers told nothing; (b) drivers told to expect to brake; and (c) drivers told to brake in response to brake light. There were 48 trials in all, but it is unclear how many were in the naive condition. In any event, there were surely practice effects. By the time the expected condition occurred, the viewers were highly experienced in the task.

Last, simulators studies (Greenshields, 1936; Lings, 1991; Scott, Chandler, & Li, 1996; Wright & Shephard, 1978) in primitive mock-ups—drivers viewed a simple traffic light or panel rather than film or computer graphic—found the fastest brake RTs ranging from 0.4 to 0.5 sec. In all of these studies, the driver responded to a light onset at a predetermined location, therefore, spatial and temporal uncertainty as well as cognitive load were very low. The relevance of these brake RTs to actual driving conditions is questionable. Both simulator and road studies (Olson & Sivak, 1986) that measured a separate movement time found that drivers required slightly over 0.2 sec to take the foot off of the accelerator and move it to the brake pedal.

In sum, the Norman (1952) estimate is probably the most ecologically valid result for the braking time under favorable conditions—low uncertainty, intense visual, foveally viewed signal, but no recent practice. The best expected brake RT is about 0.7 to 0.75 sec, which consists of about 0.5 to 0.55 perception time and 0.2 sec movement time. Authors of a previous review (DeSilva & Forbes, 1937) reached a similar conclusion.

Unexpected. A very common method tested driver RT to onset of brake lights or of a traffic light in the naturalistic observation paradigm. Authors always described these conditions as reaction times to an unexpected event because the driver is not explicitly told that the need to brake is imminent. However, the term *unexpected* is inappropriate. One of the problems with such studies is that they view drivers as a tabula rasa, as if they knew nothing and started with no expectations. In fact, drivers have many expectations based on their years of driving. They expected something unusual to happen because there is a stranger sitting in the passenger seat. They expect cars to sometimes brake ahead of them requiring an immediate brake response. They expect traffic lights to change periodically, and so forth. Such events are never totally unexpected. At most, they are temporally uncertain.

Studies of expected reaction times produced results varying over a 2:1 range. One set of studies (Chang et al., 1985; Mortimer, 1969; Sivak et al., 1981b; van Winsum & Brouwer, 1997) agree with an expected brake RT in the range of 1.3 to 1.4 sec (The Chang et al. estimate is actually the slowest because it is a median.) Another set (Gazis, Herman, & Maradudin, 1960; Sivak, Olson, & Farmer, 1982; Triggs, 1987, for railroad signal night) bunch closely at 1.14 to 1.21 sec. Alm and Nilsson (1994) also found a mean reaction time of about 1.13 (the mean of their easy and hard conditions.)

There is a third cluster of results (Alm & Nilsson, 1994, easy condition; Johansson & Rumar, 1971; Triggs, 1987, for brake lights) at 0.9 sec. The Johansson and Rumar result is undoubtedly low because the reported value is a median, the signal was auditory (a buzzer), and the drivers were explicitly instructed to brake when the buzzer sounded—it was not exactly an unexpected condition. It is unclear why Triggs's mean times for response to lead car brake lights should be so much faster than those found by Sivak et al. (1981a), van Winsum and Brouwer (1997), and Sivak et al. (1982).

Finally, there are a few anomalous findings. The Schweitzer et al. (1995) and Liebermann et al. (1995) studies again have the fastest estimates, ranging from 0.605 to 0.678. I have already suggested possible reasons for their anomalously fast times. The authors clamed that they were recording RTs to unexpected events, brake lights in a lead car. However, recall that the lead car performed a series of "alternative misleading emergency maneuvers." The need for braking could hardly be called *unexpected*. Moreover, long reaction times were discarded from the data.

There is also an anomalously slow estimate by Triggs (1987) for drivers responding to a railroad crossing during the day. Interestingly, he found that brake RT to railroad signals was much faster at night, when times agree with other studies, than during the day. Triggs attributed the difference to low signal discriminability, but the validity of this explanation is unproven.

In sum, the data vary, but the best guess is that brake RT to common, but uncertain signals lies between 1.2 and 1.35 sec. Standard deviations of results vary widely across studies, but 0.6 seems a good estimate. Therefore, the American Association of State Highway and Transportation Officials norm of a 2.5 sec brake reaction is a reasonable guess for time achievable from 90% to 95% of the general population. However, this estimate is only valid for a specific set of conditions: brake response to "normal" road events in good weather with high visibility.

