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Driver distraction: Breakdowns of a multi-level control process

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Beginning with the introduction of the car radio, there have been concerns regarding how in-vehicle technology might undermine driving safety. Those concerns are particularly apparent today as many worry about the safety consequences of introducing vastly more complex technologies into the car, most prominently cell phones. Developments in the areas of wireless communication, computing, and GPS technology make an increasing variety of navigation, email, and internet systems available to the driver (Lee & Kantowitz, 2005). This availability, coupled with increased commute times, productivity pressures, and the diffusion of work beyond the office makes it likely that drivers will use these devices while driving. For example, 90% of all cell phone owners report that they use the phone while driving (Goodman, Tijerina, Bents, & Wierwille, 1999) and 60% of total cell phone usage occurs while driving. The increasingly common use of existing technology and the rapidly emerging new technology make it imperative to understand how in-vehicle technology affects driving safety. Properly designed, the new technologies may enhance driving enjoyment and safety; poorly designed, they can be deadly.

The rapidly evolving technology brings a mixed blessing to the driver. Although hands-free cell phones may eliminate some of the visual and manual demands that undermine driving performance, many studies have shown the cognitive demands of conversation are not eliminated with hands-free devices (Brown, Tickner, & Simmonds, 1969; Redelmeier & Tibshirani, 1997; Strayer & Johnston, 2001) and may even increase if the intelligibility of the handsfree devices is less than the handheld device (Matthews, Legg, & Charlton, 2003). New devices, such MP3 players and text messaging, have the potential to impose visual, manual, and cognitive demands that may greatly exceed those of cell phones. A recent special issue of the journal Human Factors brings together recent research addressing some of this technology (Lee & Strayer, 2004). Understanding how emerging technology influences distraction is an important driving safety issue.

Limits of human cognition that underlie distraction

A large and rapidly growing body of research shows that using a cell phone while driving degrades driving performance and increases crash risk (Alm & Nilsson, 1995; Brown, Tickner, & Simmonds, 1969; Haigney & Westerman, 2001; McKnight & McKnight, 1993; Redelmeier & Tibshirani, 1997; Violanti, 1997). By one estimate, cell phone-related crashes cause approximately 2600 deaths, 330,000 injuries, and 1.5 million instances of property damage in the U.S. per year (Cohen & Graham, 2003). The true safety impact of these devices in terms of crashes and fatalities may be underestimated. Compared to alcohol-related crashes, where there is a clear marker of a causal agent, cell phones do not leave a tell-tale trace. Even in the portion of cases where cell phone records are available, it is often difficult to precisely time-stamp the crash and relate it to the distraction. Many telematics devices leave an even weaker trace. Estimating the true cost of technology induced distraction is very difficult.

One of the underlying causes of driver distraction is the limited ability to do two things at once. Early theories of human information processing described people as single channel information processing systems (Broadbent, 1958). Recent research suggests performance depends on an information processing bottleneck at one or more of the stages of perception, decision making, response selection, or motor control (Pashler, 1998). By carefully manipulating perceptual and response demands for multiple tasks, substantial evidences suggests that a bottleneck exists at the response selection or central processing stage. A bottleneck at the response selection stage forces responses to be queued and delayed at the point of response selection, but makes it possible to perceive multiple stimuli in parallel (Pashler, 1998). This finding is particularly important for predicting driver distraction because it suggests that activities that require response selection will interfere with each other to a great degree. Specifically, listening to an audio book does not require response selection, but a conversation does. As expected, the task requiring a response selection interferes with driving activities that also require response selection (Strayer & Johnston, 2001). However, there is also evidence that task interference can occur for other stages than response selection (Wickens, 2002).

Wickens (1984) developed the multiple resource theory to describe the near perfect timesharing that can occur with certain pairs of tasks. According to this approach multiple, independent attentional limited capacity resources govern dual task performance. Multiple resource theory describes how well people can do two things at once by identifying how much each task competes for resources. Processing stages, modes, and codes define these resources. If two tasks demand the same resources performance of one or both suffers. Driving requires visual and spatial resources, whereas a handsfree cell phone requires auditory and spatial resources and so the multiple resource theory would predict relatively little interference; however central processing demands will lead to interference even if the resource requirements are relatively independent (Wickens, 2002).

Driving performance and interactions with the in-vehicle technology can both suffer from competition from the other activities. For example, business negotiations by cell phone while driving suffered in comparison to those conducted when not driving (Parkes, 1993). Importantly, breakdowns in the telematics interactions can increase the telematic demand, which may have a surprisingly negative effect on driving performance.

Driving and telematics interaction as control processes

The ultimate effect of new technology on driving safety depends on a wide array of interacting factors. At the most simple level, Figure 1 shows that driver performance depends not only on the demands of the in-vehicle information system (telematics), but also on the concurrent roadway demands. Dialing a phone on a straight road during daytime may not undermine driving performance dramatically. However, dialing a phone at night on a curve could be deadly. Simultaneous peaks in both roadway and telematics demands can greatly diminish driving performance.

Driver response to demands is more complex than Figure 1 suggests. Drivers do not passively respond to demands imposed on them by the roadway and telematics. Instead drivers play an active role in defining these demands. Telematics demands depend on how and when drivers choose to interact with the device. Likewise, roadway demands depend in part on how fast drivers choose go and the route they choose.

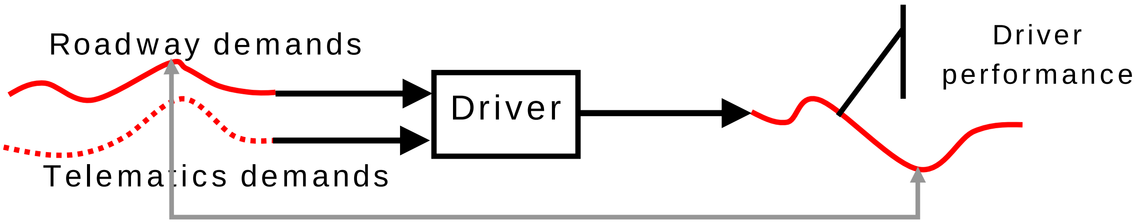

Figure 1. The concurrent peaks in driving and telematics demands can undermine driving performance.

