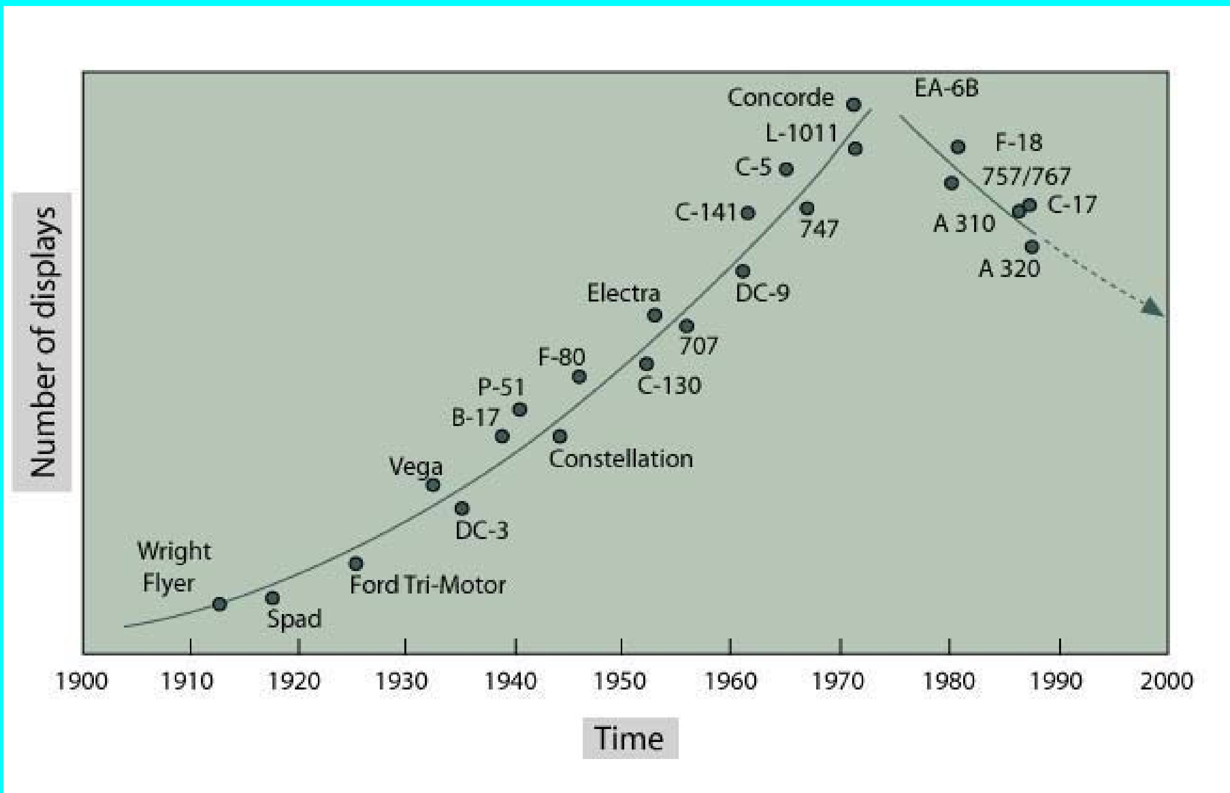
The Coming Transition in Automobile Cockpits

-

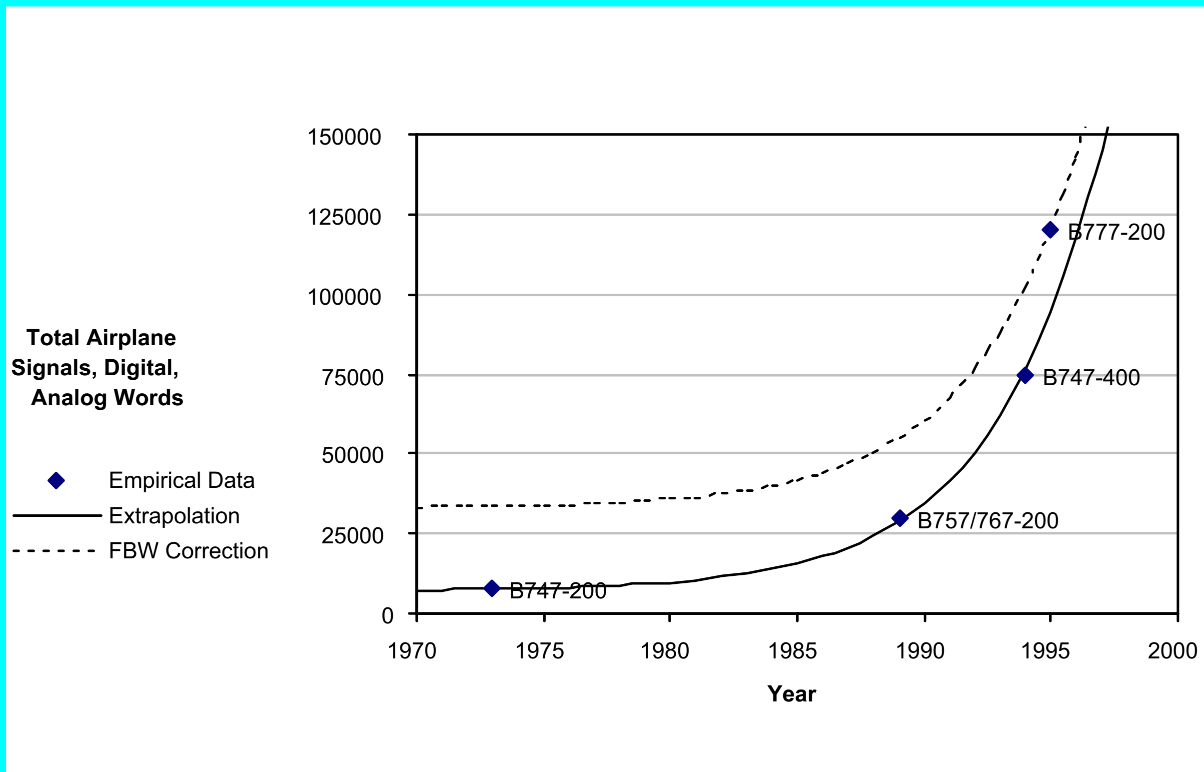
Insights from Aerospace

Prof. R. John Hansman
Department of Aeronautics & Astronautics

Evolution of Cockpit Displays



Software Growth in Aircraft



- Software size doubles every 18 months
- Compensating for “FBW offset” reduces doubling to 33 months

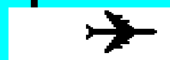
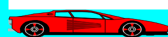
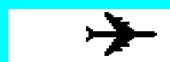
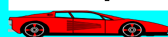
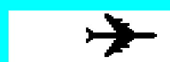
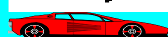
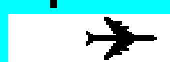
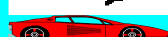
Hypothesis

- *We are entering a period of significant change in automobile Human-Machine Interaction driven by Information Technologies*
- *Automobiles will undergo a change more substantial than the change in aircraft from **"steam gauge"** to **"glass cockpits"***

Car / Aircraft Comparison

- Market
  - Capital investment (ROI)
  - Consumer product
- Number of vehicles (US)
  - 300,000
  - 200,000,000
- Safety (US)
  - 663 fatalities (1998)
  - 41,000 fatalities (1997)
- Threat response time constant
  - Order 5-60 sec.
  - Order 1 sec.
- Hazard density
  - Low, 3-D collision (vehicle, terrain, animal), WX
  - High, 2-D collision (vehicle, object, person, animal, …)
- System complexity
  - High
  - Med/low

Car / Aircraft Comparison (cont.)

- Operator selectivity/training/medical
   High
   Low
- Tracking precision (Heading)
   Order 5°
   Order 1°
- Recurrent training
   Yes
   No
- Operations procedure
   Yes
   No
- Impaired operators (Alcohol, Drugs)
   Order $1/10^7 - 10^9$
   Order $1/10^4 - 10^5$

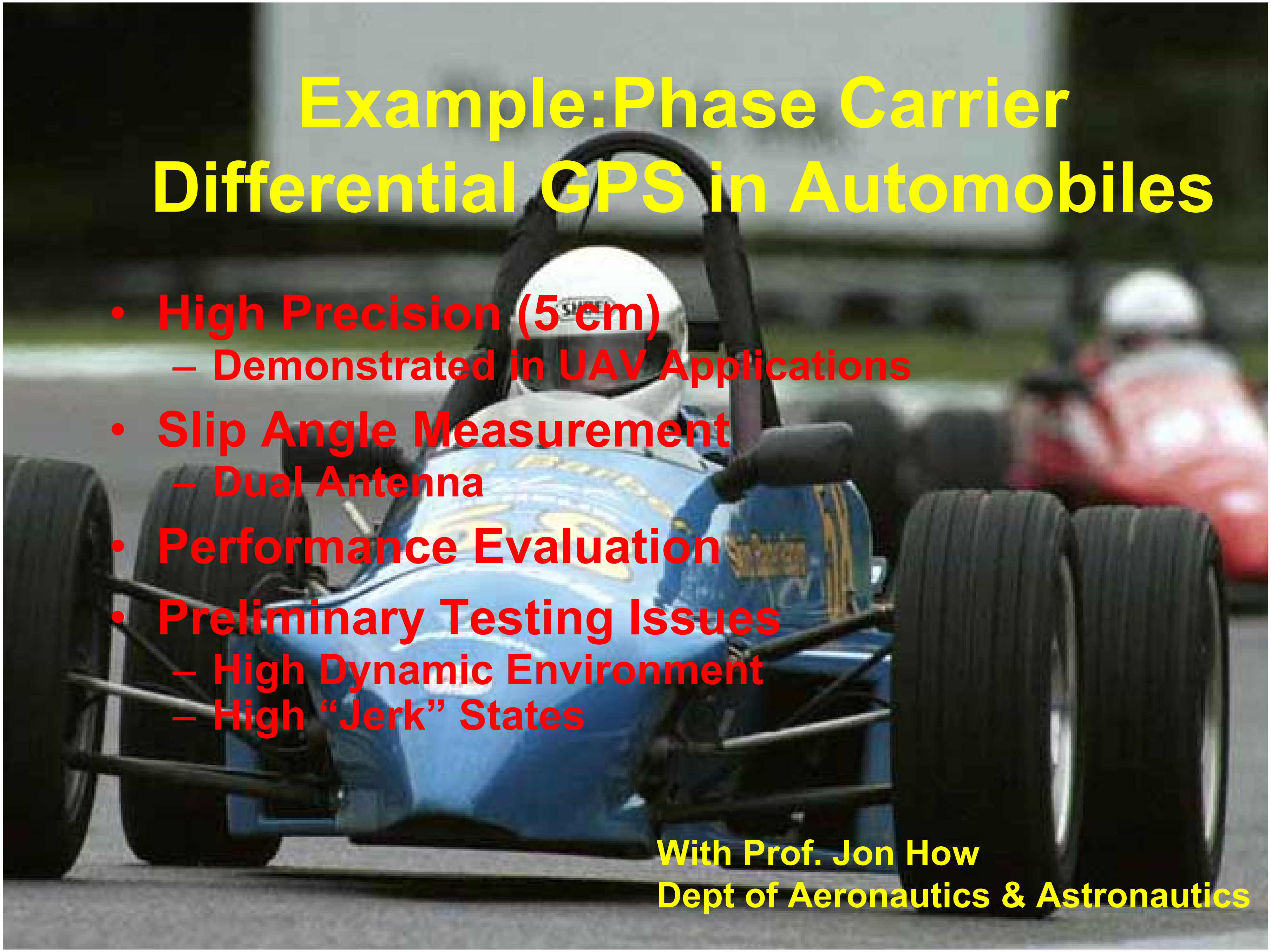
Aerospace Systems Applicable to Cars

- Control systems
  - ABS
  - Stability augmentation
- Fly by Wire/Light (FBW,FBL)
  - Integrity Concerns (eg 777)
- Critical software systems
- Fault tolerant systems

- Head up displays (HUD)
- Helmet mounted displays (HMD)
- Synthetic Vision Systems
- Sensor Fusion
- Hands on throttle and stick (HOTAS)
- Dark cockpit

- Navigation systems
  - GPS, DGPS
  - IRS/GPS
- Situation awareness displays
  - Moving map
  - Database

- Caution and Warning Systems
- Collision Alerting Systems
- Tactile alerting
  - Stick shaker
- Master caution
  - Information accessibility
  - Maintenance Diagnostics

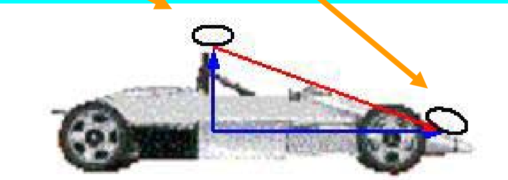


Example:Phase Carrier Differential GPS in Automobiles

- High Precision (5 cm)
  - Demonstrated in UAV Applications
- Slip Angle Measurement
  - Dual Antenna
- Performance Evaluation
- Preliminary Testing Issues
  - High Dynamic Environment
  - High “Jerk” States

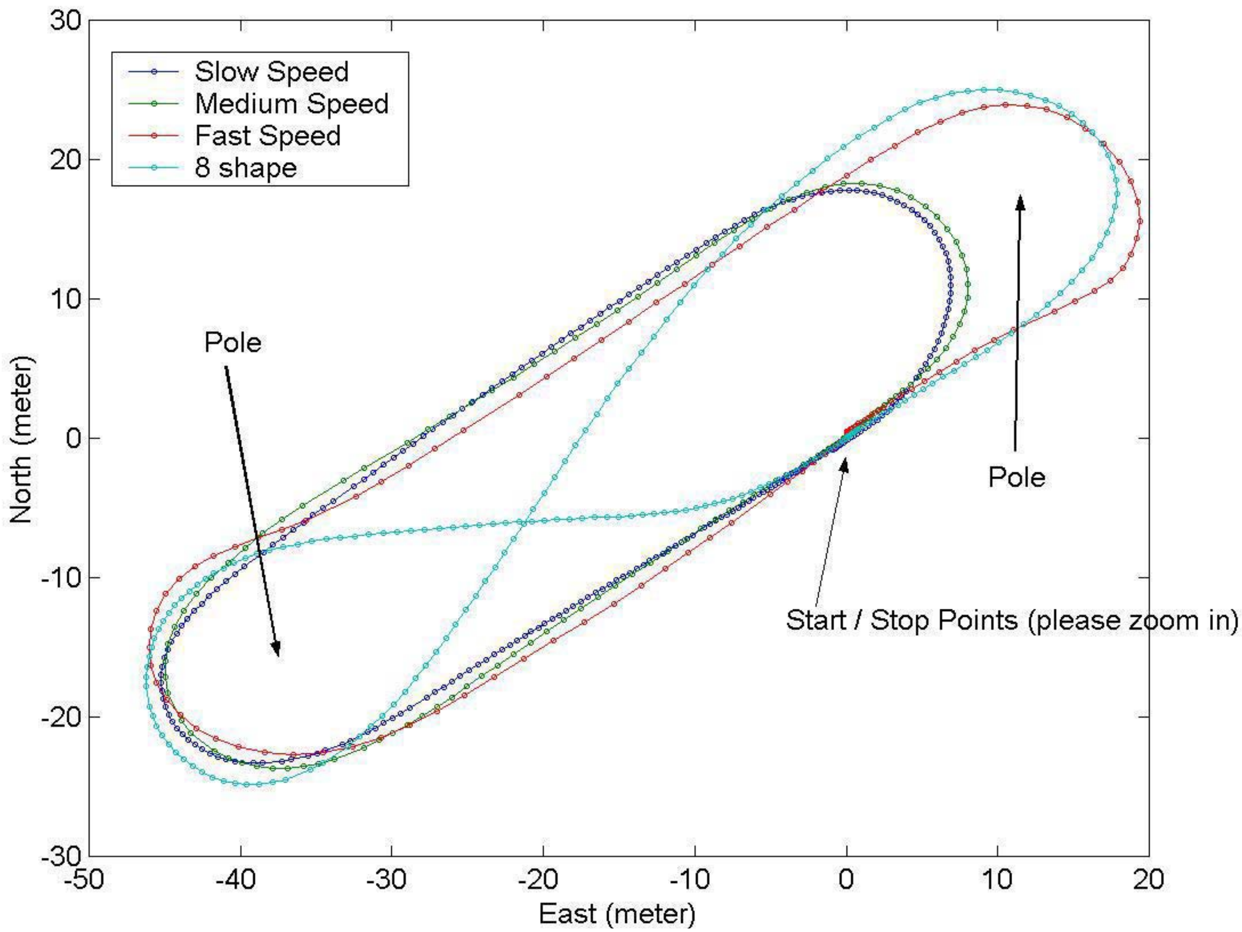
With Prof. Jon How
Dept of Aeronautics & Astronautics