Surprise intrusion. A few studies tested RT for truly unexpected, low probability signals. Most of these studies fit into the category of the *intrusion* (or *incursion*) paradigm, in which an object suddenly moves into the driver's path from off the road. (Of course, each participant provides only one trial in order to maintain the surprise.) Although such events do happen in normal driving, they have very low probability and drivers have not had sufficient experience to develop automatic response.

Surprise incursions produce slow brake RTs. Hankey (1996) performed the best study, in which the driver traveled a country road at 55 mph when another vehicle suddenly cut across an intersection immediately ahead. He found that brake RTs ranged from 1.55 to 1.80 sec depending on time-to-collision. RT for steering was about 0.3 sec faster, roughly the extra time it takes to move the foot from accelerator to brake pedal. Summala and Koivisto (1990) measured brake RTs for the surprise intrusion of a policeman holding up his hand to stop traffic. They also found the brake RTs depended on time-to-collision, and the estimate (reading from their graph) of 1.7 sec at a 3-sec time-to-collision agrees well with Hankey's 1.8 sec under a similar time constraint. However, the studies differed greatly in the effects on urgency at other times-to-collision, perhaps because of different bases for their contact time estimates (see later). Lerner (1994) reported a similar mean time of 1.5 sec for a road study where a trash barrel on a chain rolled out into the road. Finally, McGehee et al. (2000) reported a perception time of 1.28 sec for drivers on a track. Adding the 0.3-sec movement time brings the total to an estimated 1.58 sec. Times for a simulator study 0.3 sec faster. Regardless of the differences, these surprise intrusion studies report the longest brake RT in the literature.

There were slightly lower values reported by several simulator studies: Arbuthnott (1980) (1.27 sec, no noise condition) and Broen and Chiang (l996, 1.33 sec.) Barrett (Barrett et al., 1968; Barrett & Thornton, 1968) published two simulator studies with slower brake RT of 1.05 and 1.02 sec. (These data may have been from the same experiment). I have already suggested reasons that simulator studies should produce faster times—lower cognitive load and lower uncertainty. However, there is no obvious reason for Barrett's relatively fast times.

Olson and Sivak (1986), one of the most frequently cited brake RT studies, fits best in this class. Drivers traveled over a rise, found an object (yellow foam) in the road and braked. Although there was no intrusion from the side of the road, discovery of an obstacle in the roadway was presumably a genuinely unexpected event.

Olson and Sivak (1986) found that the RT for this unexpected condition was 1.1 sec, about a half second faster than time reported by Lerner (1994) and Hankey (1996) and Summala and Koivisto (1990). There are several likely explanations for the difference. First, the 1.1 sec estimate is a median, which should be lower than the mean. Another reason for the faster brake RT was the location of the obstacle in the middle of the road. Its appearance in the central visual field would cause fast detection. Intrusions from the side, on the other hand, would be detected by the less-sensitive visual periphery.

Moreover, the Olson and Sivak (1986) unexpected condition was hardly that. There was no direct measurement of the drivers' perception time. Instead, the authors determined perception RT by having the participants redrive the route and call out when they saw the foam. By then, of course, drivers knew that there was an obstacle in the road ahead, so this was an expected not an unexpected condition.

The only other anomalously low estimate is 0.97 sec by Triggs (1987). However, this was a minor intrusion, someone changing a tire by the side of the road. The lane was not blocked as in the other intrusion studies, and urgency was low.

In sum, the data clearly show that the surprised driver takes longer to brake. Overall, it takes the average driver roughly twice as long, 1.5 sec or more, to respond to an intrusion compared to a completely expected event, which requires only about 0.75 sec.

Intrusion probably slows reaction at all three mental-processing stages of human RT. Detection is slower due to the need to use the peripheral retina; perception is slower because the event is unusual and requires time to interpret; and response selection is slower because the driver must weight braking versus steering.

Moreover, data show that movement time is also slower when the driver is surprised. Most studies also found movement times over 0.3 sec, a 50% increment over those obtained under expected conditions. The difference might reflect the slower brake RTs that occur when participants have no chance to practice (Lings, 1991) or possibly uncertainty over response selection. In any event, for real world estimates, 0.3 sec is probably more accurate than the 0.2 sec times sometimes suggested by authoritative sources (e.g., Shinar, 1977).