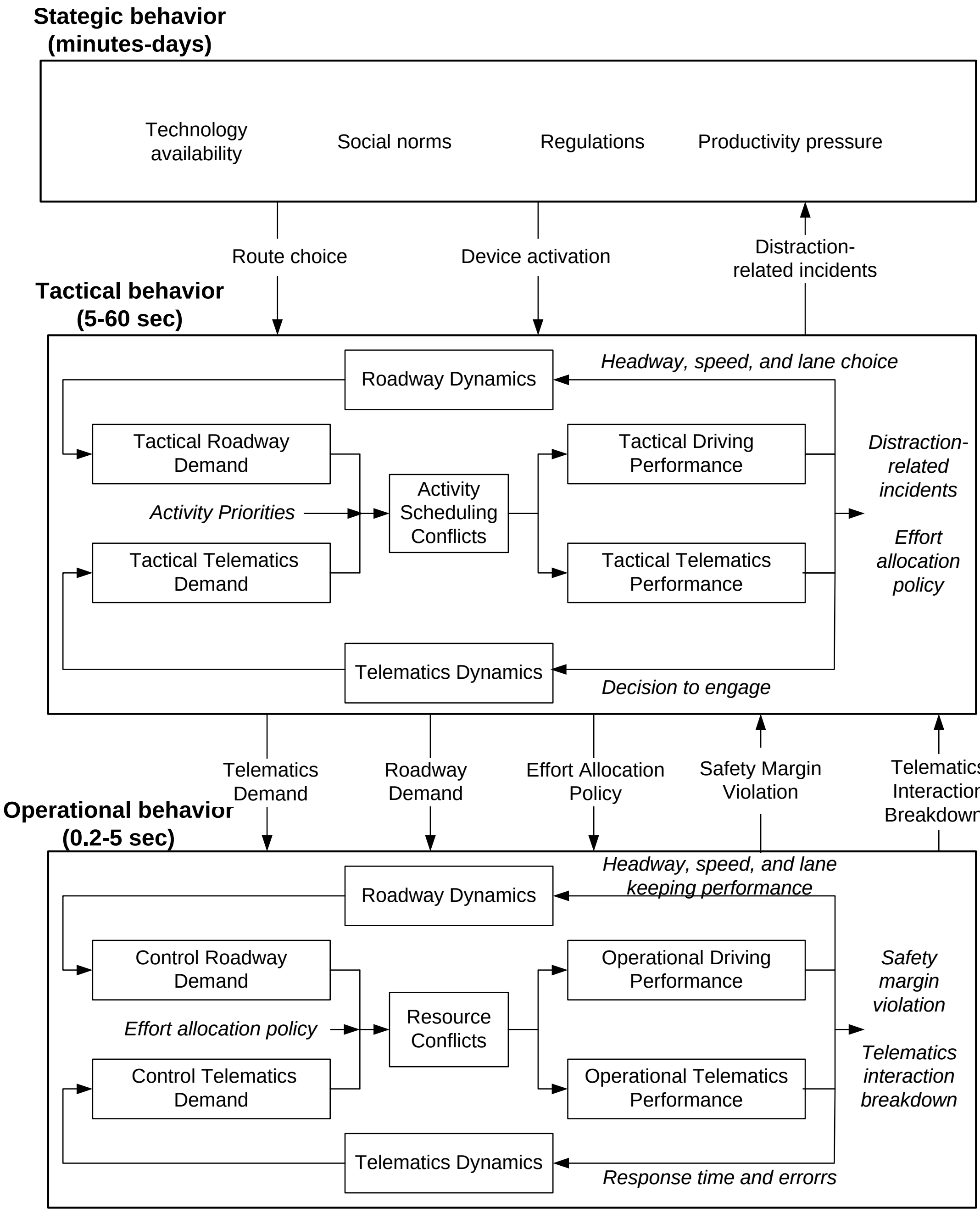

Figure 2. Distraction results from breakdowns of multi-level control that is shared between telematic interactions and driving (Lee & Strayer, 2004).

Both feedback and feedforward processes guide drivers' response. With the feedback process, drivers adjust their behavior on previous levels of driving performance. Drivers use feedback control to adjust their speed in response to the increasing demand of a cell phone conversation. With the feedforward process, drivers adjust their behavior based on anticipated demands. Drivers use feedforward control in choosing not to place a call until after they negotiate a difficulty maneuver, such as merging onto the highway. Feedback and feedforward control play a critical role in defining the demands to which the driver must respond (Sheridan, 2004).

Multi-level control in driving

The timescale at which drivers engage in feedback and feedforward control ranges from fractions of a second to days. Figure 2 reveals some of these interactions by distinguishing between three levels of driving behavior associated with distraction (Allen, Lunenfeld, & Alexander, 1971; Michon, 1985; Ranney, 1994). Strategic behavior describes driving and telematic activities at a very molar level, with a time scale of minutes to days. Tactical behavior describes driving and telematic tasks at a finer level, with a time scale of 5-60 seconds. At the bottom of the figure, operational behavior describes tasks at a micro level, with a time scale of 0.2-5 seconds. Each of these levels provides a different description of how the characteristics of new technology interact with the driver to influence distraction-related safety problems.

With cell phones, the top of Figure 2 describes the factors that might lead drivers to bring a cell phone into the car. At the strategic level, societal norms and regulations might discourage drivers from bringing a cell phone into the car, but handsfree technology and productivity pressures might encourage drivers to bring a cell phone into the car to do so. At the tactical level, the immediate roadway demands might influence the decision to answer the phone and the perceived demands of a conversation might lead drivers to adopt longer headways or slower speeds. At the operational level, the cognitive demands of the conversation influence headway, speed and lane keeping performance. Each level of Figure 2 provides a different perspective of how the demand of the roadway and the telematics might interfere and undermine driving safety.

Problems with feedback control

Driving provides poor feedback, particularly concerning the inappropriate use of telematics. Because driving is often forgiving, drivers can neglect the driving task to a dangerous degree and suffer no immediate consequences. Even when drivers receive feedback in the form of a crash it seldom results in a lasting change in behavior (Rajalin & Summala, 1997). Similarly, a well-designed device that reduces distraction at the operational level may actually undermine driving safety if it encourages drivers to use the device more frequently while driving. This *usability paradox* occurs when increased ease of use reduces the distraction of any particular interaction, but increases overall risk by encouraging drivers to use the device more frequently. This tendency for drivers to adapt to improvements and undermine the expected safety benefit is a common phenomenon. For example, when roadway improvements are made (lanes widened, shoulders added, lighting improved) speeds increase (Evans, 1991). Drivers may view handsfree cell phones as safe to use while driving and so make more calls than they would with a handheld cell phone. Another example of poor feedback is that good control of one driving task provides false confidence for another. Experienced drivers are able to maintain their lane position using peripheral vision while interacting with a visually demanding device and so receive continuous feedback suggesting they are monitoring the driving environment well. However, the visual demands severely degraded their ability to detect events (Summala, Nieminen, & Punto, 1996). Such misleading feedback can give drivers a false sense of how safely they can drive while interacting with telematics devices.

Problems with feedforward control

Feedforward control is difficult because roadway and telematics demands are unpredictable. In addition, drivers tend to neglect future demands and focus on the current situation. As an example, drivers tend to answer cellphones independent of the upcoming roadway demands (Nowakowski, Friedman, & Green, 2002). Another challenge to effective feedforward control is that breakdowns in control at the operational level can lead unexpected demands and poor management of the telematics and driving demands. Speech recognition systems, particularly in the context of a noisy car, will likely induce errors. Such errors can lead to an unanticipated and increasing spiral of demand. Inexperience also undermines feedforward control in a way that can be particularly devastating. The tendency for young drivers to underestimate risks already plays a major role in driving safety (Fisher, Laurie, Glaser, Connerney, Pollatsek, Duffy & Brock, 2002). Interaction with telematics will likely exacerbate problems of feedforward control and the difficulty drivers have in anticipating and responding to upcoming demands.

The most powerful factors governing distraction may be the most difficult to quantify and shape. In particular, social norms governing acceptable risks and specifically, whether it is socially acceptable to use a cell phone while driving, may have the largest effect on driving safety. Subtle design modifications that reduce distraction at the operational level of behavior may have a much smaller effect on driving safety compared to changes in societal norms that influence the strategic level and make the use of a device while driving taboo. The driving behaviors influenced by telematics devices and the complex feedback processes make a comprehensive understanding of driver distraction a substantial challenge.

Mitigation strategies for driver distraction

Addressing the issue of driver distraction is often approached from a legislative perspective in which laws are developed to limit or eliminate drivers' use of certain technology while driving. The ban on handsheld cell phones is a salient example. Using sensor and computer technology may be a more effective approach to reducing distraction and enhancing safety. A wide range of distraction mitigation strategies are possible and this section presents a taxonomy and provides examples of some promising strategies (Donmez, Boyle, & Lee, 2003).