Track Hardware Layout

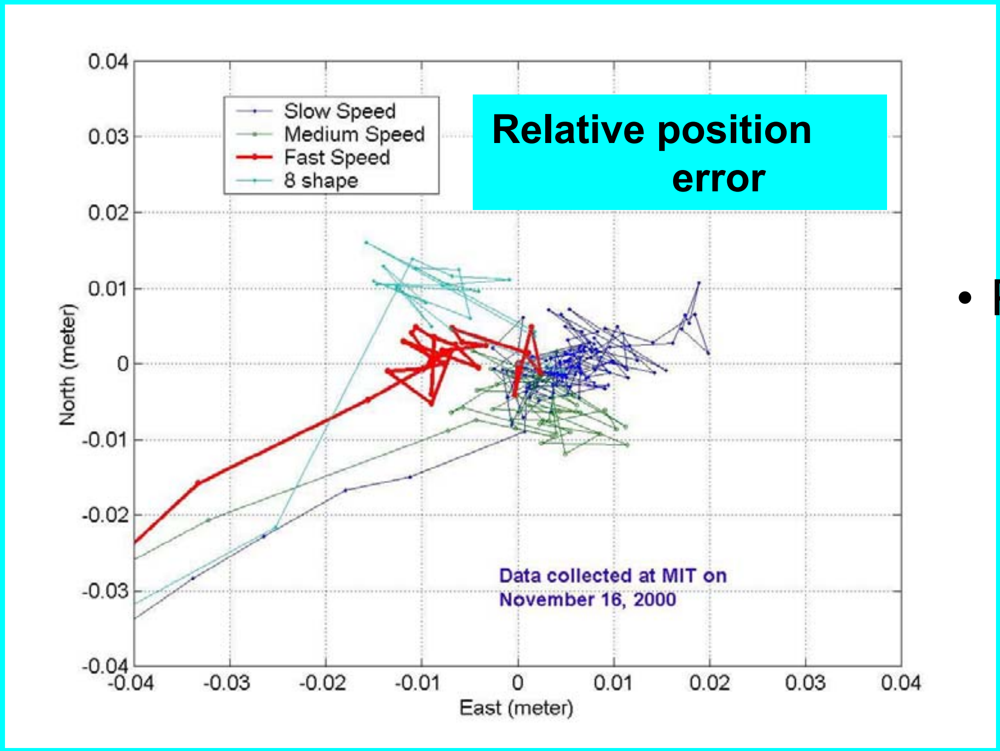


- Two 2 GPS antennas were mounted on the car to form a single baseline
- Data-Linc Group (SRM6000) Modem antenna also attached to roll bar
  - Real-time communication with ground station

MIT Run Results

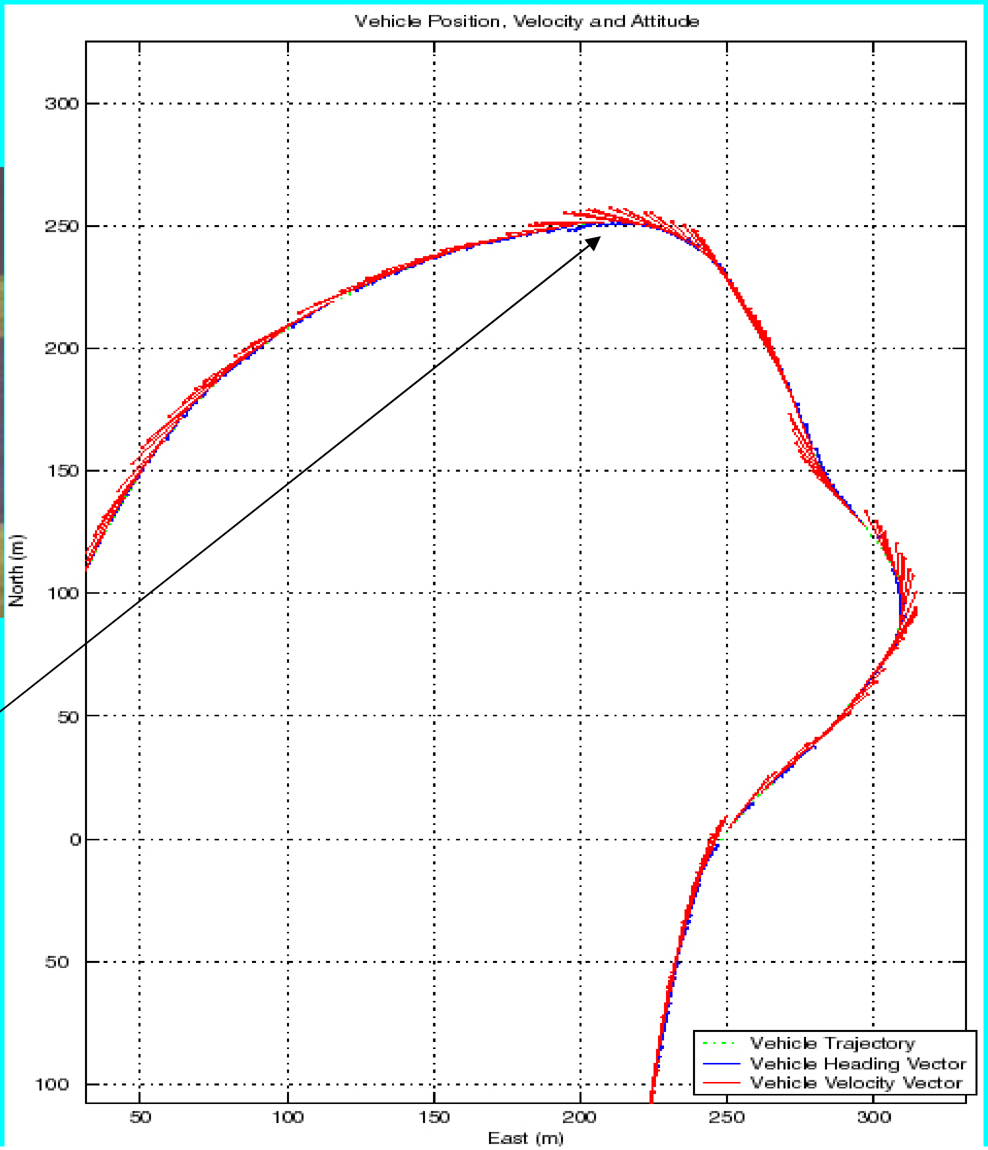


Typical Performance



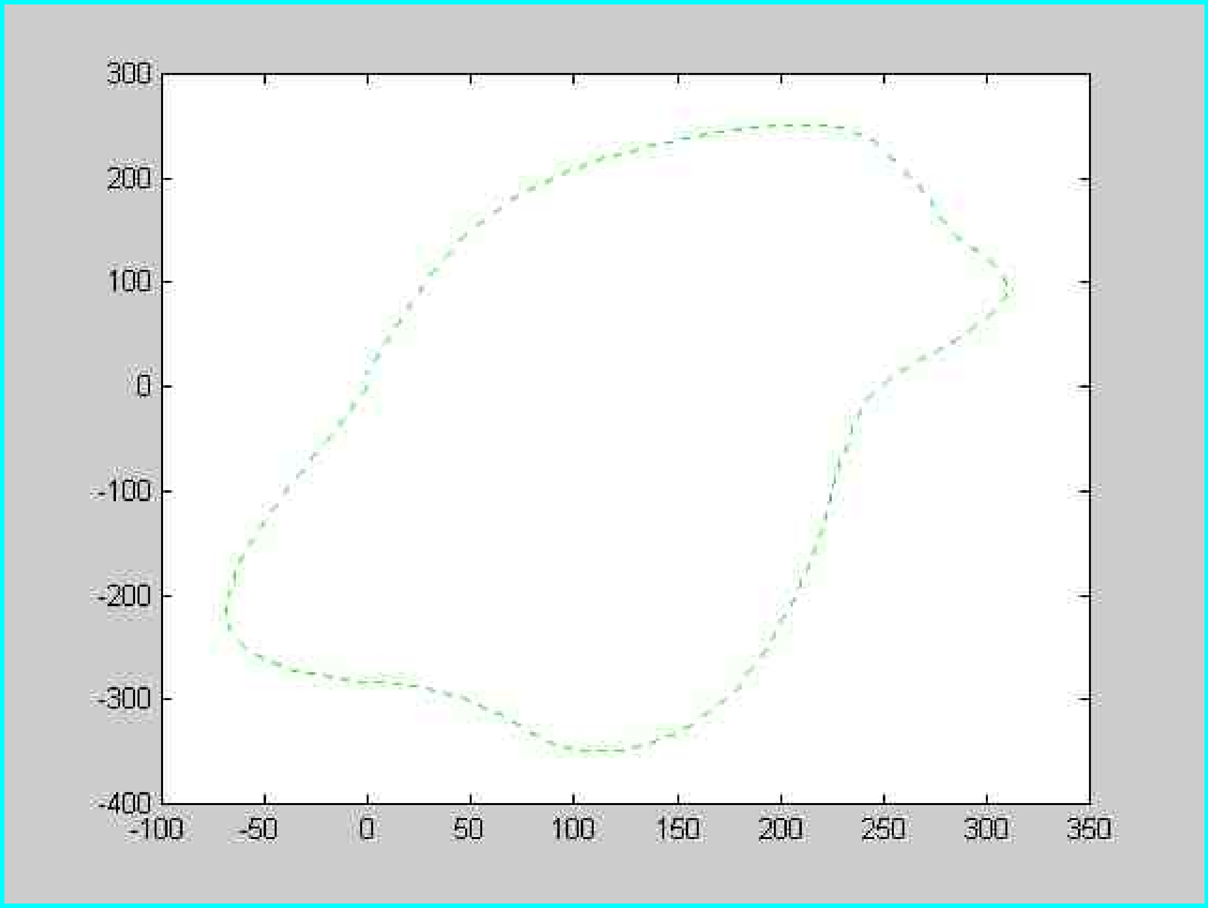
- Precise state determination
  - 2 - 5 cm position error
  - 1 - 2 cm/s velocity error
  - 1 - 2 degrees heading
  - @ 5 - 10 Hz