Age

Basic RT studies generally find a slowing with increased age (e.g., Welford & Birren, 1965.) Surprisingly, brake RT studies have produced mixed results. Older drivers responded more slowly in some cases (Broen & Chiang, 1996; Greenshields, 1936; Lings, 1991; Nilsson & Alm, 1991; Sivak et al., 1981b, for pushing a button; Summala & Koivisto, 1990). However, other studies (Korteling, 1990; Lerner, 1994; Olson & Sivak, 1986; Wright & Shephard, 1978; see also Kloeppel, Peters, James, Fox, & Alicandri, 1994) found no slowing with age.

There are several possible explanations for the absence of a robust age effect. One is sample bias. Older people who are in better health are more likely to drive and therefore to be participants in driving studies. Another explanation is experience. Olson and Sivak (1986) suggested that older drivers are more practiced, which compensates for any slowing of perception or movement. Arbuthnott (1980) supported this conclusion by finding that older drivers more quickly recognized dangerous situations. Last, the definition of *older driver* varies with each study. A common definition is 56 years of age in driving studies, but most basic research uses an much higher definition of older, usually at least 60 or 65.

However, part of the answer may also lie in methodology. Researchers using simulators tend to find age effects, whereas road studies do not (with the exception of Summala & Koivisto, 1990). Even when found, the effect is only 100 ms at most. Age effects are likely small relative to other factors and are easily lost in the noise. Moreover, aging affects people very differently, making older drivers an inherently heterogenous population and their data accordingly noisier. The effect may only reveal itself in the more carefully controlled simulator studies that generally employ more participants and record more trials per participant.

Another difficulty is that the effects of aging on brake RT may depend on other, often uncontrolled, variables. One factor that may encourage an age effect is cognitive load. Alm and Nilsson (1995) found that cellular phone use caused a greater slowing of RT in older drivers than in younger drivers (see also, McKnight & McKnight, 1993; Wolffsohn, McBrien, Edgar, & Stout, 1998.) However, an earlier study (Nilsson & Alm, 1991) reported that a cell phone task had similar effect on all age groups.

Korteling's (1990) road study captures the difficulties in demonstrating an effect of age on brake RT. He concluded that there was no age effect, although older drivers had a mean brake RT 0.05 sec slower than that of young participants. Moreover, driving conditions that increased cognitive load doubled the young–old difference to 0.1 sec, yet the difference again failed to reach statistical significance.

In conclusion, although the data from driving studies are mixed, it is difficult to ignore the significant slowing demonstrated in many basic research studies. Moreover, there are enough positive driving results (e.g., Summala & Koivisto, 1990, reported a 0.3 sec slowing) to suspect that an aging effect exists in brake RT. The magnitude of the effect likely grows with increased information-processing demands and task complexity, but exact magnitude is uncertain. Alm and Nilsson (1995), for example, found a 1.5 sec difference between young and old drivers with cognitive loading, but this study used a very difficult signal to detect. Moreover, all of the studies described here used high visibility conditions. Normal aging produces major vision losses, so brake response would likely slow significantly at night and in poor weather. However, even if braking slows with age, it may not constitute a major problem. Older drivers apparently compensate for their poorer braking, at least in part, by driving more slowly (e.g., Summala & Koivisto, 1990).

Gender

The research data are mixed. Some studies found faster response by men (Lings, 1991; Sivak et al., 1981b, for pushing a button; Wright & Shephard, 1978; see also American Automobile Association, 1952), although others found no difference (Hankey, 1996; Nagler & Nagler, 1973). None have found that women are faster.

Urgency

Many investigators hypothesized that drivers would respond faster under greater *urgency*, by which they invariably meant shorter time-to-collision. A priori, one might guess that greater urgency produces faster RT because of the greater arousal—the Yerkes-Dodson law (Yerkes & Dodson, 1908). Results, however, suggest that brake RT is a Ushaped function, decreasing with greater urgency but then paradoxically becoming very long when time-to-collision is short.

Studies have manipulated time-to-collision by varying speed, distance, or both. Chang et al. (1985) found that reaction time to a yellow light decreased a half second as speed increased from 25 mph to 40 mph, whereas further increases in speed up to 55 mph produced no additional effect. Liebermann et al. (1995) and Schweitzer et al. (1995) tested effects of both speed and following distance on brake RT. They found no speed effect, but the negative result may have been due to the comparison of very similar speeds, 60 kph and 80 kph. On the other hand, shorter following distances (6 m vs. 12 m) produced faster response in both studies. Sivak, Post, Olson, and Donohue (1981a) measured push-button responses rather than actual braking and also found that drivers responded faster to a combination of higher speed and shorter following distance. However, the following distance effects may not be one of urgency but rather of probability. Drivers know from experience that when they are trailing the next car by a substantial distance there will be little need to brake in order to avoid collision. As the distance diminishes, the need for braking increases so that it becomes a more probable response.