Recent reviews of automation and its effect on human performance highlight the important considerations of for distraction mitigation strategies (Lee & See, 2004; Parasuraman, Sheridan, & Wickens, 2000; Sheridan, 2002)). Sheridan (2002) has defined eight levels of automation that range from high (e.g. automation takes control and ignores human) to moderate (e.g. automation executes action only if human approves) to low (e.g. human does it all). These distinctions have been used to integrate studies of automation in many domains and can be used to identify design tradeoffs with distraction mitigation strategies. These mitigation strategies can be further categorized according to whether they address driving-related (e.g. steering, braking) or non-driving related tasks (e.g. tuning the radio, talking on the cell phone). Strategies that address driving related tasks focus on the roadway environment and directly support driver control of the vehicle, whereas strategies for non-driving related tasks focus on modulating the driver interaction with telematics (Donmez, Boyle, & Lee, 2003).

Table 1. Mitigation strategies for driver distraction (Donmez, Boyle, & Lee, 2003).

LEVEL OF AUTOMATION	DRIVING RELATED STRATEGIES		NON-DRIVING RELATED STRATEGIES	
	System initiated	Driver initiated	System initiated	Driver initiated
High	*Intervening*	*Delegating*	*Locking & Interrupting*	*Controls Pre-setting*
Moderate	*Warning*	*Warning Tailoring*	*Prioritizing & Filtering*	*Place-keeping*
Low	*Informing*	*Perception Augmenting*	*Advising*	*Demand Minimizing*

One particularly promising set of mitigation strategies falls under the category of driving related tasks. Three levels of automation define these substantially different strategies within this category: *intervening* (high automation), *warning* (moderate automation) and *informing* (low automation). *Intervening* involves the system taking control of the vehicle and performing one or more driving-related tasks during hazardous situations when the driver is too distracted to react in a timely manner. *Warning* alerts the driver to take a necessary action. A collision avoidance system is a function that employs *warning* as a strategy and encompasses both visual and audio alerts. This is considered a moderate level of automation compared to *intervening* since the driver is still in control of the vehicle. Lee et al (2002) showed that this type of system benefited both distracted and non-distracted drivers. A concern with this system is the distrust and disuse can result from high false alarm rates. This problem also contributes to driver's response to, and acceptance of the system, which may influence the system effectiveness (Parasuraman, Hancock, & Olofinboba, 1997). *Informing* provides drivers necessary information that they typically would not observe if distracted. For example, a speed limit indicator might provide information on changes in posted speed limits. Donmez et al.(2003) discuss the other mitigation strategies in detail.

Conclusions

Current technological and societal pressures will make distraction-related crashes more prevalent unless steps are taken. An important contribution to distraction related crashes include fundamental limits of human perception and cognition. People have limited capability to do more than one thing at a time. As a consequence, telematics interactions that occur while driving are risky. The degree of risk posed by cognitive limits depends on how they contribute to breakdowns in the multi-level control process that includes strategic, tactical, and operational responses.

Considered in this context, distraction results from:

- Conflict between driving and telematics demands—information overload.
- Poor feedback that leaves drivers unable to adjust their behavior to compensate for the telematics demands.
- Inadequate support of feedforward control that makes it difficult to anticipate and respond to peaks of telematics and roadway demands.

Considering distraction as a breakdown in a multi-level control process has critical implications for telematics design, development of adaptive telematics to mitigate distraction, and measures and methods to evaluate telematics devices.

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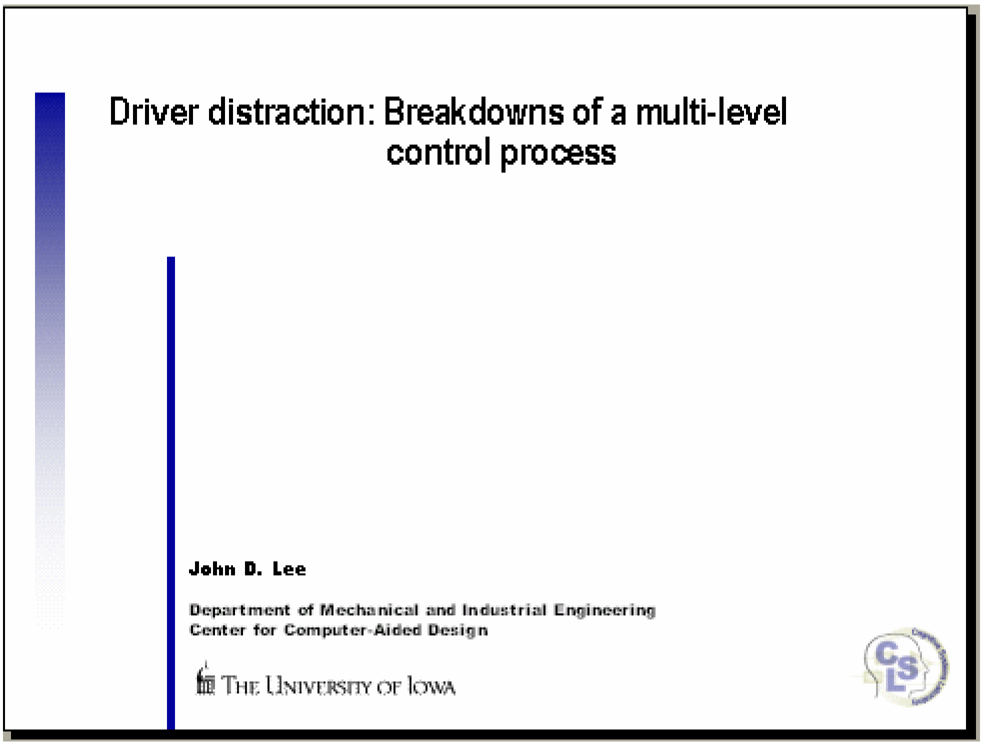
PRESENTATION SLIDES



Technology trends

- 135,000,000 cellphone subscribers as of 2002 in US
- 85% of those who have phone use it while driving
- 60% of total cellphone usage is while driving
- 8% of drivers on the road are talking on the phone
- Crash costs: $15 billion, 1,500 lives in US