Track Results - Slip Measurements

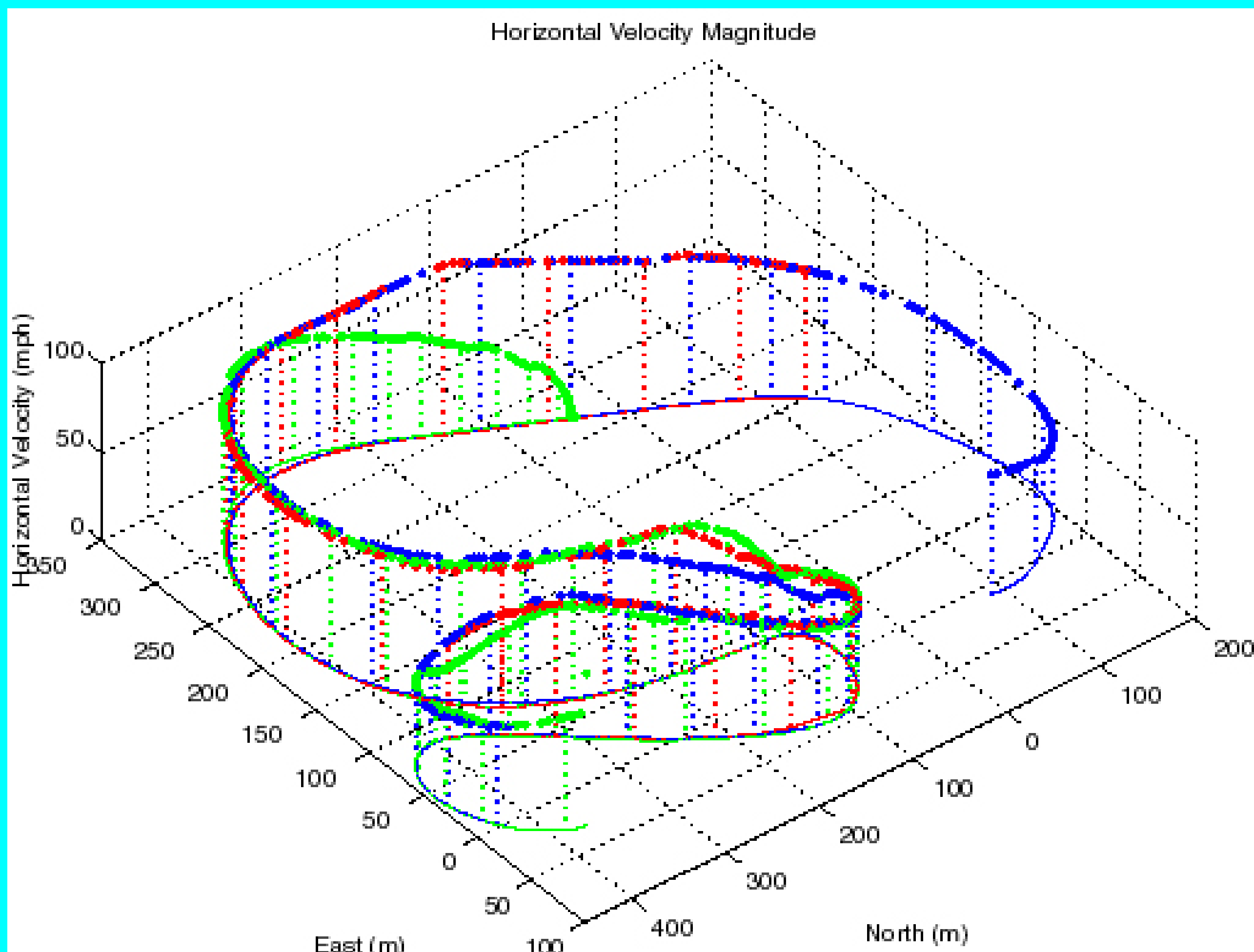


- Car **heading** and **velocity** vectors not aligned

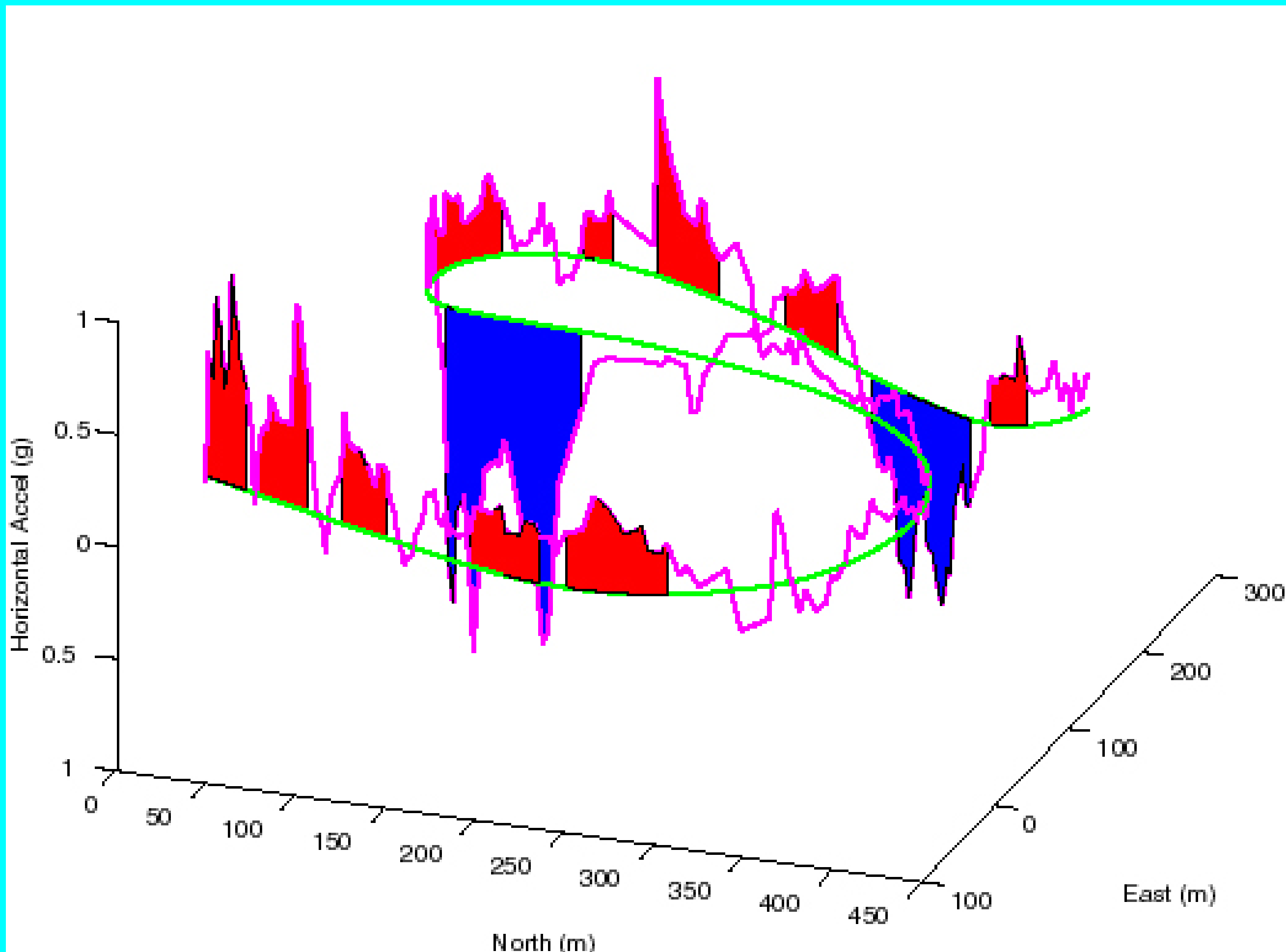
Track Results -Slip Measurements



Comparative Lap Results



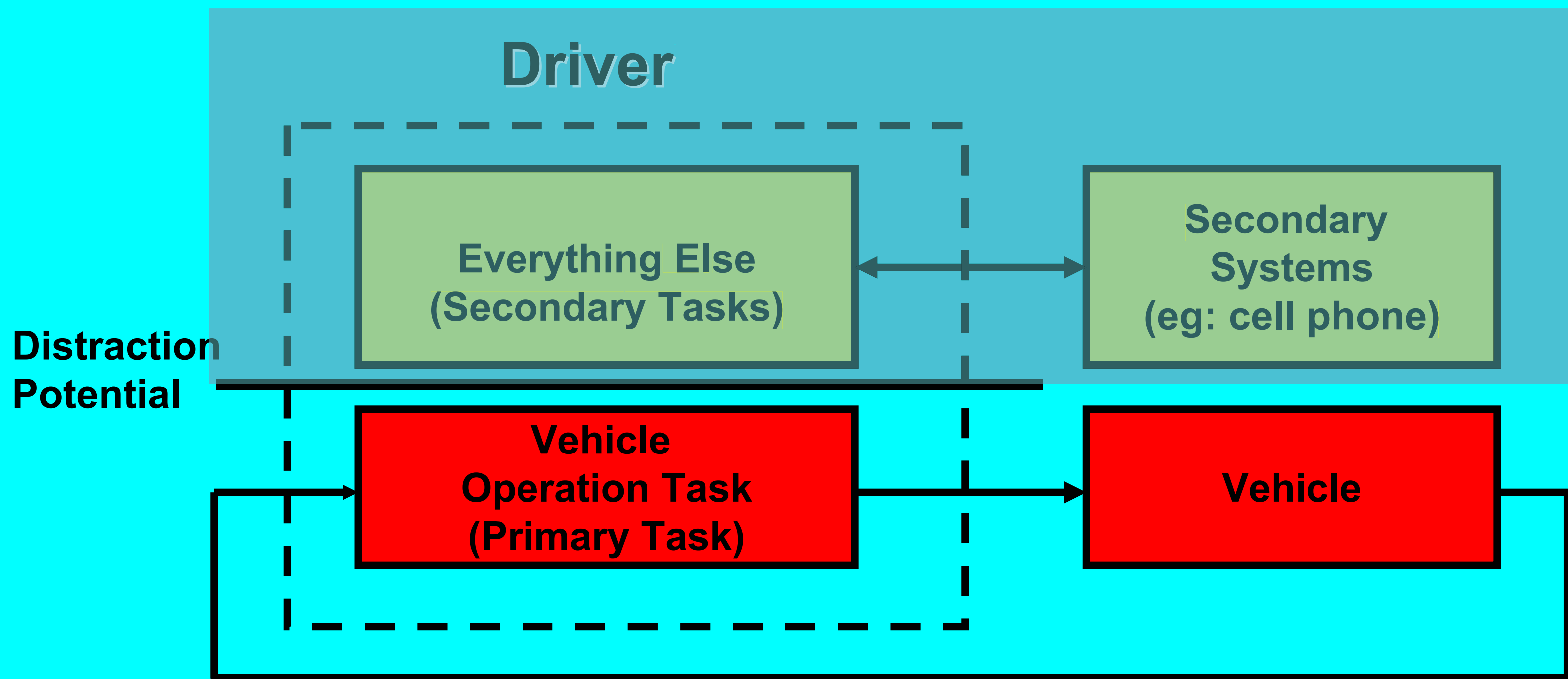
Acceleration vs Position



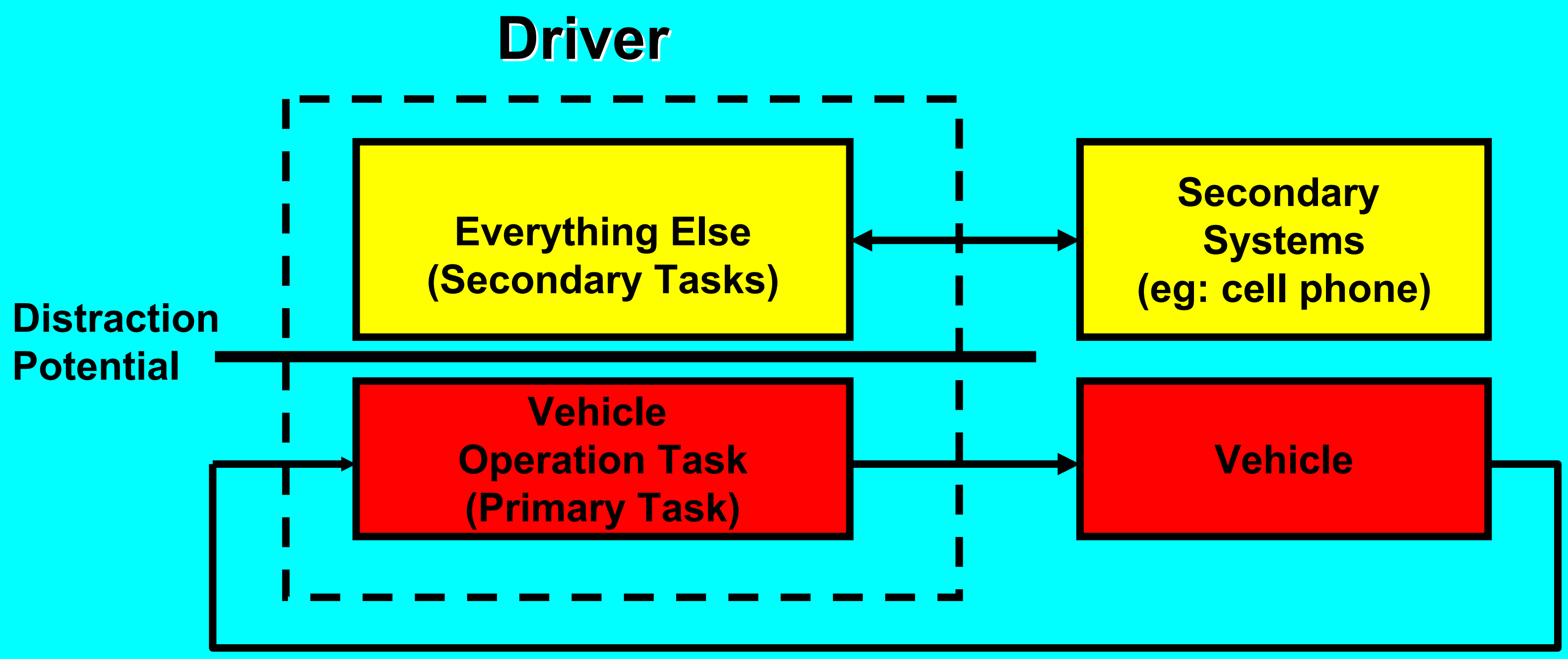
“Human Centered” Information Requirements Analysis

- Integrated Human Centered Systems Approach
- “Semi-Structured” Decision Theory
- Driver Distraction Analysis

Driving Task Definition



Primary Task Analysis

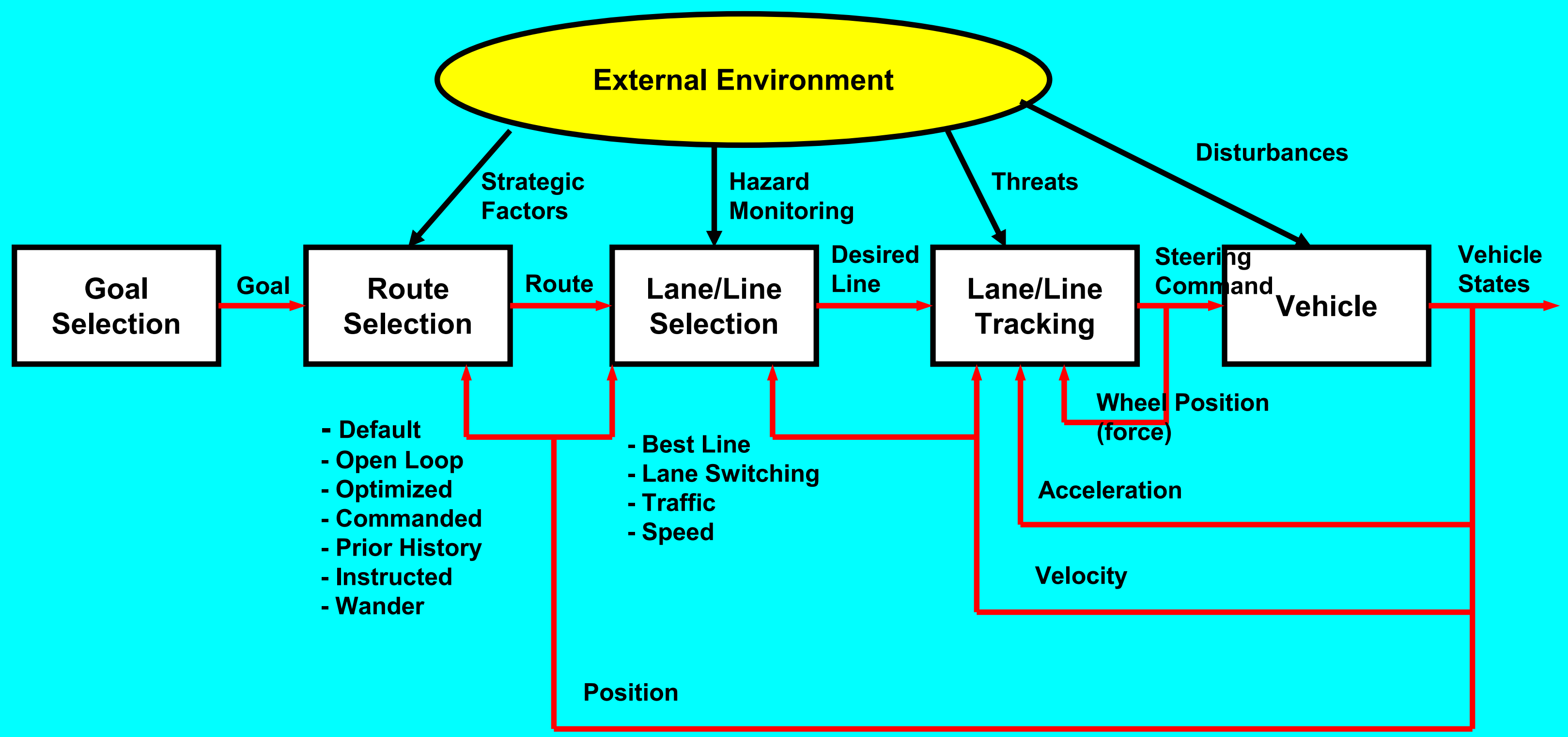


Vehicle Operation Tasks

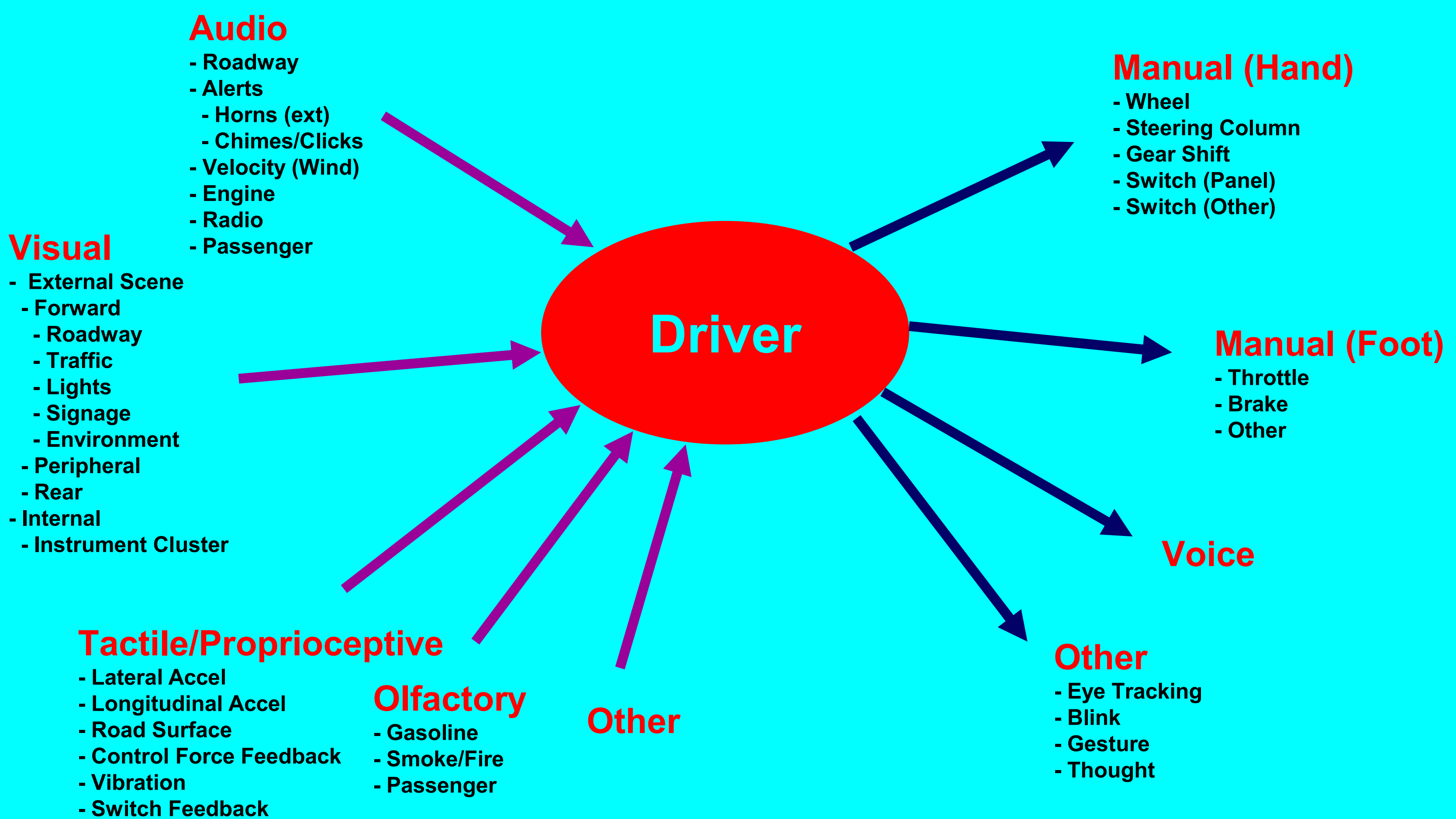
- **Vehicle control tasks [skill based]**
  - *Lateral control (steering)*
  - *Longitudinal control (accel., braking)*
- **Tactical decisions [rule based]**
  - *Maneuvering*
  - *Systems management*
- **Strategic decisions [knowledge based]**
  - *Route selection*
  - *Goal management*
- **Monitoring [skill, rule, knowledge]**
  - *Situation awareness*

[Rasmussen: Skill Rule Knowledge Hierarchy]