Summala and Koivisto (1990) measured RT as a function "subjective urgency" (p. 681), time-to-collision based on a formula that combined preferred speed, stopping distance, and deceleration. They concluded that RT decreased by almost 1 sec as time-to-collision decreased from 6 sec and approached 0.

In contrast, Hankey (1996) found that brake RT increased 0.4 sec as time-to-collision grew shorter, from 4.35 to 2.85 sec. As time-to-collision decreases, probability of steering increases relative to braking (Malaterre, Fernandez, Fleury, & Lechner, 1988). A very short time-to-collision likely forced the driver to decide whether there was sufficient time to brake or whether steering was the only possible action. This introduced mental-processing time for response selection. Moreover, the driver had to weigh the risk of steering into the oncoming lane, possibly check traffic there first, and then to fight the highly learned tendency to avoid traveling in the "wrong" lane. Often, drivers both braked and steered, which might take more mental response programming and slow both.

Although both Summala and Koivisto (1990) and Hankey (1996) used a surprise intrusion paradigm, the opposing conclusions are likely due to methodological differences. First, the authors figured time-to-collision differently. The Summala and Koivisto estimate included the time required for the car to brake to a halt, whereas Hankey estimated the contact time for a driver maintaining full speed of 55 mph. It is also worth noting that Summala and Koivisto showed a data point at a negative time-to-collision, so the validity of the formula must be questioned. Another possibility is that Hankey's participants were driving much faster. Summala and Koivisto did not state the speed of their drivers, but it seems reasonable to guess that the test took place in the city, where speeds would be much lower than the 55 mph used by Hankey's drivers on an empty rural road. Moreover, although Hankey's drivers had a response alternative, it seems unlikely that any of Summala and Koivisto's drivers would have considered simply steering around the policeman rather than obeying the "stop" command. Hence, there was no response competition. Last, drivers seeing a car cut them off at an intersection often expect it to stop (van Elslande & Faucher-Alberton, 1997), creating a slight hesitation and a longer RT.

Overall, the evidence suggests that drivers will respond faster under shorter time-to-collision, at least until time becomes very brief and there is the opportunity for alternative responses. When confronted with severe emergency, drivers probably slow response to increase time required for assessing the situation and to check feasibility of other escape actions.

Cognitive Load

Several investigators predicted that high cognitive load would slow RT. Attention is a limited resource, so any factor that draws from the resource pool will distract the driver from detecting the brake signal and slow RTs.

One method for increasing cognitive load is to complicate the driver's path. Presumably, following turns in a winding road requires more attention than simply steering a straightaway. Results support this assumption. Korteling (1990) found slower brake RTs when a lead car varied speed and the road had more turns. Alm and Nilsson (1994) found longer times for a simulated road that contained sharper turns.

Another source of cognitive load is use of in-car devices. Summala et al. (1998) found slower response when drivers viewed in-car displays. However, looking at objects inside the car forces the driver to view the road through the peripheral visual field and to accommodate to a near distance, so slowing might be an effect of poorer vision as well as cognitive load.

One recent hot topic in cognitive loading is the potential danger posed by cellular phone use. Although it would be expected that attentional allocation to nondriving tasks should slow response, visual tasks are much less impaired by a concurrent auditory task, such as listening, than by a second visual task. A priori, it is therefore not clear whether cellular phone use would be a significant hazard.

Epidemiological studies (e.g., Redelmeier & Tibshirani, 1997; Violanti, 1998; Violanti & Marshall, 1996), however, have concluded that accident likelihood increases dramatically during cell phone use. Moreover, studies found the same results for telephones with and without hand controls, suggesting that the effect is due to loss of attention and not to interference of motor control. Of course, epidemiological studies cannot determine whether such relations are cause and effect.

Several experimental road (Brookhuis & de Waard, 1994; Lamble, Kauranen, Laakso, & Summala, 1999; McKnight & McKnight, 1993) and simulator (Alm & Nilsson, 1995) studies attempted to demonstrate the cause–effect relation by testing drivers during cellular phone use. All found that cellular phones increased RTs by about 0.5 sec.