- $10-100 Billion market for telematics devices by 2010

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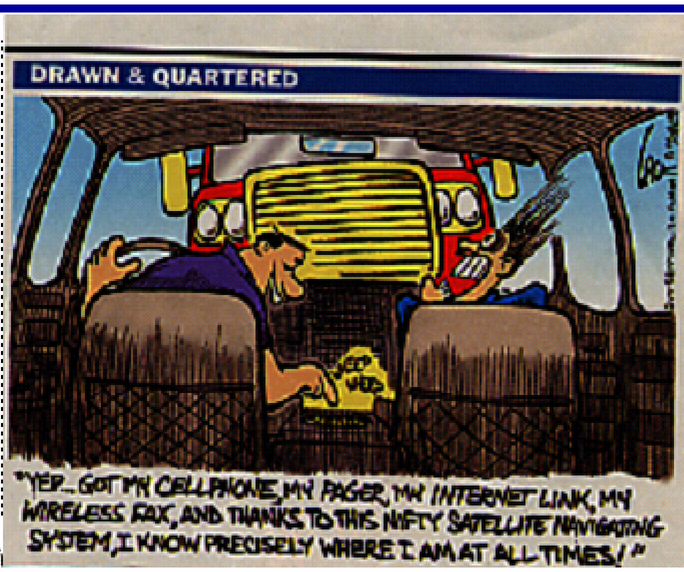
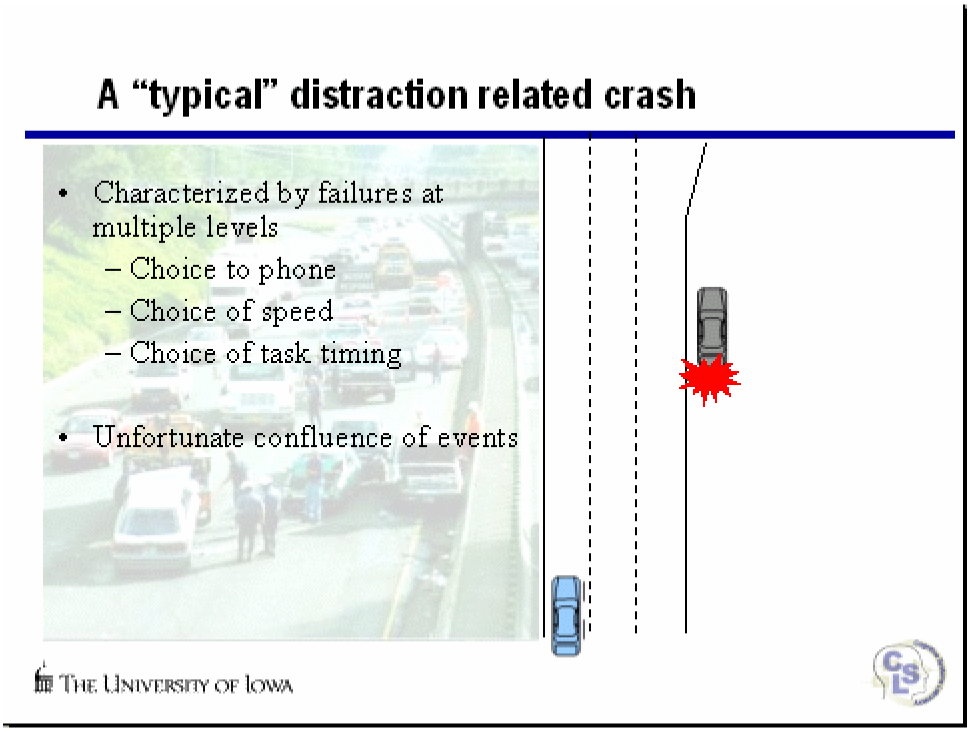
Knowing where you are and technological "aids"




A "typical" distraction related crash
• Characterized by failures at multiple levels
– Choice to phone
– Choice of speed
– Choice of task timing
• Unfortunate confluence of events
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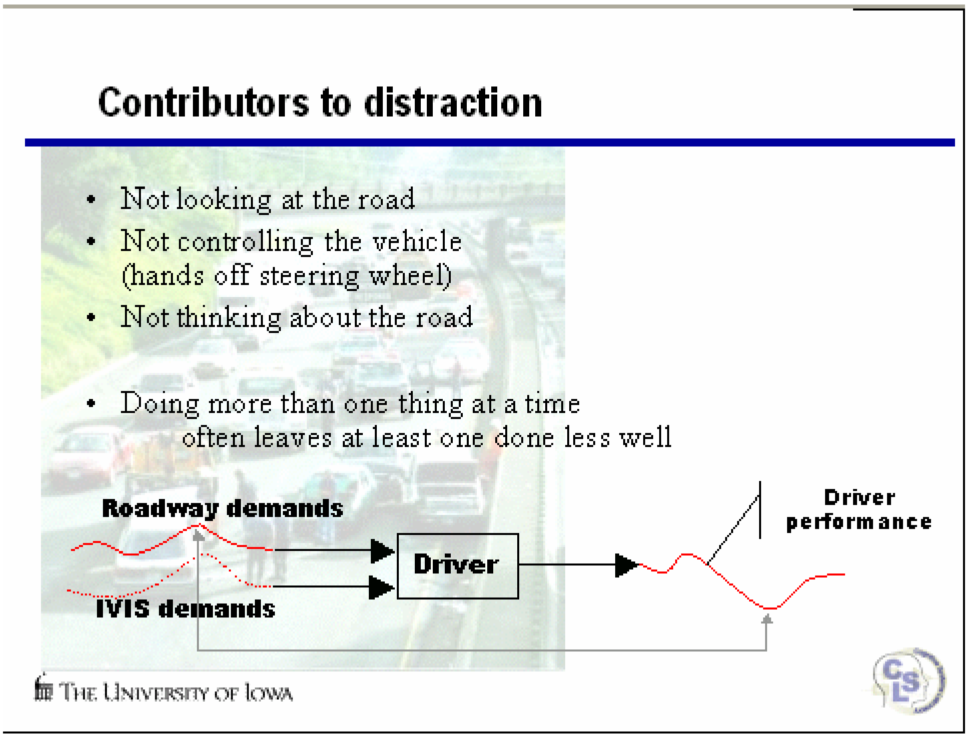
Contributors to distraction
• Not looking at the road
• Not controlling the vehicle (hands off steering wheel)
• Not thinking about the road
• Doing more than one thing at a time often leaves at least one done less well
Roadway demands
IVIS demands
Driver
Driver performance
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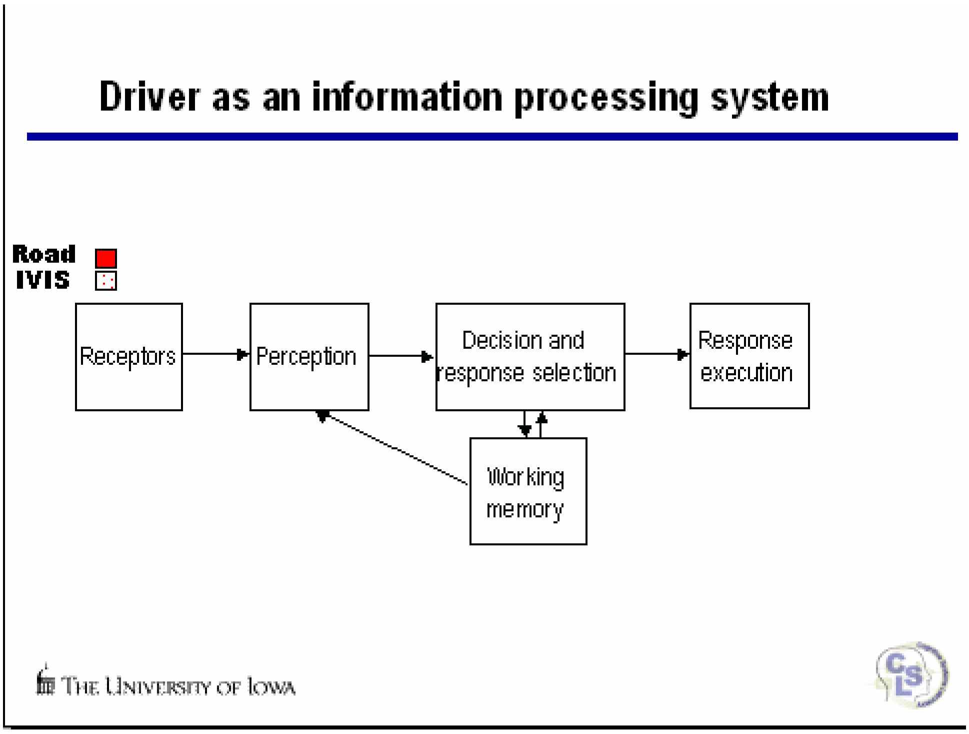
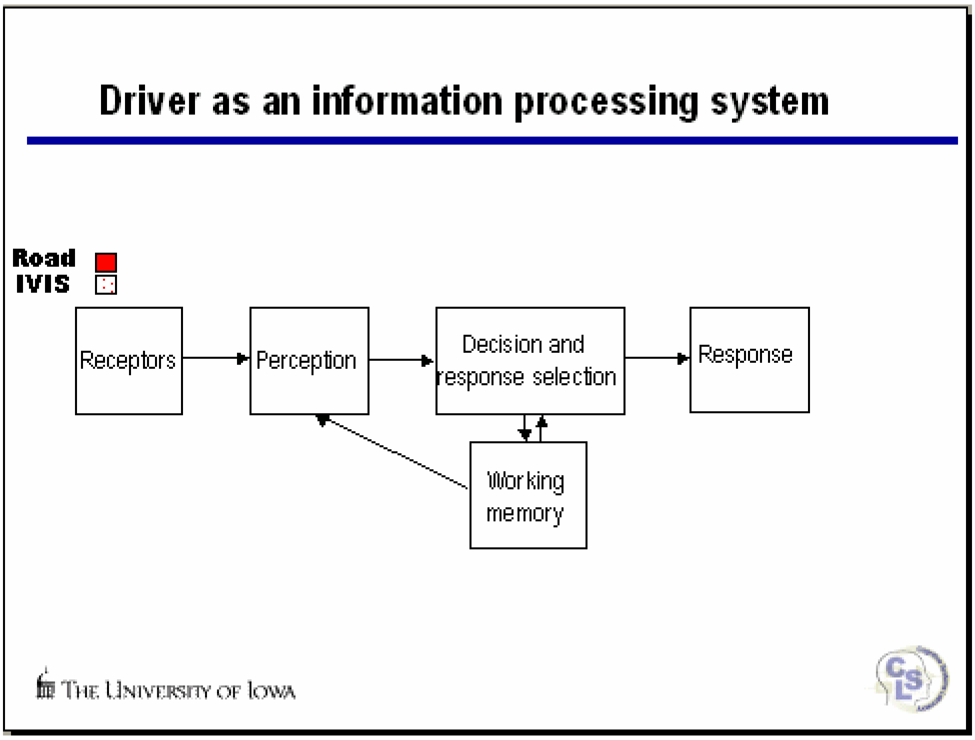