Lateral Tracking Loop



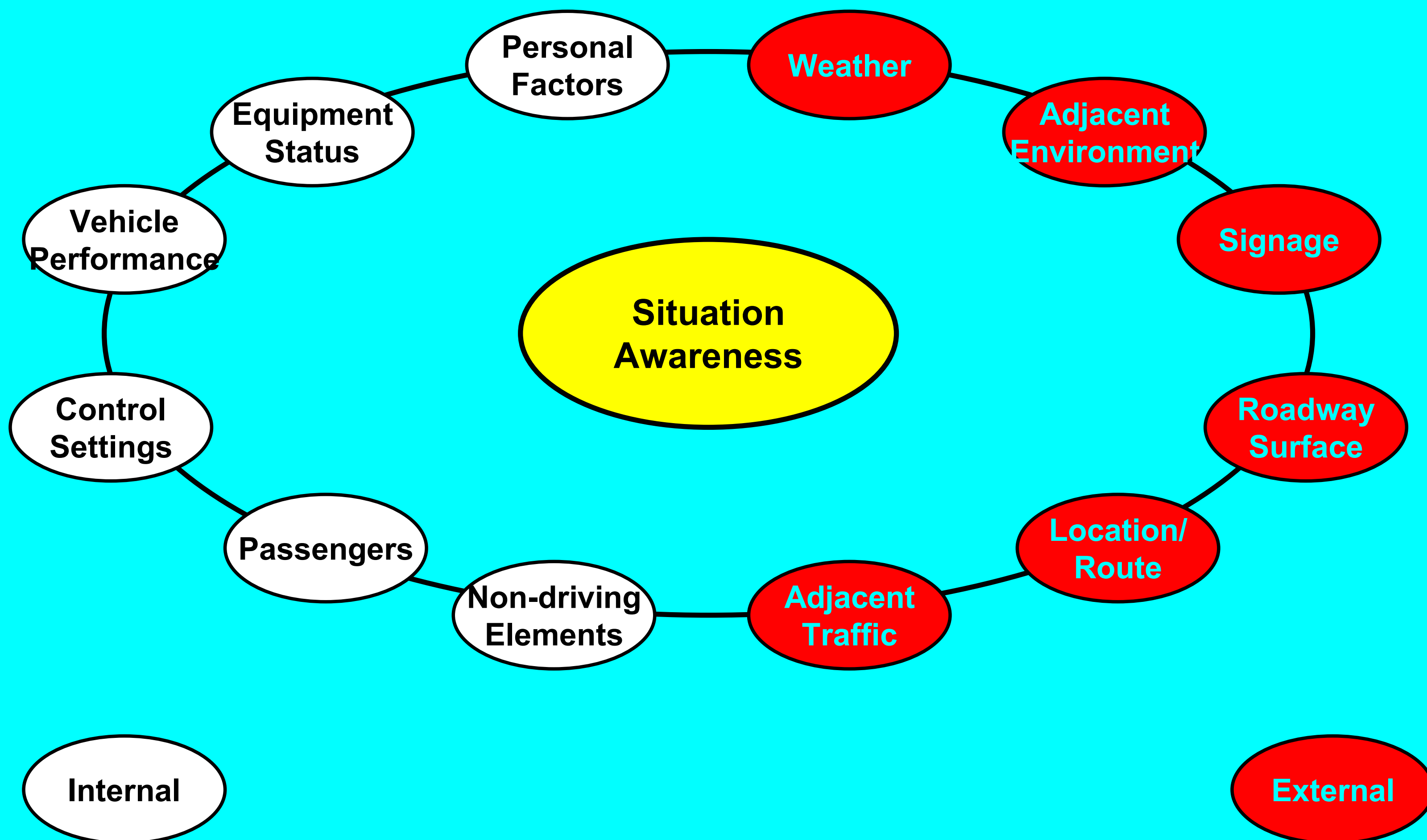
Driver Input/Output Modes



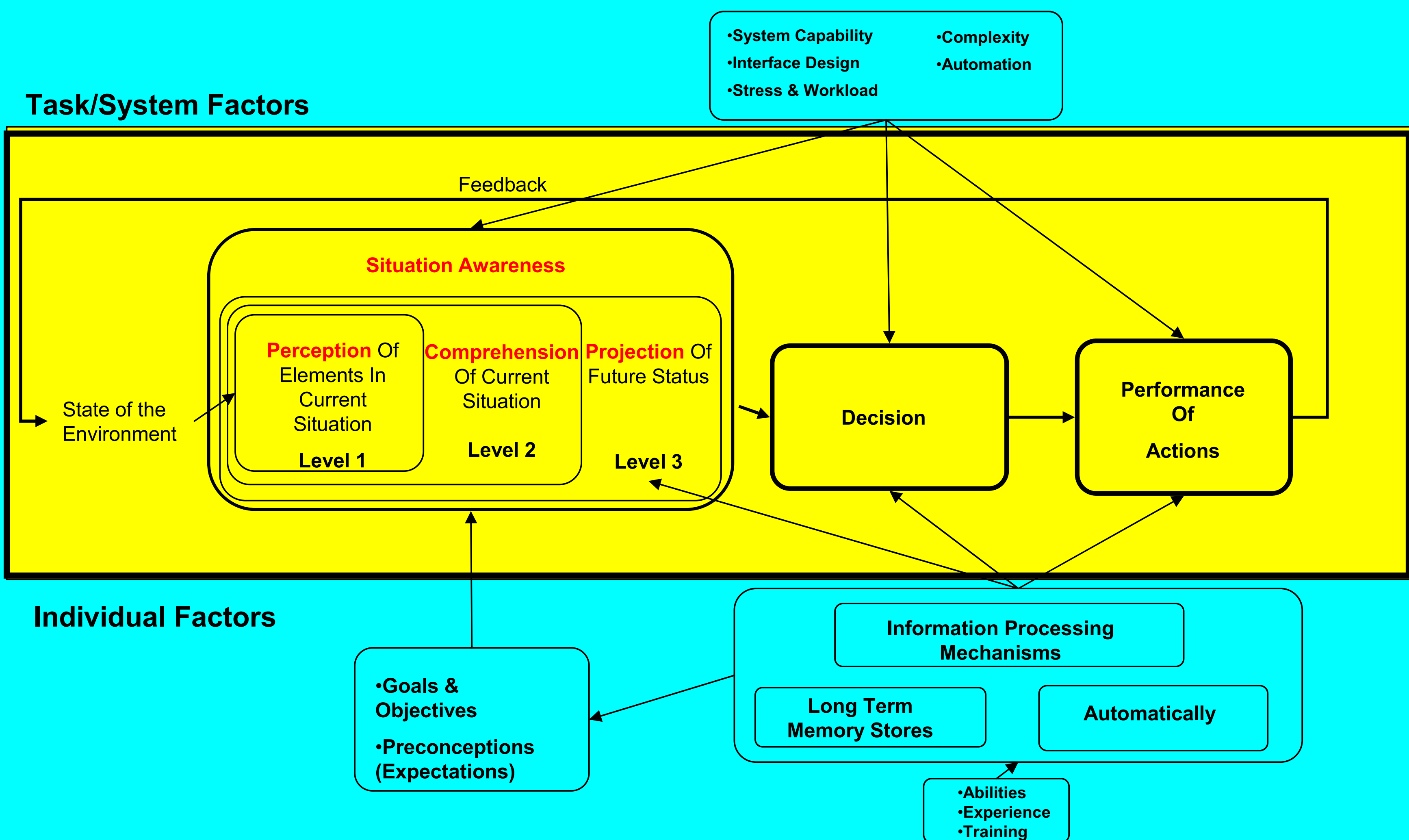
“Situation Awareness”

- *Term originally defined for air combat*
- *Working Definition: Sufficiently detailed mental picture of the vehicle and environment (i.e. world model) to allow the operator to make well-informed (i.e., conditionally correct) decisions.*

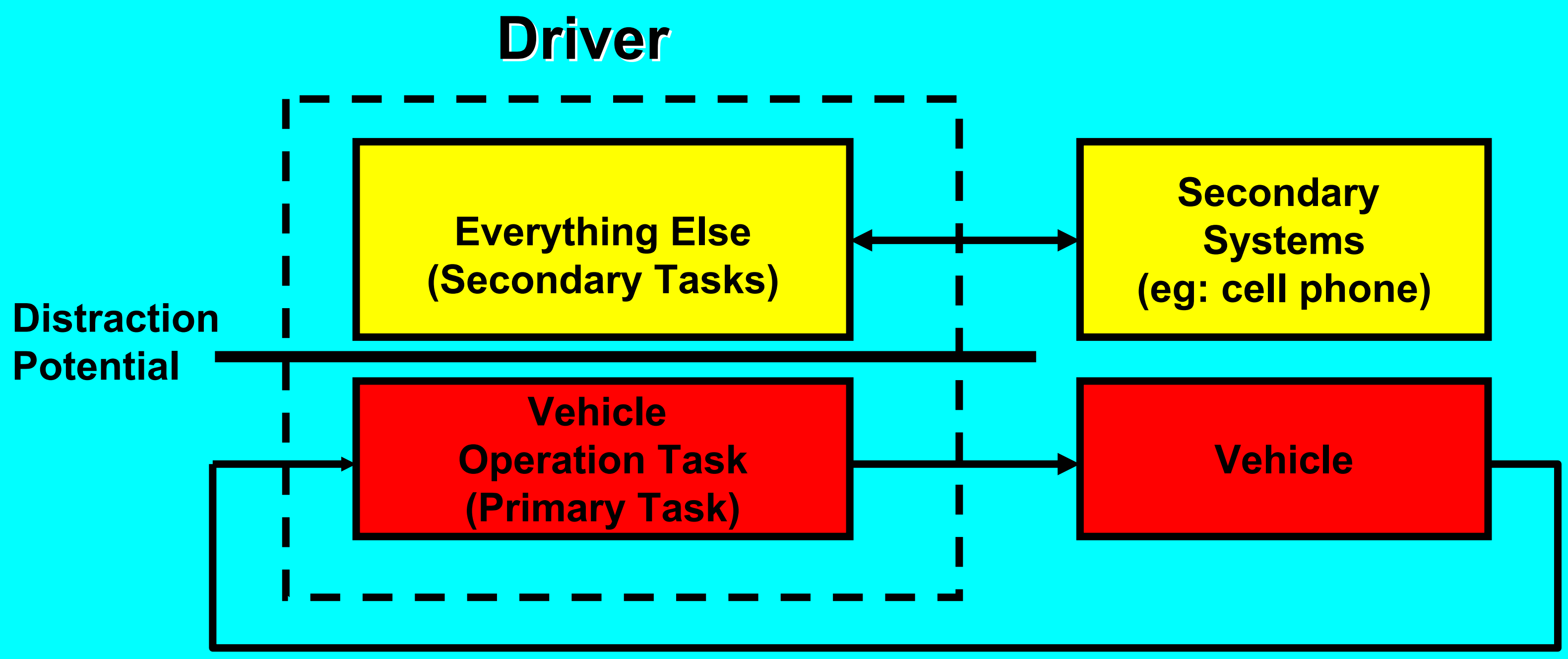
Driver Situation Awareness Components



Endsley Situation Awareness Model



Driving Task Definition



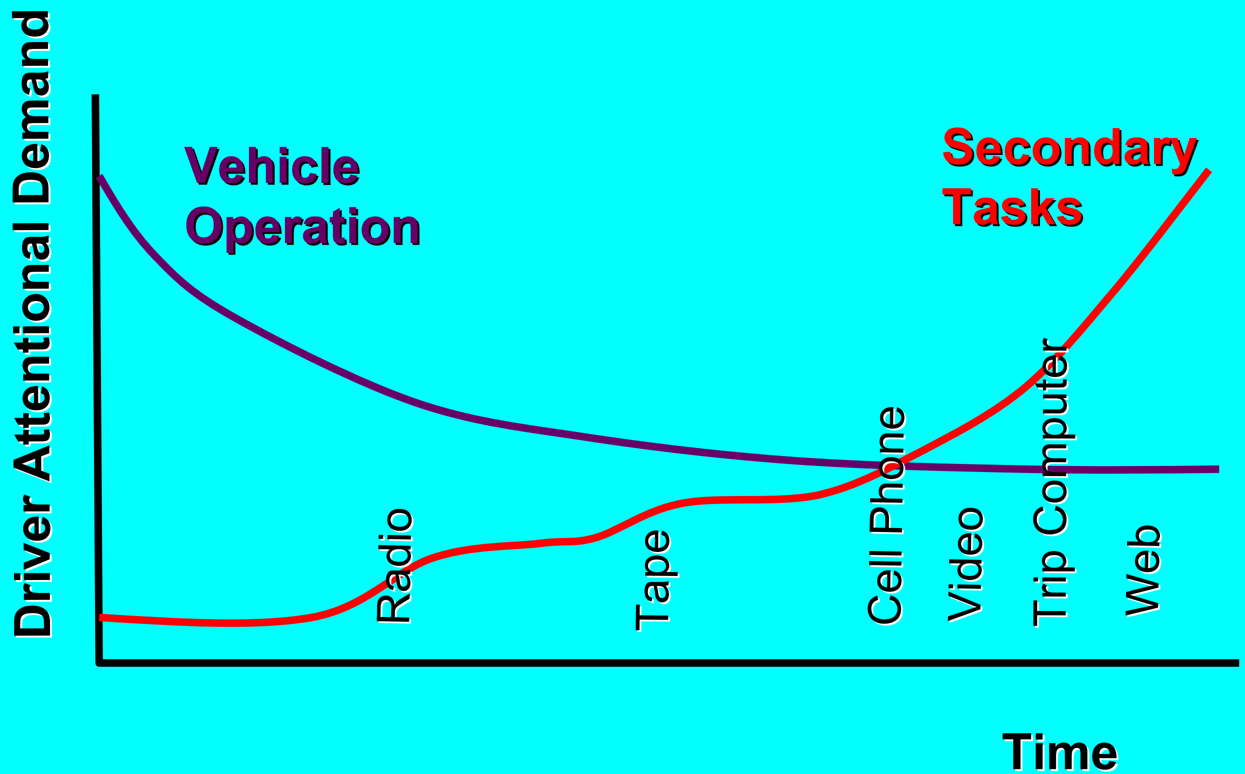
Interaction Metaphors

- Car as *home*
- Car as *kitchen*
- Car as *bathroom*
- Car as *bedroom*
- Car as *music room*
- Car as *playroom*
- Car as *entertainment ctr*
- Car as *toolbox*
- Car as *closet*

- Car as *office*
- Car as *comm center*

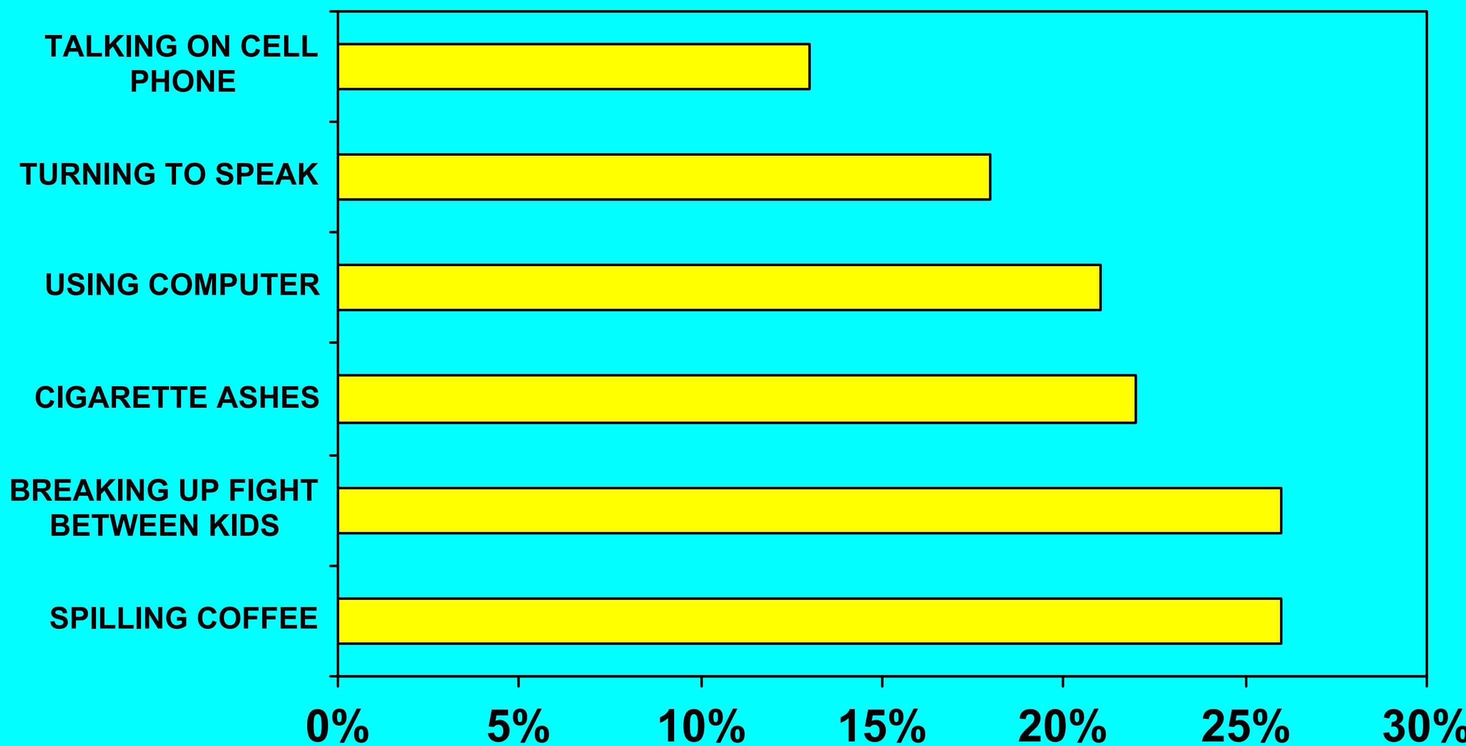
- Car as *image statement*
- Car as *clothing*
- Car as *jewelry*
- Car as *sports equipment*
- Car as *safe space*
- Car as *cocoon*

Trends in Driver Attentional Demand



Time Spent in Vehicles (US)
- Average 350 hrs/yr/person
- 500 Million hrs/week

76% of Drivers Report Activities Have "Caused/Nearly Caused" an Accident



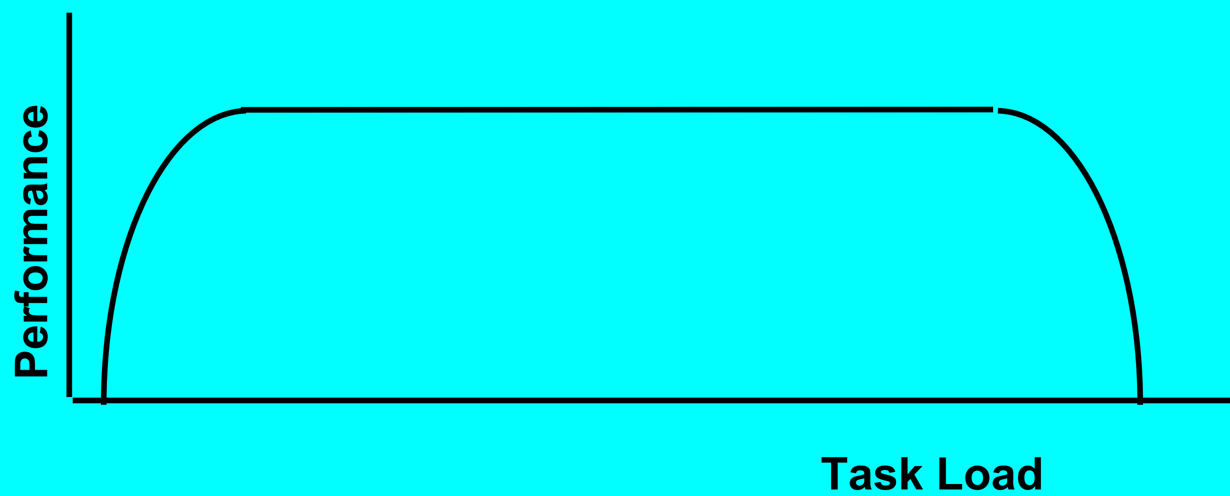
Source: Opinion Research Corp Interviews, Time5/8/00 (N=1016)

Concerns Regarding High Secondary Task Loads

- Growing Evidence and Public Perception of Safety Problem
- Cell Phone use in US
  - 115-120 Million Active Cell Phones
  - 50-70% Use in Vehicles
  - 3.9% of Drivers Using (Daylight Hours)
- NE Journal of Medicine Estimate
  - 4 fold increase in collision risk using cell phone
- NHTSA Estimates
  - 1.2 Million Accidents (25-30%) caused by Distracted Driver
    - Not limited to cell phones