These results may exaggerate the hazard. In the studies cited earlier, the signal was acceleration–deceleration of a lead car, and, except for Alm & Nilsson (1995), there was no discrete signal, such as brake lights, a traffic signal, or even a roadway hazard. Instead, the drivers had to detect a much subtler cue, such as change in size, distance, and so forth, a notion confirmed by the unusually long control RTs. Discrete signals, such as the onset of a light, are more likely to break through attention, especially if they suggest a highly practiced response. For example, Summala et al. (1998) found that brake RTs were 1 to 2 sec slower when the lead car does not have operating brake lights.

Nilsson and Alm (1991) performed a better simulator study in which the brake signal was the sudden appearance of a red square on the "roadside." The concurrent use of a cell phone lengthened RTs by about 0.4 sec.

Moreover, not all studies have found a negative effect of cellular phone use. Alm and Nilsson (1994) paradoxically found drivers speaking on a cellular phone may decrease RT when road conditions are tricky. From a strict cognitive load viewpoint, this should have produced the slowest RTs of all. One guess is that the drivers may have been aware that they were engaging in risky behavior and actually became more attentive to the road. Often, drivers confound theoretical expectation by taking risk-compensatory precautions.

In sum, there is empirical research showing that drivers who are using cellular phones have slower brake RTs. Studies (e.g., Briem & Hedman, 1995; Lamble et al., 1999) of other driving behaviors also found performance deterioration during cellular phone use. However, the extent of the danger and the conditions that modulate it are uncertain. Even authors of recent epidemiological studies (e.g., Min & Redelmeier, 1998) have begun to back off the extreme conclusions from earlier analyses. The issue is still open, and there is clearly a need for more research under more varied conditions.

Responses: Braking Versus Steering

Whereas most driver RT studies have examined braking responses, a few have measured steering times. Hankey (1996) found that drivers could make initial steering response about 0.3 sec faster than initial braking. This makes sense, because the movement time should be far less than the 0.3 sec needed to move the foot from the accelerator to the brake pedal. Summala, Leino, and Vierimaa (1981) measured steering RTs using a minor intrusion, a car door opening into the driver's lane. They claimed that RT was 1.5 sec, which would agree nicely with Hankey's results. However, his graphs clearly show that initial course correction had begun somewhat earlier, at about 1 sec. In sum, it seems likely that initial steering response is a few tenths of a second faster than initial braking.

Summary of Brake RT Results

There is no single "best-guess" value for brake RT. However, there is sufficient convergence among studies of similar methodology to enable reasonable estimates for specific situations. Overall, the literature demonstrates that expectancy has the greatest effect. With high expectancy and little uncertainty, the best driver response time is about 0.70 to .075 sec, of which 0.2 sec is movement time. With normal, but common, signals such as brake lights, expected times are about 1.25 sec. Last, the most ecologically valid driver response time for surprise intrusions is about 1.5 sec, including a 0.3 sec movement time. These are all mean values, so subtract roughly 0.1 sec to estimate the median.

Urgency is another important variable. Drivers respond faster when highly aroused by shorter time-to-collision. The size of this effect varies greatly across studies from a hundredths of a second to a full second, so it is difficult to set a single normal value or even a reasonable range of values. However, extreme emergency may actually produce longer RTs, especially if there is competition among response alternatives.

The data on age are conflicting, but it seems likely that older people respond 0.1 to 0.3 sec more slowly in many cases. However, older drivers probably compensate with lower speeds. This lower urgency may be part of the reason that they respond more slowly. Data on gender effects are also unclear. There is probably some effect, however, because men are sometimes faster than women, but no study shows women being faster than men.

Drivers are also likely to respond more slowly when there is high cognitive load, either from driving (complex roadway) or nondriving (cellular phones) factors. It is impossible, however, to precisely quantify the effect due to the wide variation in results. If the brake signal is common and meaningful and likely to break through the attentional filter (a brake light flash ahead), the effect is probably a few tenths of a second at most. When the brake signal is subtle (such as acceleration–deceleration), the effect may be upwards of half a second. However, divers might compensate for the risk by attending to the road more, not less, than under normal conditions.

All of these conclusions are admittedly based on a rough mental combination across diverse studies mixed with some general trends in the basic RT literature. Unfortunately, there can be no other way. No single study can reproduce the full complexity of human behavior and its sensitivity to environmental variables. Moreover, studies cannot be quantitatively combined because no mathematical formalism can capture the subtle effects of methodology and variable interaction or incorporate general knowledge from the basic science literature on RT, perception, and cognition. For the time being, RT estimation remains part science and part intuition, that is, part application of a general knowledge about human factors.

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