Driver as an information processing system
Road
IVIS
Receptors
Perception
Decision and response selection
Response execution
Working memory
The University of Iowa


Driver as an information processing system
Road
IVIS
Receptors
Perception
Decision and response selection
Response
Working memory
The University of Iowa

Theoretical perspectives on capacity limits and attentional failures

- **Multiple resource theory (MRT)** (Wickens, 1984; Wickens. 2001)
  - Tasks compete for limited processing resources
  - Modes, Codes, and Stages define resources
  - Focal and Ambient visual resources
- **Bottleneck theory** (Pashler, 1998; Strayer & Drews, 2001)
  - Serial processing of response selection
  - Exogenous and endogenous processes govern visual attention
- **Control with a limited capacity processor** (Moray, 2000; Sheridan, 2004)
  - Serial, intermittent sampling and control
  - Dynamic task management

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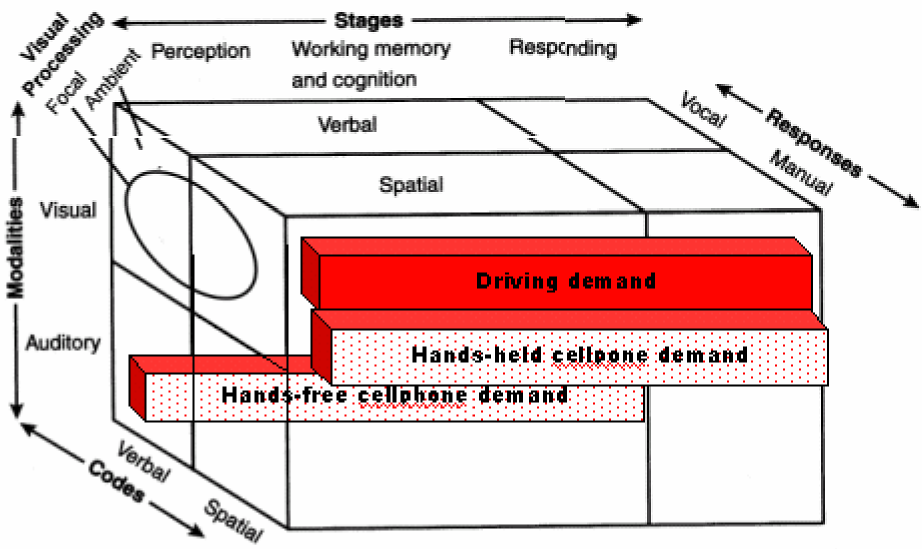
Multiple resources to respond to competing roadway and IVIS demands



Quantification of distraction with MRT (Boer, 2000)

Task	Task Description	PDT RT	SE	Input Auditory	Input Visual	Code Verbal	WM Verbal	Cog Proc Verbal	Code Spatial	WM Spatial	Cog Proc Spatial	Output Voice	Output Manual
		RT	1000 SE	I_A	I_V	C_V	WM_V	CP_V	C_S	WM_S	CP_S	O_V	O_M
4	Select one of three given answers to a question.	413 / 428	469 / 480	1	0	3	4	3	0	0	0	1	0
5	Subtract 7 repeatedly starting at number around 950 *	439 / 477	520 / 548	0	0	1	1	1	3	2	3	1	0
6	Check map position and name of location shown on navigation screen.	465 / 453	508 / 527	0	1	1	1	1	2	1	2	1	0
7	Look at list of 4 names on display and select favorite.	498 / 465	575 / 535	0	1	2	2	2	2	2	1	1	0
8	Change AC mode as instructed by pushing switch next to screen.	477 / 528	591 / 634	1	1	1	1	1	1	1	1	0	1

Corr.Coef. 0.8828 | Corr.Coef. 0.9396

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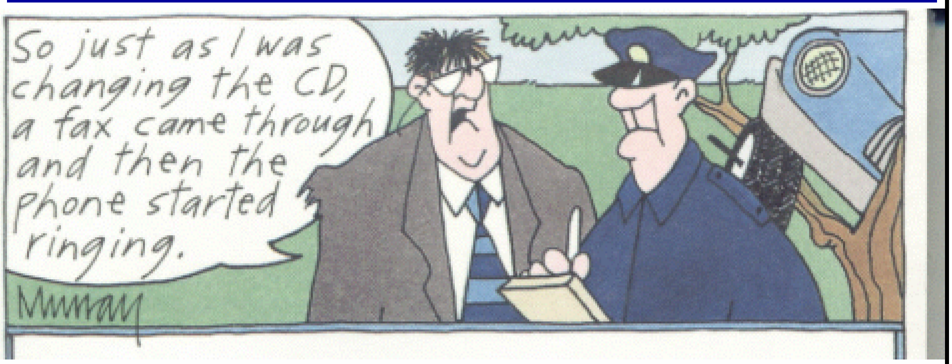
Limits of MRT predictions of distraction



- Superadditive effects for multiple IVIS tasks
- Dominance of response selection bottleneck for cognitive tasks

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Response bottleneck disrupts visual attention and event detection