- *Note: These effects may be latent in normal operations and may only manifest in non-normal or emergency situations*

Typical Performance vs. Task Load Curve



Distraction Components

- **Manual**
  - *Inability or delay in operation of vehicle control*
  - *Hands occupied or out of position (cell phone)*
- **Visual**
  - *Head Down Problems*
  - *Visual Accommodation*
  - *Visual Clutter*
  - *Visual Compulsion*
- **Cognitive**
  - *Lack of cognitive engagement with primary Task*
  - *Latency in mental context shifts*
  - *Multi-tasking capabilities*
  - *Prioritization*
- **Emotional**
- *High Individual Variability in Multi-Tasking Capability*

Distraction Data Sources

- Controlled Experiments
  - Vary Secondary Task Load (Independent Variable)
    - Visual
    - Cognitive
  - Measure
    - Performance
    - Response to Disturbance
    - Situation Awareness
  - Need to Increase Task Loading to Saturation
  - Need to Include Unanticipated Events
  - Need Lowest Common Denominator Population
- Field Data
  - Event Recorders
  - Cell Phone Triggered
- Subjective Survey Data

Controlled Experiment Issues (1)

- Simulator Testing
  - Controlled Scenarios +
  - Safe to go to Task Saturation
  - Face and Cue Validity Issues -
  - Simulator Sickness -
  - Cost -
- Dual Control Vehicle Testing (Test Track)
  - Good Validity +
  - Safety Issues at Task Saturation -
  - Cost +

Controlled Experiment Issues (2)

- Variability in Primary and Secondary Tasking
  - How do you measure Secondary Task Load?
  - How do you control Secondary Task Load?
- Performance Measures
  - *Tracking*
  - *Reaction Time*
  - *Side Task Performance*
- Subjective Workload Measures
- Situation Awareness Measures
  - *Testable Response Method*

Simulator Studies of Driver Cognitive Distraction Caused by Cell Phone Use

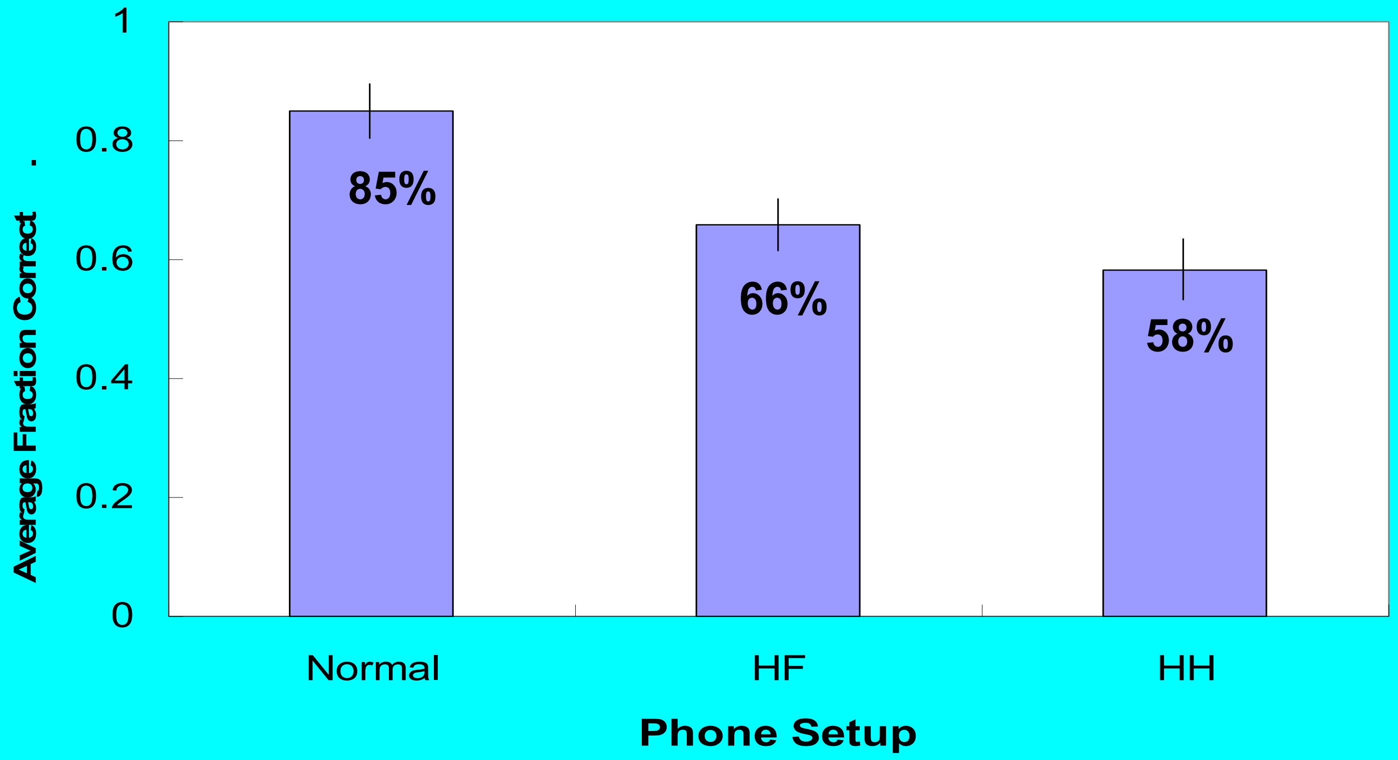
- **Independent Variables**
  - Cognitive Loading
  - Hands free/Hands Fixed
- **Dependant Variables**
  - Situation Awareness
  - Reaction Time
  - Tracking

MIT Age Lab Simulator

Cognitive Loading Levels

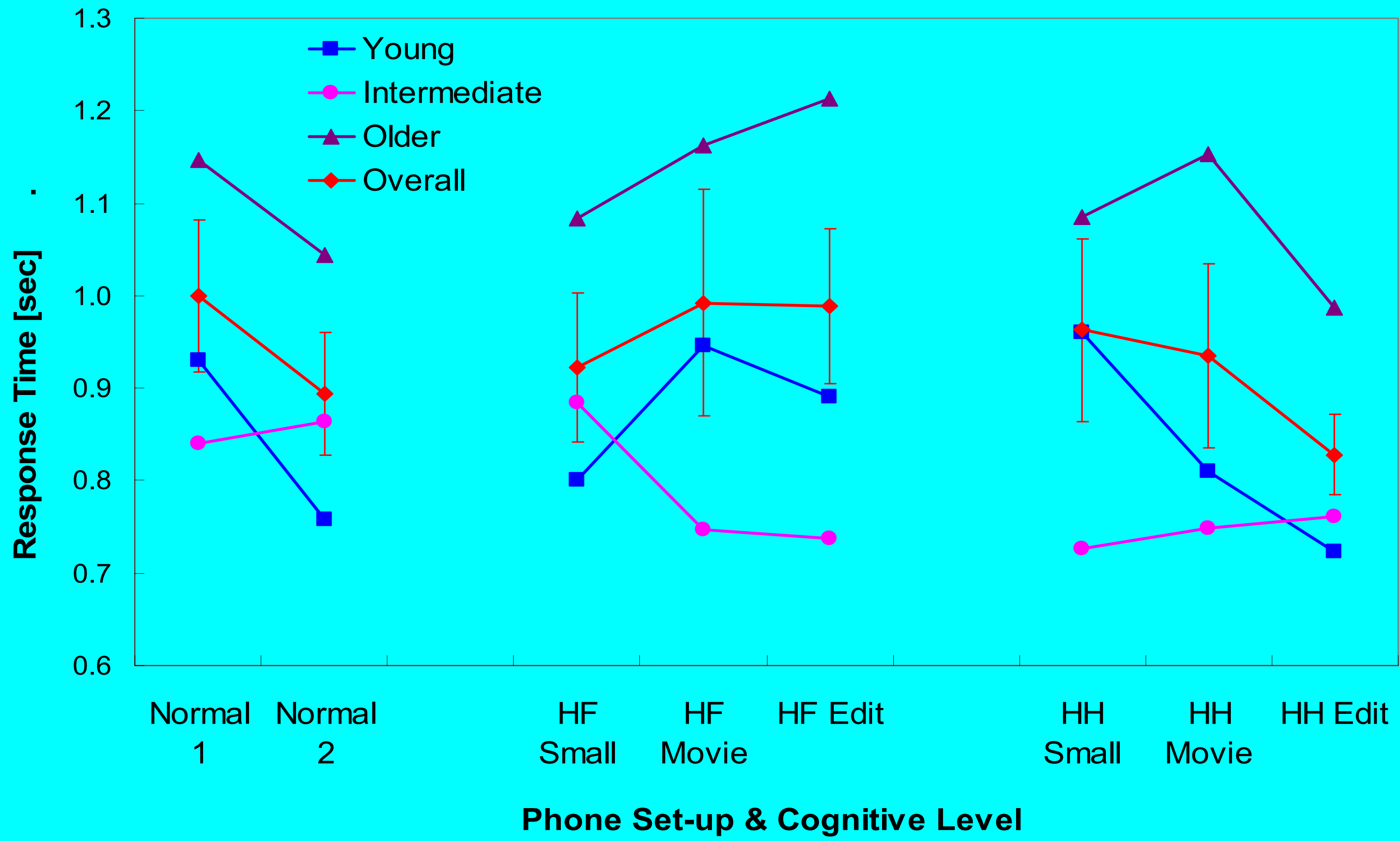
- **Low**
  - *Small talk*
- **Medium**
  - *Discuss movie/opera/ballet plot-line*
- **High**
  - *Edit document by phone*

Results: Situational Awareness



- Significant reduction in SA with Cell Phone Use
- No significant difference between HF& HH

Stop Sign Response Time Results by Age Group



- Significant effect of Age
- No significant effect of Cell Phone Use

Approaches to Enhancing Focus in the Information Rich Cockpit

- *Heads-Up Operation*
  - Parsing operating logic
  - Glance Display Designs (< 1 sec)
  - Tactile input devices
- *Voice Input-Output*
  - not a Panacea
- *Prioritization Systems*
  - Intelligent Situation Assessment
  - Interruption "Stand-by" Architecture Example
    - ***Communications***
    - ***Information Systems***
    - ***Non Critical Warnings***

300-MIT Testbed

- Collaboration
  - MIT Media Lab CC++
  - Motorola
  - DiamlerChrysler
- Highly Instrumented Platform
  - External Environment
  - Internal Environment
  - Vehicle States
  - Driver Cognitive and Emotional States
- Prototype Platform
- Platform - Chrysler 300M

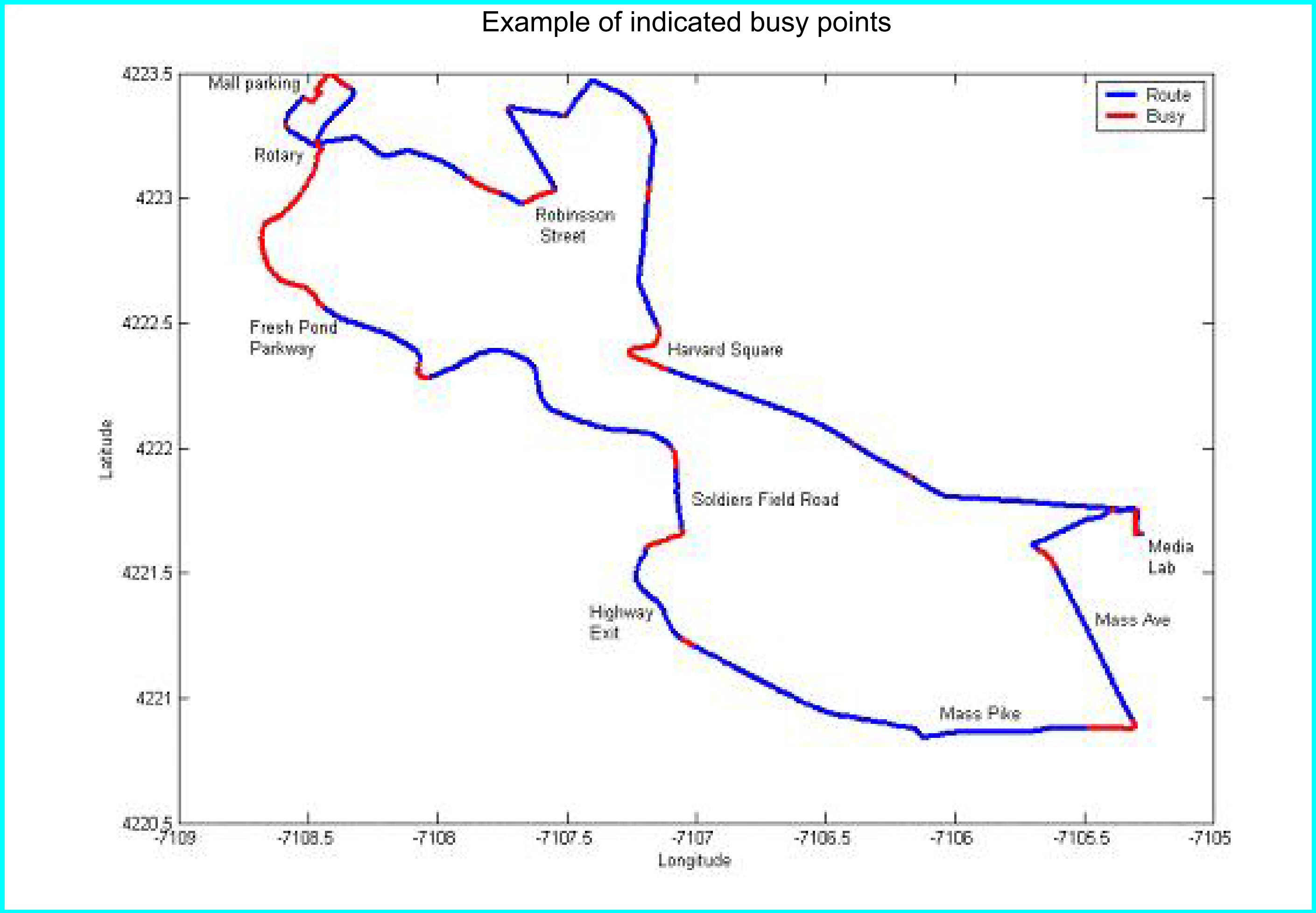
“Standby” System

Issue: Criteria for automatic “Standby Status

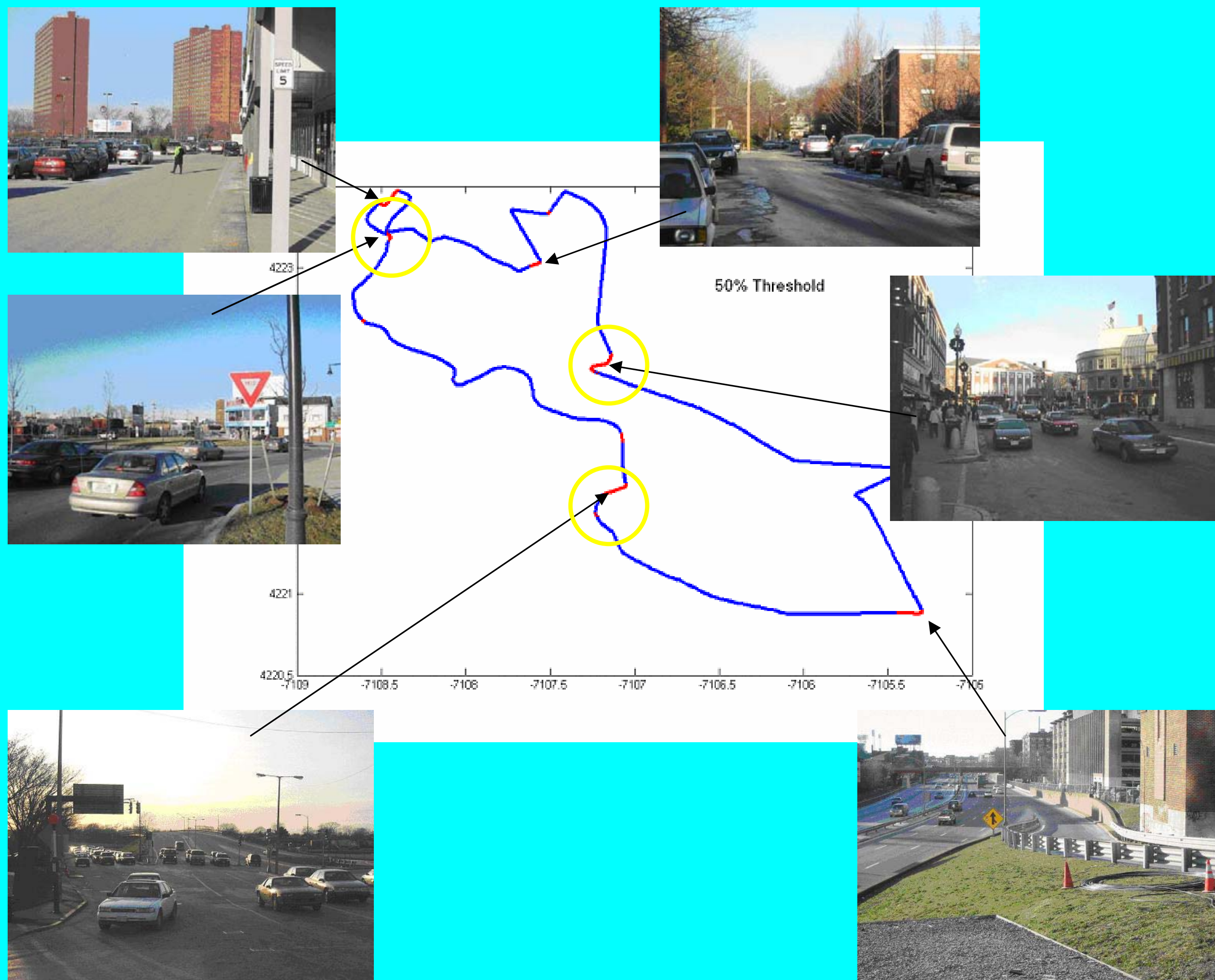
300M Experiment to Determine Indicators of Driver “Busy” States

- 20+ Subjects Drove Challenging Trajectory in Boston-Cambridge Area in 300M Instrumented Vehicle
- Subjects indicated transitions between “Busy” and “non-Busy” States
- Attempted Correlation with Observable States

Example “Busy” State Data



Good Correlation with Specific Locations



Merge onto Major Roadway

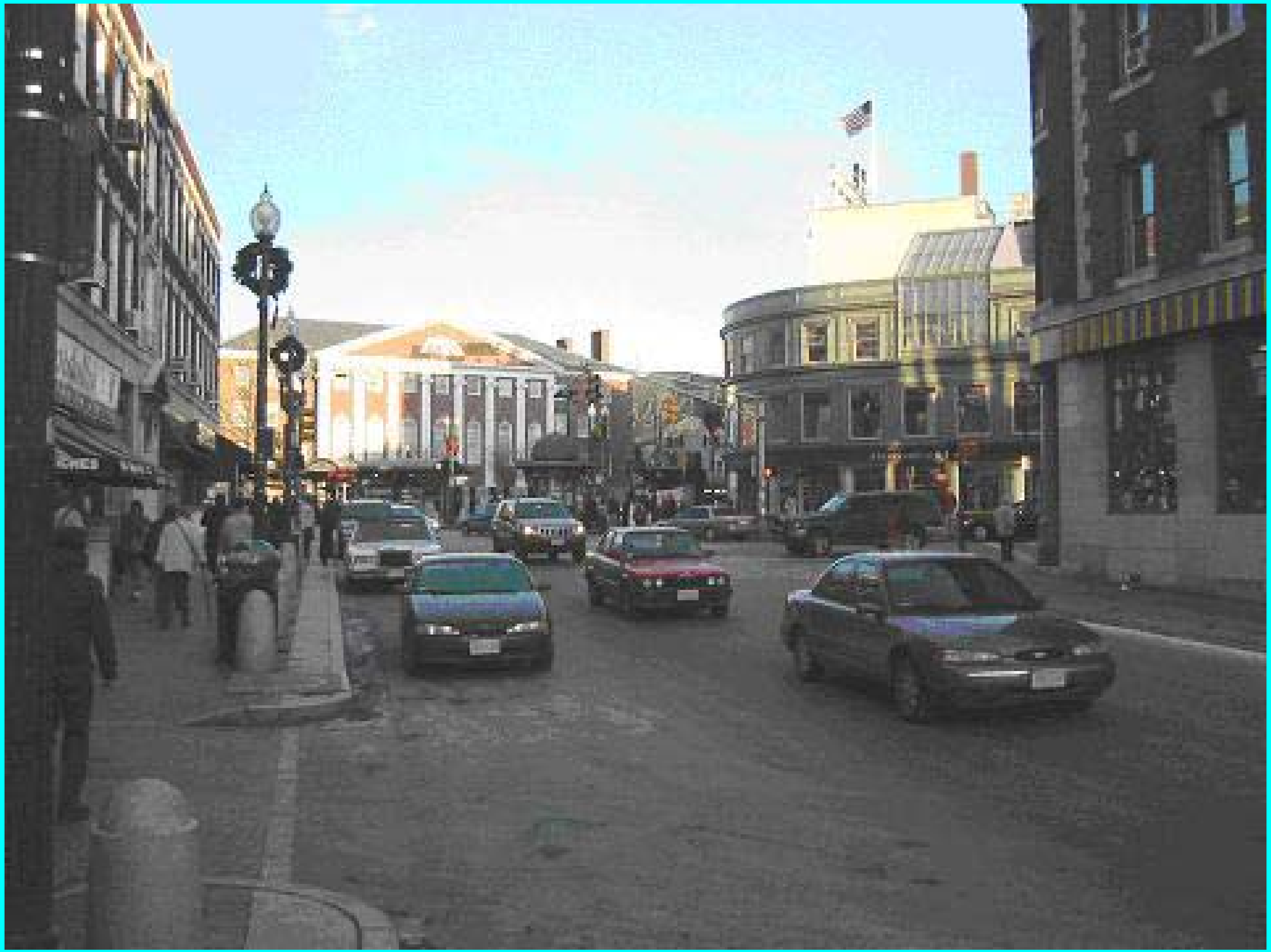
Complicated Intersection With Merging Traffic

Rotary

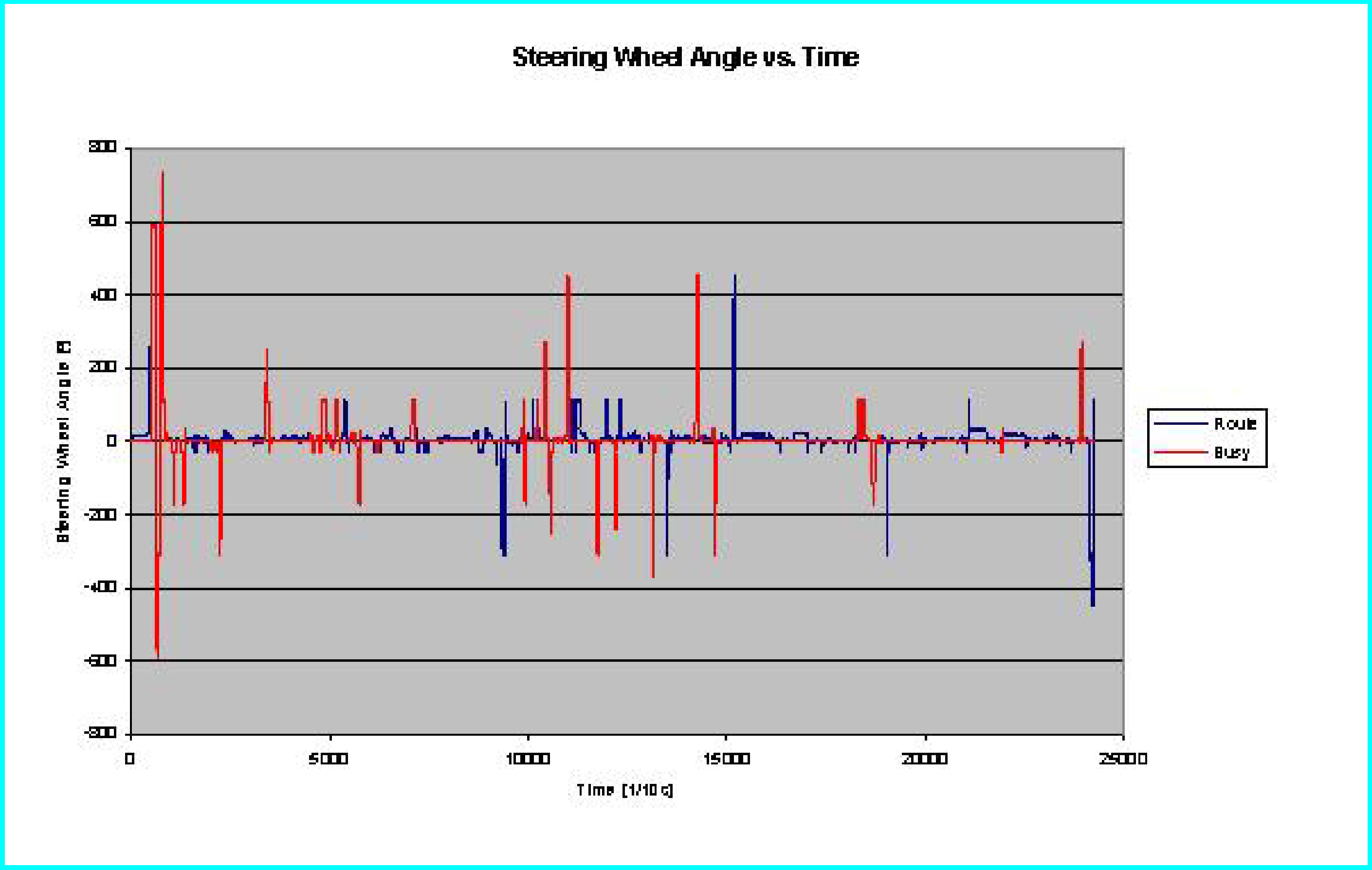
Parking Lot with Pedestrians

Narrow Side Street

Complex Urban Location "Harvard Square"



Weak Correlation with Simple Dynamic States



Results Consistent With Subjective Reporting of High Workload Tasks

- Merge points
- Pedestrians
- Rotaries
- Narrow Streets
- Busy Intersections
- Unfamiliar Locations
  - Searching for Locations
- Construction Zones
- Poor Weather Conditions

- **Potential for Adaptive Learning Algorithims with Multi-Attribute Correlations**

Approaches to Enhancing Focus in the Information Rich Cockpit (cont.)

- *Enhanced Perception*
  - IR/MMW Radar (eg Cadillac Night Vision System)
  - Multidimensional video (“super mirror”)
  - Prioritized audio
- *Situation Awareness Displays*
  - Datalink
- *Alerting Systems*
- *Advanced Internal Diagnostics Architectures*
  - “Master Caution”
- *Driver Condition Monitoring*
- *External Visual Systems*
  - Active Signage

Enhanced Vision
Synthetic Vision

Enhanced Vision | **Synthetic Vision**

- **Goal is to increase safety and capacity**
- **Challenge is to ensure no adverse effects are created**

Boeing is investigating these technologies, including evaluating prototype systems on the 737 Technology Demonstrator in early 2002. While these technologies hold promise for increasing safety and potentially improving airport capacity, the designs must be approached carefully to ensure no harmful side effects are induced.

Enhanced Vision

Picture of the outside world created by real-time weather and darkness penetrating on-board sensors (eg. Cameras, FLIR, MMW radar, and weather radar).

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GPS Progressive Route Guidance

- Progressive Turn Guidance
- Current Limitations
  - Complex Intersections
  - Database Resolution
  - Database Structure
  - C/A Code Precision
  - Limited command set
- Potential to degrade SA
  - Dependency
  - Not robust to interruptions/errors
  - Head Down
  - Lack of "Naturalistic Interface"
    - Kamla Topsey & Kate Zimmerman Expt.

Naturalistic Direction Study

- 13 Subjects: Directions categorized
- Most common types:
  - Street names and route signs 26%
  - Left/right turn indication 23%
  - Distance by Reference point
    - Stoplights/ Stop signs 21%
    - Landmarks 11%
- Least common types:
  - Distance by measurement 4%
  - Heading 1%

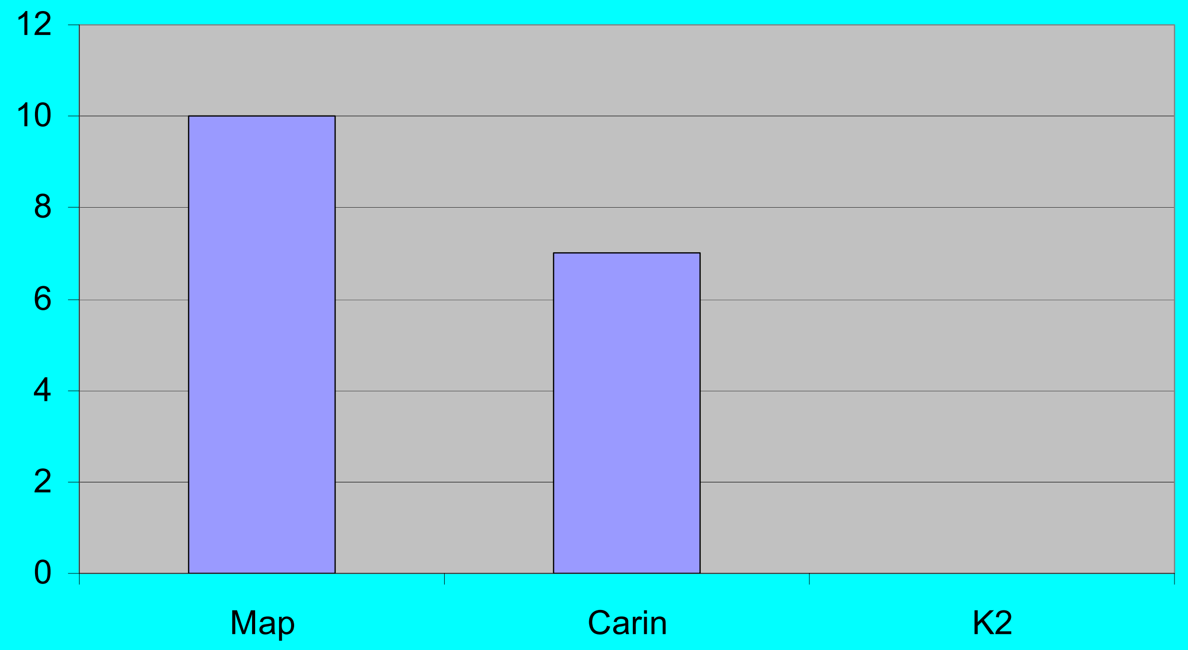
K2 Navigation System Prototype

- No visual demand: voice-based
- Syntax:
  - Reference + Action + Target
- Examples:
  - “At the next light, make a left onto the street between UNO’s Pizzeria and Fleet Bank”
  - “Just after the Star Market bear right onto Belmont St.”

Testing

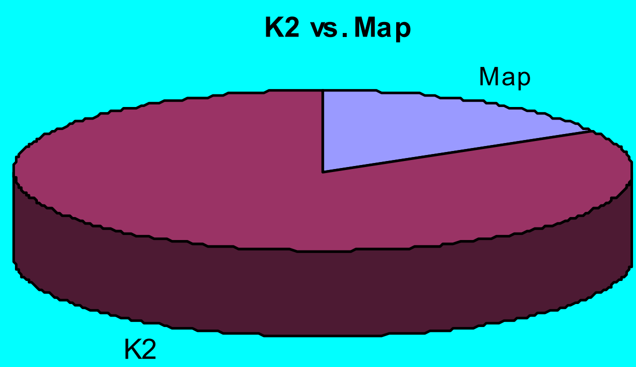
- Systems: Map, Carin, K2
- Routes:
  - Start from MIT
  - Use 15 commands
  - All include a rotary
- Subjects:
  - 2 males, 4 females
  - 20-21 years old
  - 4-5 years driving experience
  - Unfamiliar with driving in Boston area

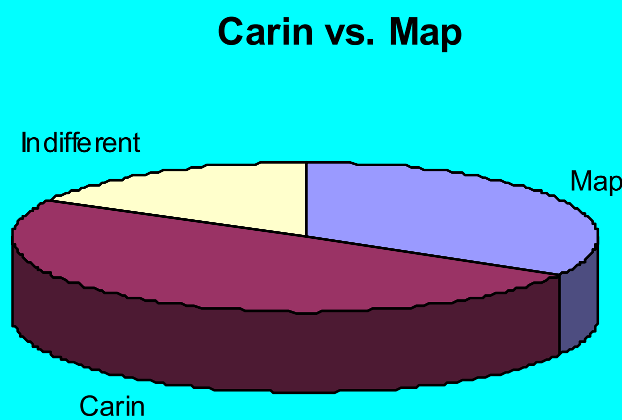
Results: Navigation Errors

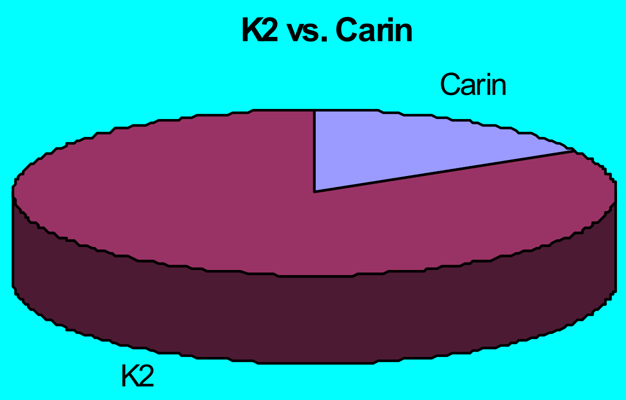


An error is defined as any deviation from the intended path.