- Hands free is not risk free—minimizing resource competition does not eliminate dual-task performance decrement
- Listening tends not to degrade driving, but responding does
- Visual attention is severely limited, but effective
  - Exogenous process guides eyes to changes
  - Endogenous process guides eyes to meaningful element
  - IVIS interactions undermine endogenous guidance of attention

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CB demo

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CB results

- CB
- Calibration of confidence

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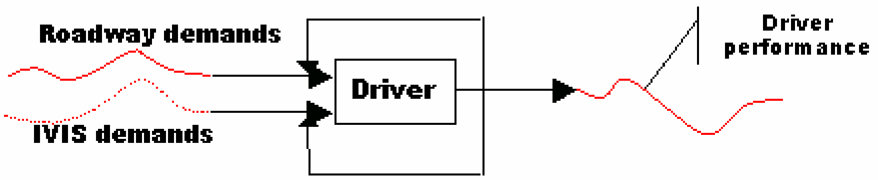
Drivers are controllers, not passive information processors



- Consequence of roadway and IVIS demands depends on:
  - Feedforward—adjusting based on expected demands
  - Feedback—adjusting based on previous performance
- Feedforward—engage IVIS before peak roadway demand
- Feedback—decrease speed to maintain safety margins

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Distraction: a problem of control

- Distraction is not simply information overload
- Distraction is the breakdown of a multi-level control process
- Breakdowns across multiple levels of interaction
  - Conflicts (overload)
  - Poor feedback
  - Impaired feedforward control

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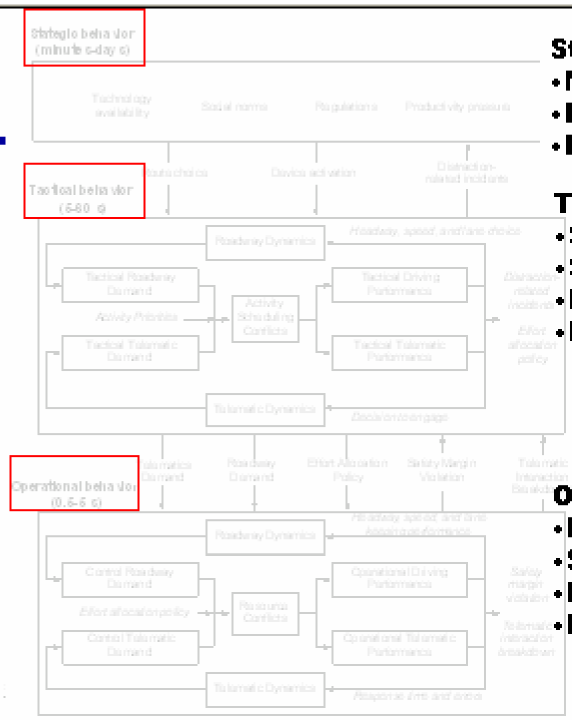
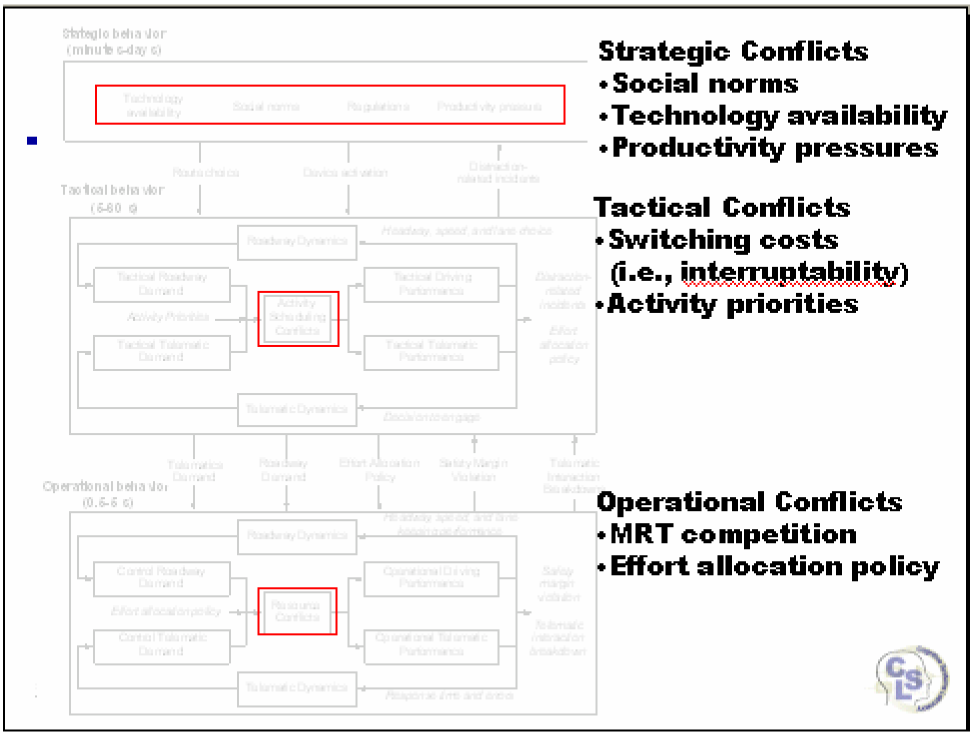
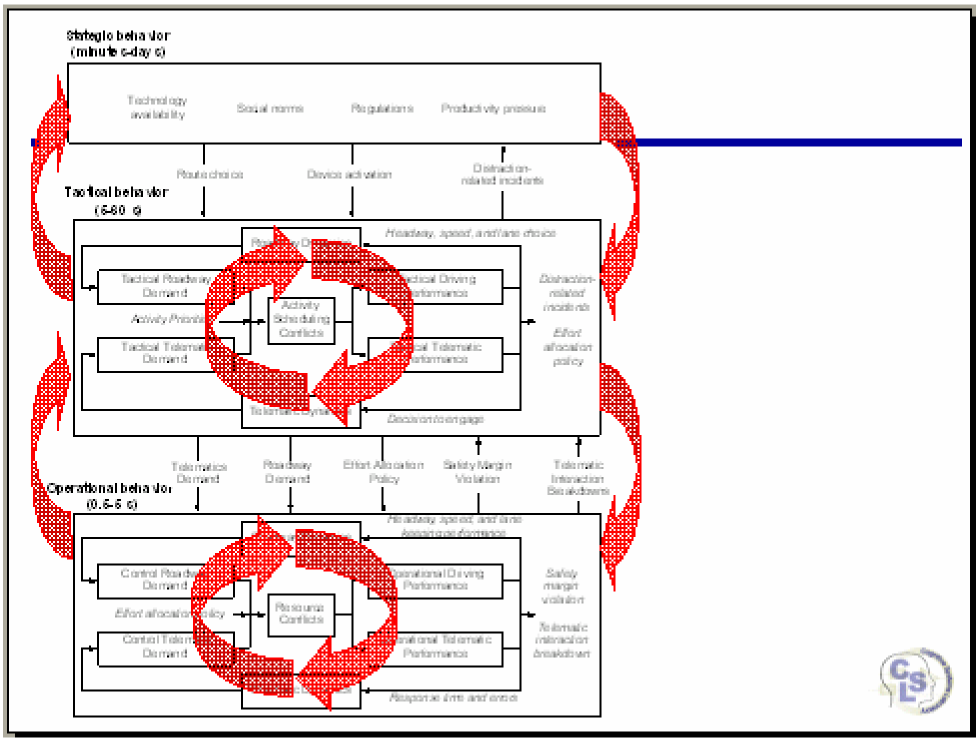