Results: Comparative Ratings







Recently Developed Weather Datalink Products

ARNAV

Avidyne

Bendix/King FAA FISDL

Control Vision

Digital Cyclone

Echo Flight

Garmin

UPS – AirCell

Vigyan

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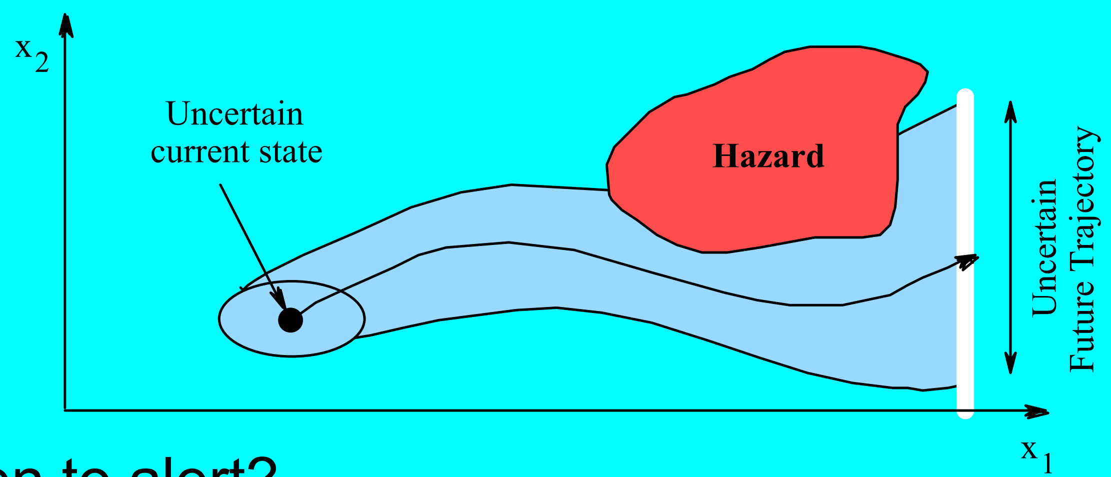
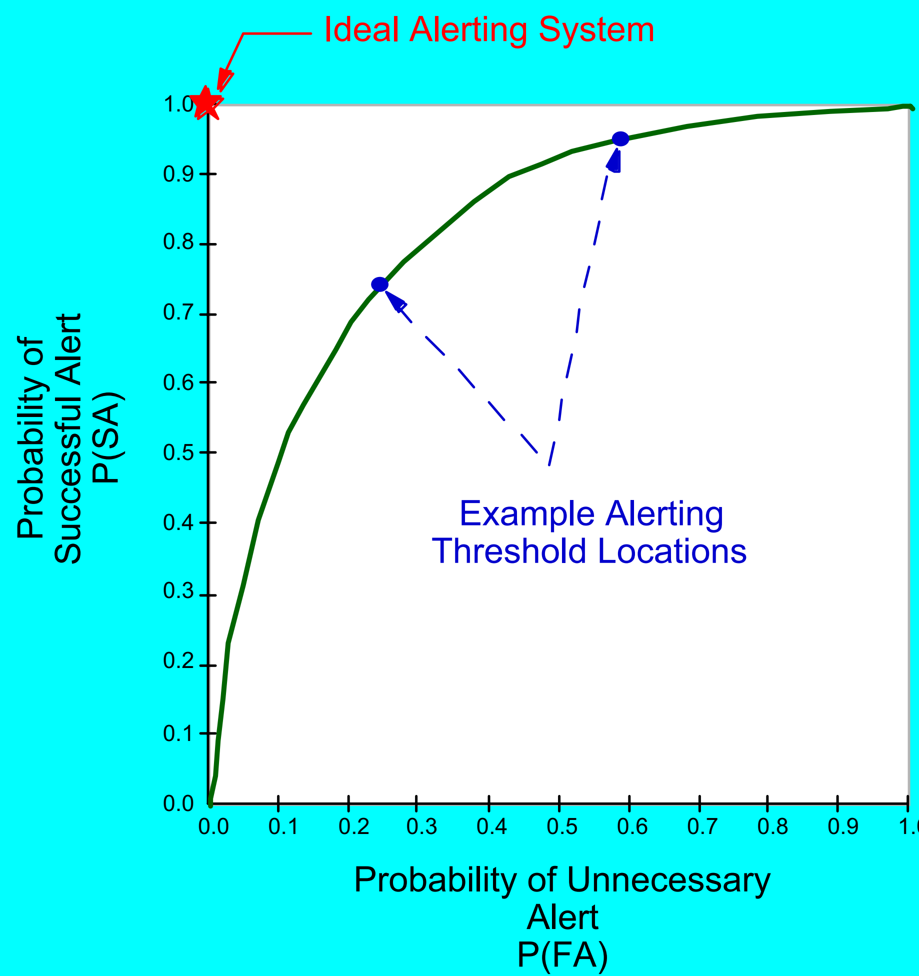
Fundamental Tradeoff in Alerting Decisions

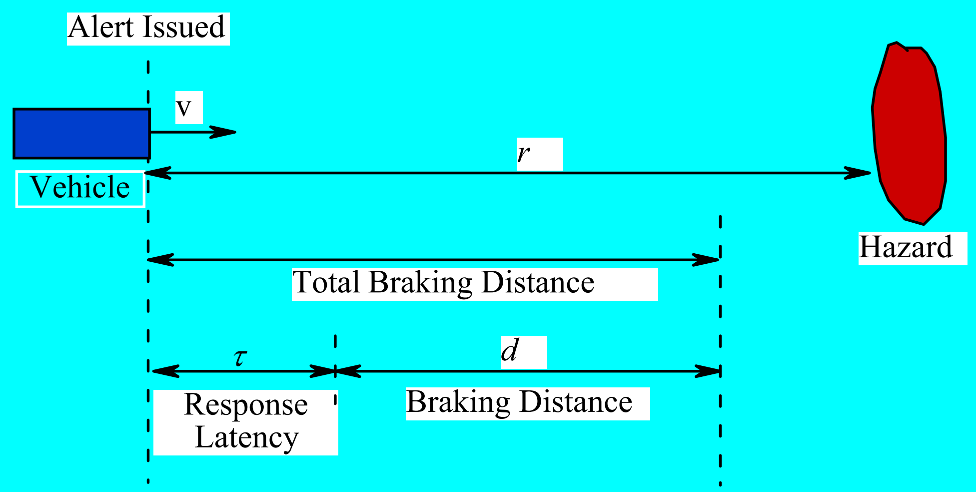


- When to alert?
  - Too early ⇒ Unnecessary Alert
    - Operator would have avoided hazard without alert
    - Leads to distrust of system, delayed response
  - Too late ⇒ Missed Detection
    - Incident occurs even with the alerting system
- Must balance Unnecessary Alerts and Missed Detections

System Operating Characteristic Curve



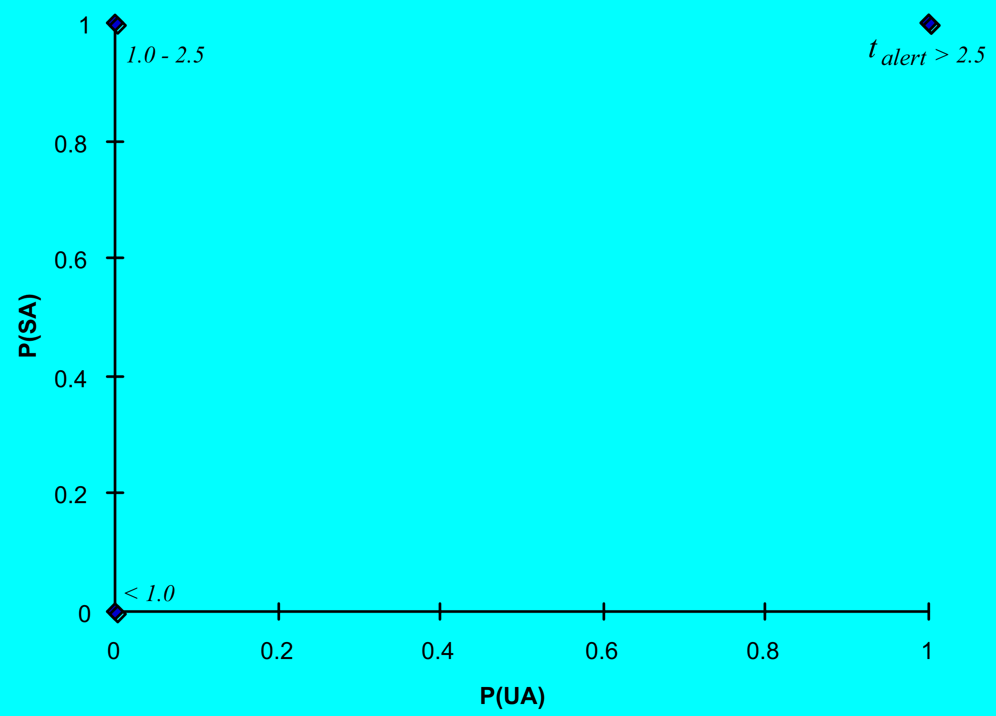
Kinematics



- Alert time: $t_{alert} = (r - d)/v$
  $t_{alert} = 0 \rightarrow$ braking must begin immediately
  $t_{alert} = \tau \rightarrow$ alert is issued τ seconds before braking is required

- Determine P(UA) and P(SA) as function of t_{alert}
- **V = 35 mph in following example**

Case 1: Perfect Sensors

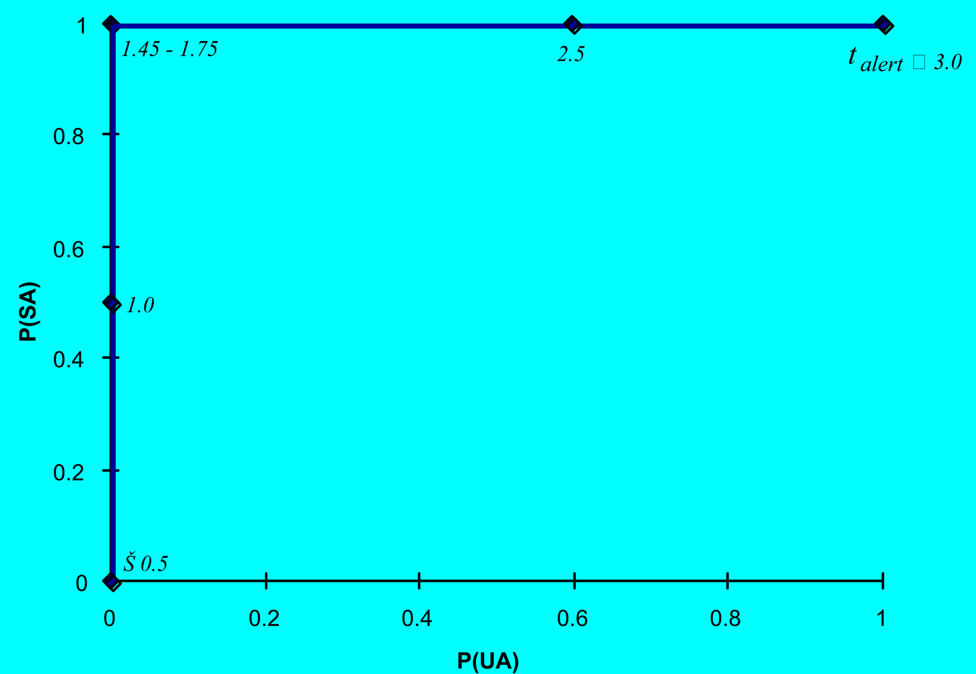


τ = 1.0 s, a = 1/2 g

Deterministic: probabilities are 0 or 1

Ideal performance achievable for t_{alert} between 1.0 - 2.5 s

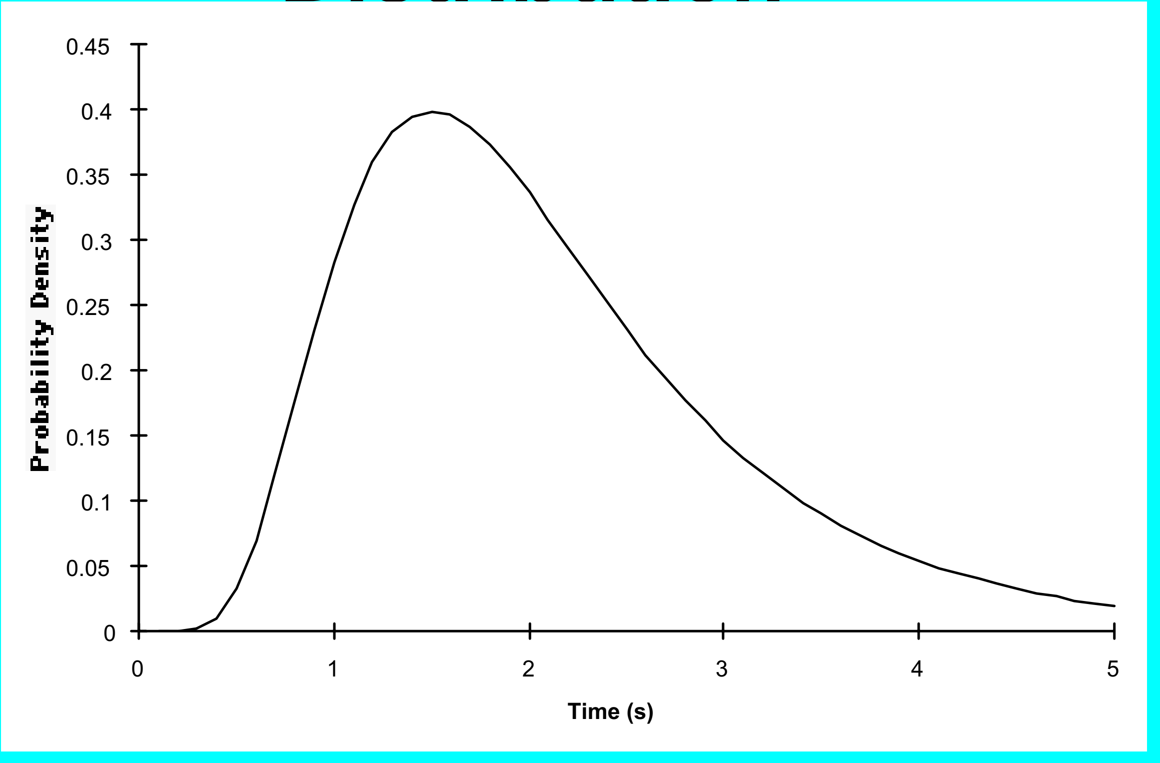
Case 2: Add Sensor Uncertainty



σ_r = 0.7 m σ_v = 0.4 m/s τ = 1.0 s a = 1/2 g

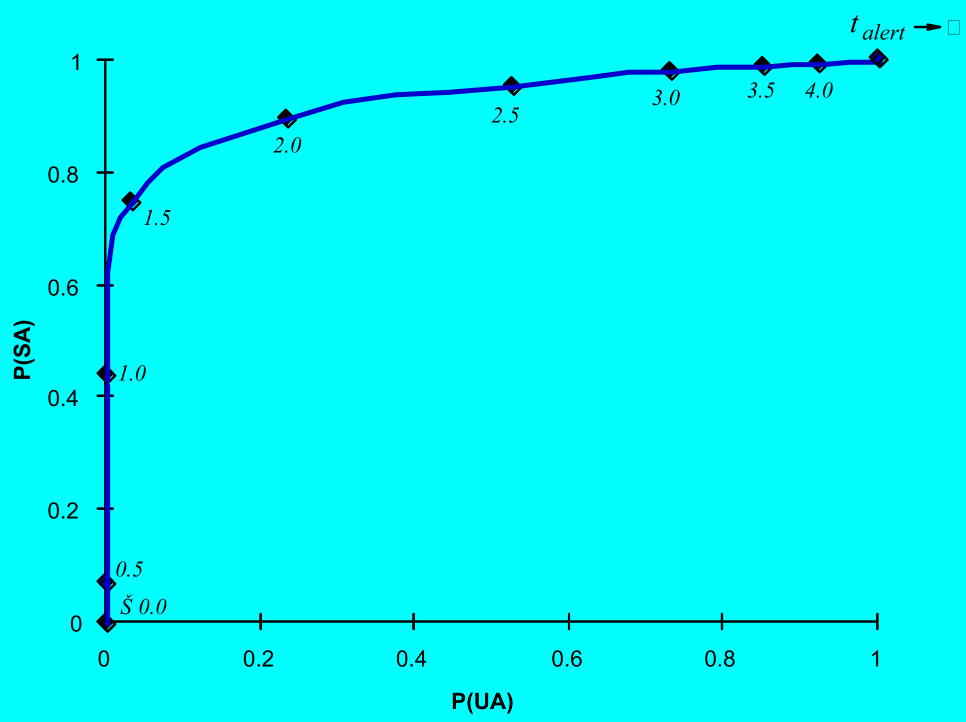
Nearly ideal performance for t_{alert} between 1.45 - 1.75 s

Example Response Time Distribution

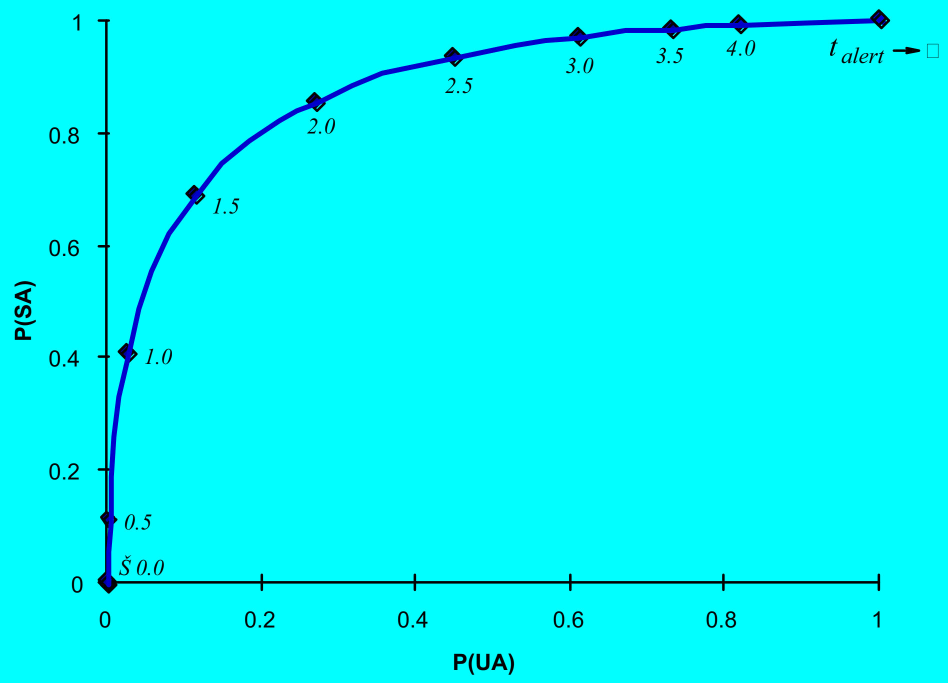


Lognormal distribution (mode = 1.07 s, dispersion = 0.49) [Najm et al.]