Strategic Behavior
- **Minutes-days**
- **Route choice**
- **Device activation**

Tactical Behavior
- **Seconds-minutes**
- **Speed choice**
- **Lane choice**
- **Decision to engage**

Operational Behavior
- **Milliseconds-seconds**
- **Speed control**
- **Lateral position control**
- **IVIS interactions**


Strategic behavior
(minutes-days)
Tactical behavior
(5-60 s)
Operational behavior
(0.5-5 s)
Strategic Conflicts
•Social norms
•Technology availability
•Productivity pressures
Tactical Conflicts
•Switching costs
(i.e., interruptability)
•Activity priorities
Operational Conflicts
•MRT competition
•Effort allocation policy


Strategic behavior
(minutes-days)
Technology
availability
Social norms
Regulations
Productivity pressure
Route choice
Device activation
Distraction-
related incidents
Tactical behavior
(5-60 s)
Headway, speed, and lane choice
Tactical Roadway
Demand
Activity
Scheduling
Conflicts
Tactical Telematic
Demand
Distraction-
related
incidents
Effort
allocation
policy
Decision to engage
Telematics
Demand
Roadway
Demand
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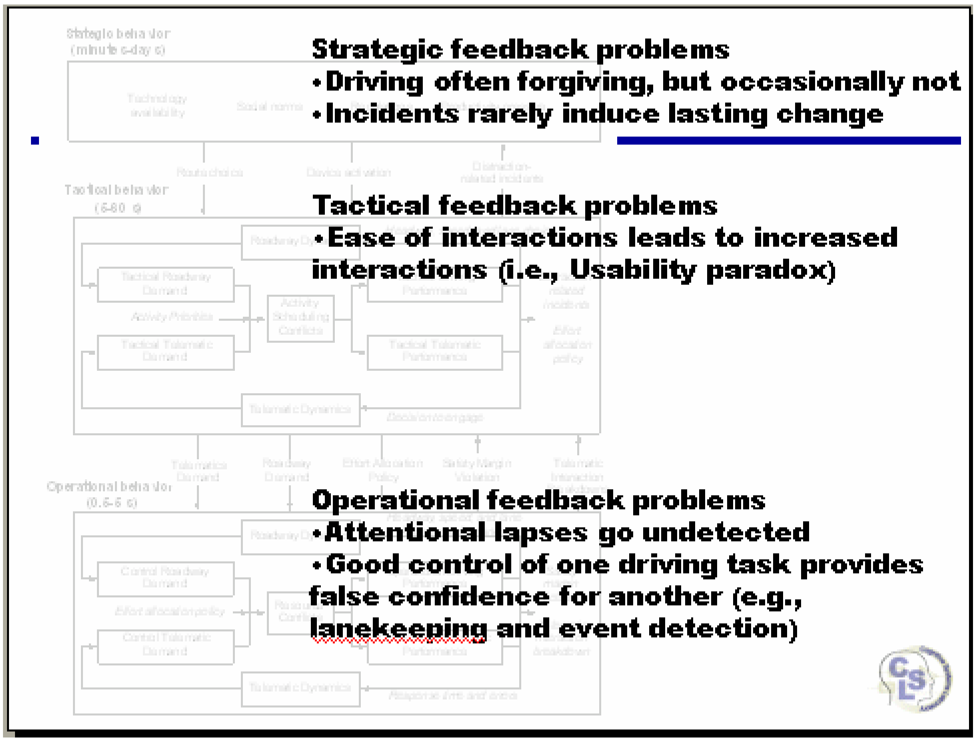
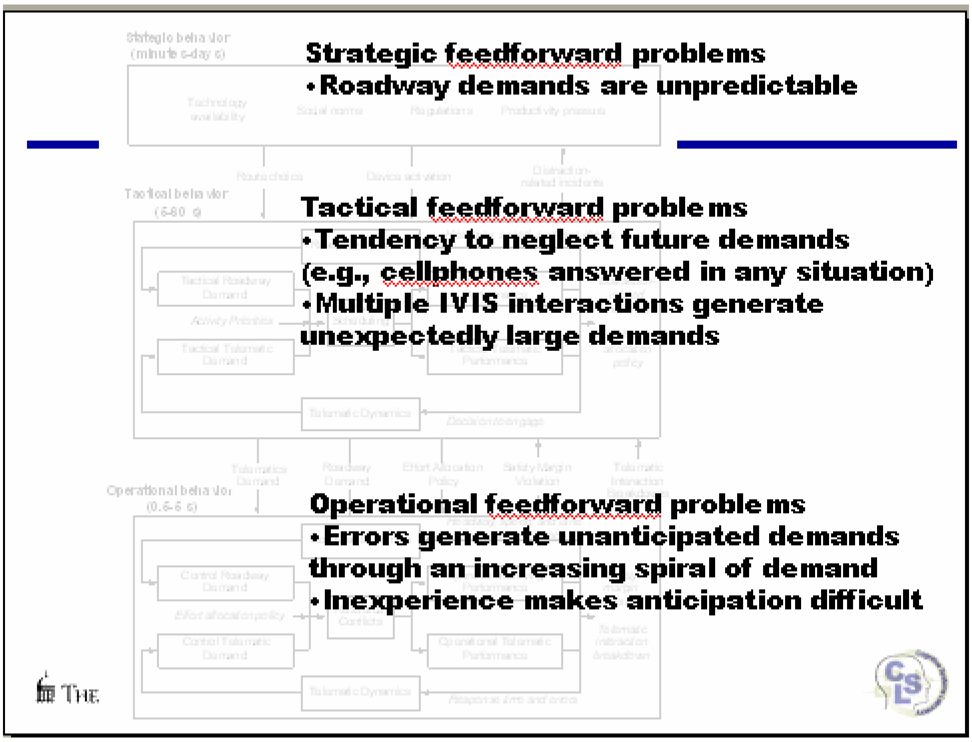
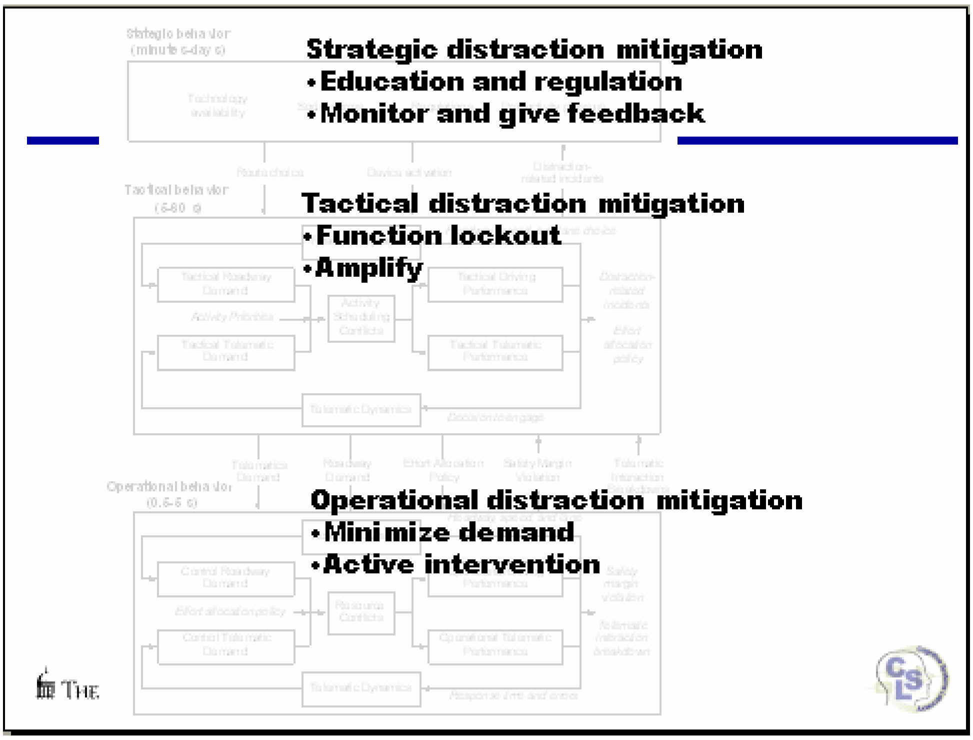
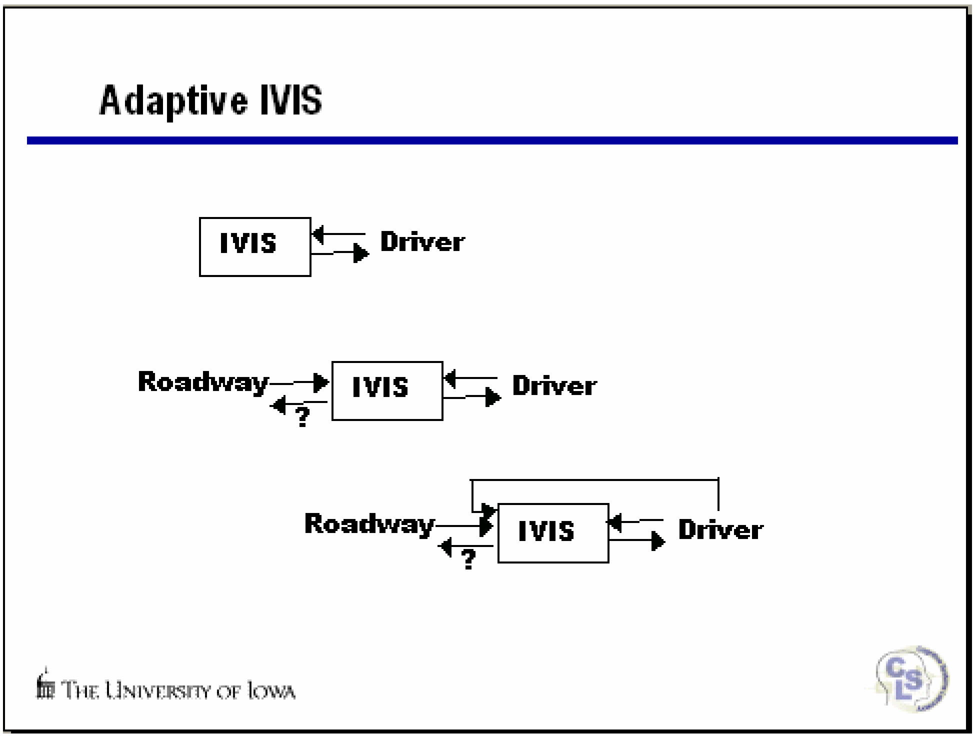
Policy
Safety Margin
Violation
Telematic
Interaction
Breakdowns
Operational behavior
(0.5-5 s)
Control Roadway
Demand
Resource
Conflicts
Control Telematic
Demand
Safety
margin
violation
Telematic
interaction
breakdown


Strategic feedback problems
•Driving often forgiving, but occasionally not
•Incidents rarely induce lasting change
Tactical feedback problems
•Ease of interactions leads to increased interactions (i.e., Usability paradox)
Operational feedback problems
•Attentional lapses go undetected
•Good control of one driving task provides false confidence for another (e.g., lanekeeping and event detection)


Strategic feedforward problems
•Roadway demands are unpredictable
Tactical feedforward problems
•Tendency to neglect future demands (e.g., cellphones answered in any situation)
•Multiple IVIS interactions generate unexpectedly large demands
Operational feedforward problems
•Errors generate unanticipated demands through an increasing spiral of demand
•Inexperience makes anticipation difficult


Strategic distraction mitigation
•Education and regulation
•Monitor and give feedback
Tactical distraction mitigation
•Function lockout
•Amplify
Operational distraction mitigation
•Minimize demand
•Active intervention
THE


Adaptive IVIS
IVIS
Driver
Roadway
IVIS
Driver
?
Roadway
IVIS
Driver
?
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Distraction mitigation function (Donmez, Boyle, Lee, 2003)

LEVEL OF AUTOMATION	DRIVING RELATED STRATEGIES		NON-DRIVING RELATED STRATEGIES	
	System Initiated	Driver Initiated	System Initiated	Driver Initiated
High	*Intervening*	*Delegating*	*Locking & Interrupting*	*Controls Pre-setting*
Moderate	*Warning*	*Warning Tailoring*	*Prioritizing & Filtering*	*Place-keeping*
Low	*Informing*	*Perception Augmenting*	*Advising*	*Demand Minimizing*

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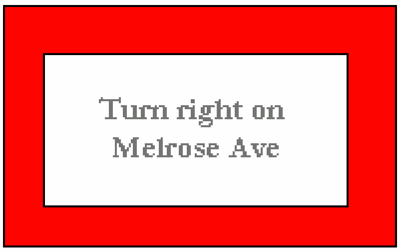
Advising (Adaptive based on roadway or driver state)



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Distraction mitigation function (Donmez, Boyle, Lee, 2003)

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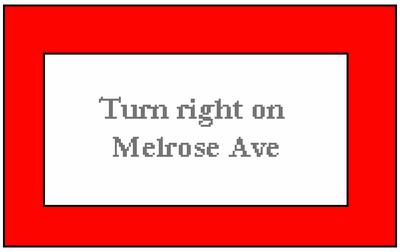
Locking (Adaptive based on roadway or driver state)



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Distraction as a breakdown in a multi-level control process—Conclusions

- Technological and societal pressures will make distraction-related crashes more prevalent
- Fundamental limits of human cognition make IVIS interactions risky
- Distraction occurs at multiple levels (Strategic, Tactical, Operational)
- Distraction results from
  - Conflict and overload
  - Poor feedback
  - Inadequate feedforward control
- Distraction as a breakdown in a multi-level control task has critical implications for
  - IVIS design
  - Adaptive IVIS to mitigate distraction
  - Measures and approaches to evaluate IVIS

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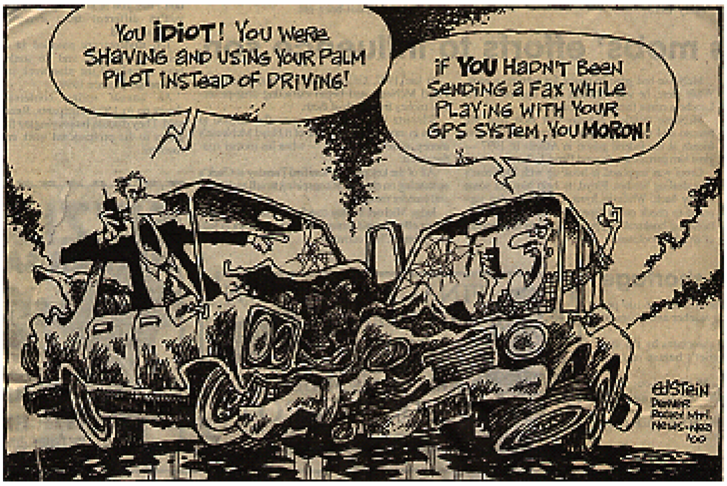
The future? Breakdowns in multi-driver compensatory processes



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