Case 3: Add Response Delay Uncertainty



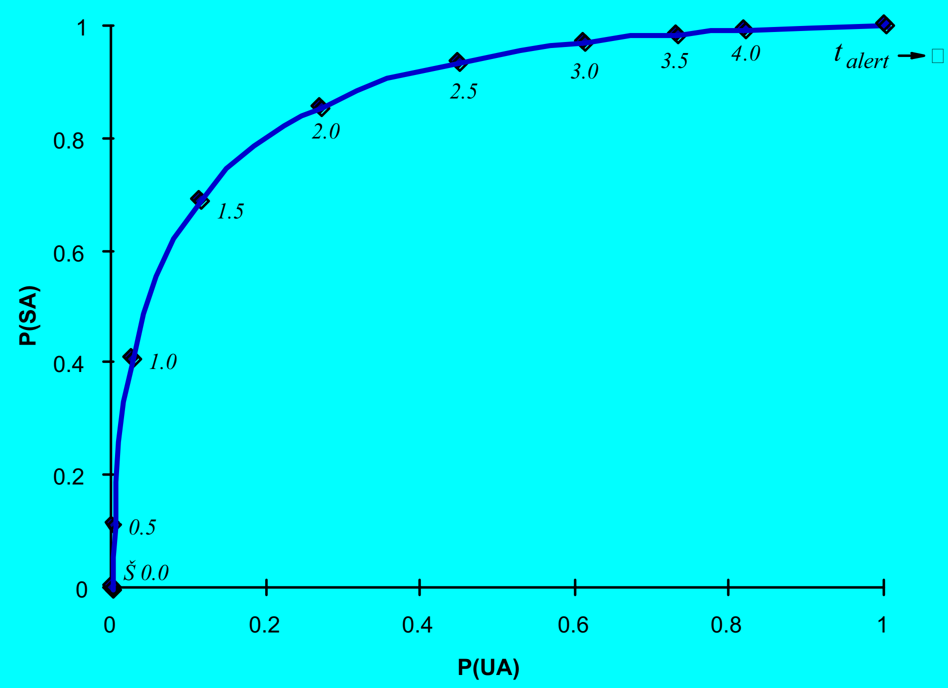
Case 4: Add Deceleration Uncertainty



$\sigma_a = 3\ \mathrm{ft/s^2}$

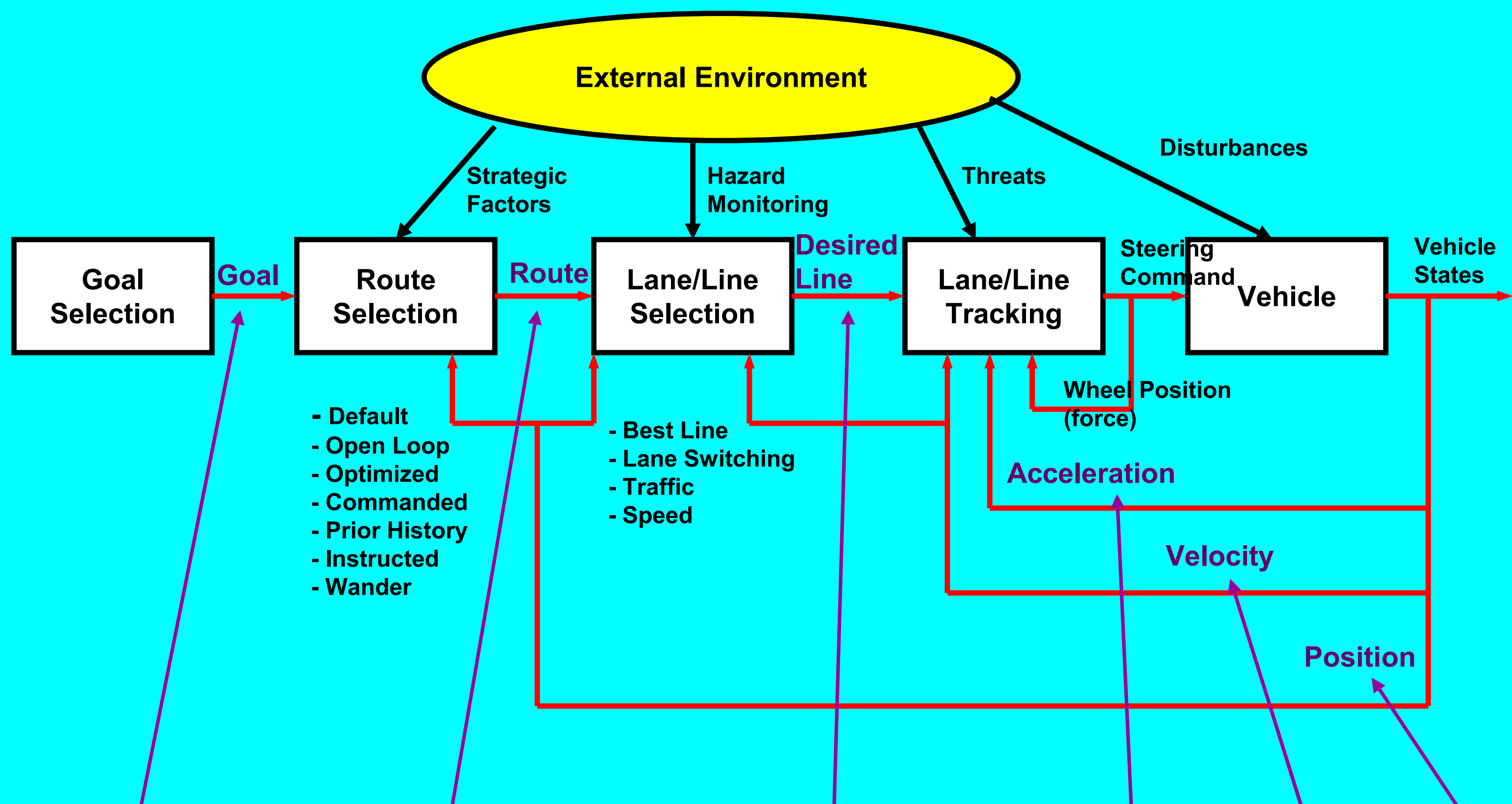
Kinematics Sensors (eg RADAR) Limited by Vehicle Dynamics and Response Time

Need Intent States



Courtesy of Prof Jim Kuchar, MIT Dept of Aero/Astro

Intent States in the Lateral Tracking Loop



X = (Goal, Subsequent Planned Trajectory, Current Target State, Acceleration, Velocity, Position)

Intent Observability States

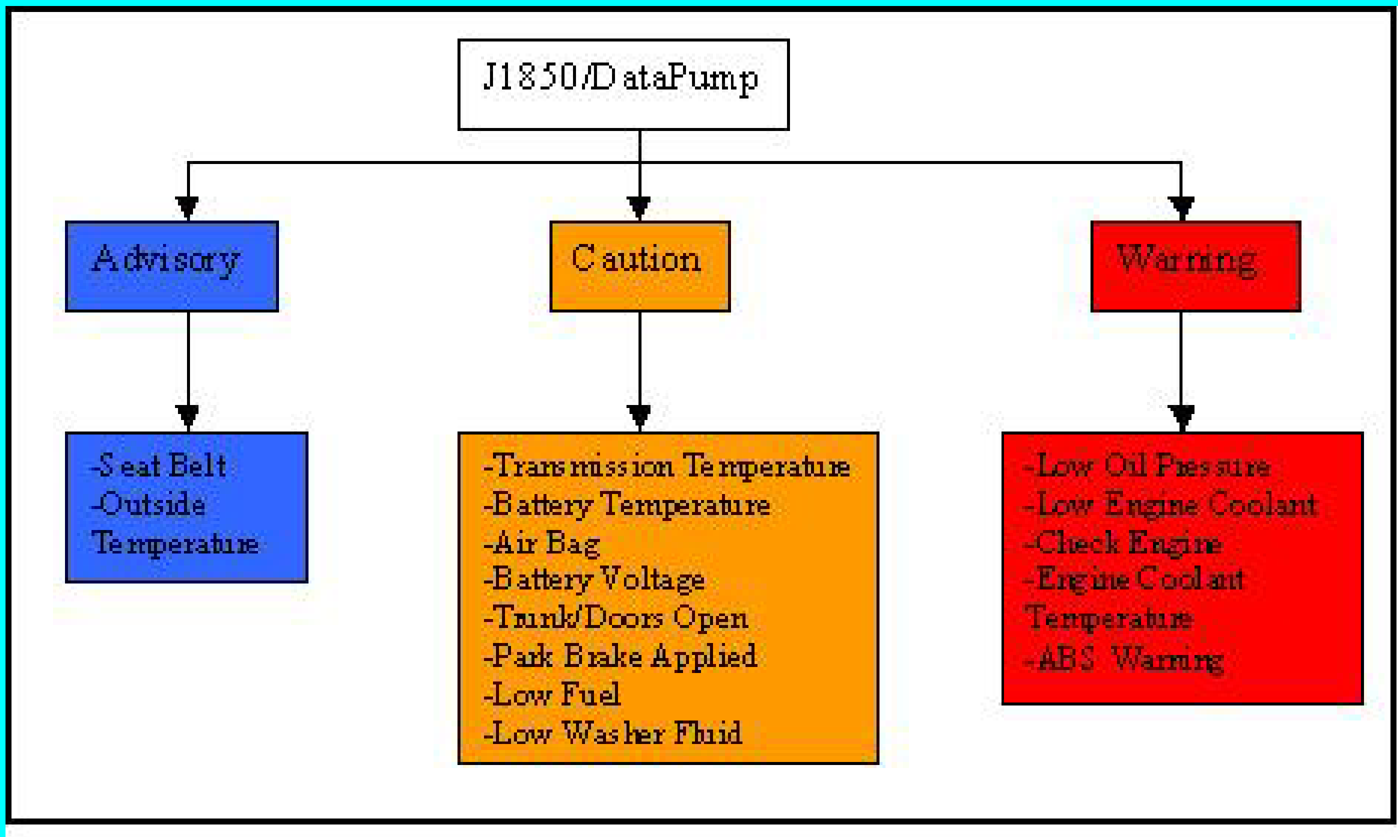
- Roadway
- Indicator Lights
  - Break Lights
  - Turn Signals
  - Stop Lights
- Acceleration States
- GPS Routing
- Head Position
- Dynamic History
- Tracking Behavior

Approaches to Enhancing Focus in the Information Rich Cockpit (cont.)

- *Enhanced Perception*
  - IR/MMW Radar (eg Cadillac Night Vision System)
  - Multidimensional video ("super mirror")
  - Prioritized audio
- *Situation Awareness Displays*
  - Datalink
- *Alerting Systems*
- *Advanced Internal Diagnostics Architectures*
  - "Master Caution"
- *Driver Condition Monitoring*
- *External Visual Systems*
  - Active Signage

“Master Caution” System

"Master Caution" Architecture



Approaches to Enhancing Focus in the Information Rich Cockpit (cont.)

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300M Face Analysis

- Driver Internal State
  - Vigilance
  - Stress
- Driver Habits
  - Scan Patterns

300M Pupil Tracking

IBM BlueEyes Camera

Image with
On-Axis LEDs off

Image with
On-Axis LEDs on

Difference Image

Approaches to Enhancing Focus in the Information Rich Cockpit (cont.)

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Discussion

Aerospace Experience

- Drive by Wire
  - Criticality - Fault Tolerance
    - B-777 example
- Collision alert criteria
  - Alert vs.. autobrake
    - F-16 example
  - Complex threat field
  - False alarm issue
    - System Operations Curves
- HUD applications
  - Limited FOV
    - Runway, alignment,
    - Gunsight applications
  - Visual Accommodation
    - Infinity Optics
    - Visual anomalies
      - e.g...Lack of Fusion
- Situation Awareness (SA) displays
  - Testing Methods

Technology Migrating into Automobile Cockpits

- Mobile Communications (Voice, Data)
- Portable Devices (Cell Phone, PDA, Wireless)
  - Not Controlled by Automobile Industry
- Entertainment / Info Systems (CD, Web)
- Navigation and Guidance (GPS, DGPS)
- Advanced Displays (Flat Panel, HUD)
- Sensors (Radar, IR, MEMS)
- Databus Architectures (CAN,AIRINC)
- On-board Processors (Embedded, Auto-PC)
- Control augmentation (ABS, Cruise C)
- ...

Background: Current Systems

- Information Structure:
  - Distance to turn
  - Street names
  - Heading
- Interface:
  - Moving maps
  - Icons
  - Voice instructions

Current System: Phillips Carin

- Uses maps, icons, and voice commands to guide the driver

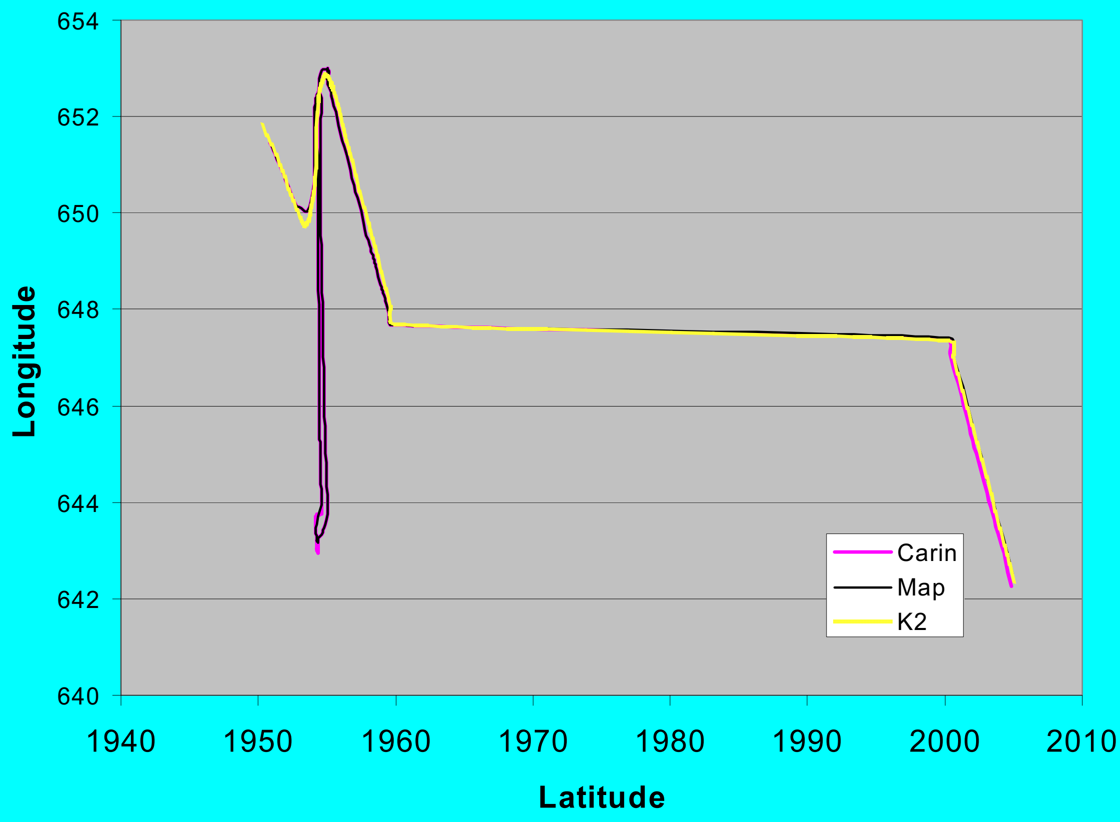
Direction Study Conclusions

- Humans and navigation systems both use street name and direction of turn to describe the action
- They differ in the method used to warn the driver of the upcoming action
  - Humans rely on external reference points: landmarks, stoplights
  - Navigation systems use distance & heading

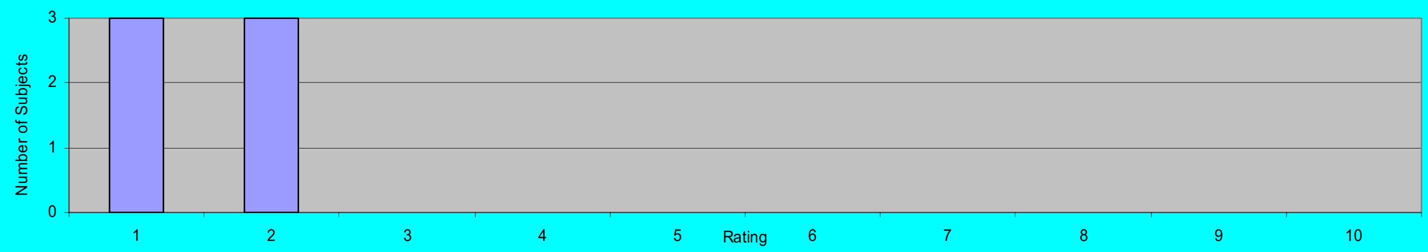
Data

- Subjective feedback
  - Cooper-Harper rating scale evaluation
  - Best & worst features evaluation
  - Comparative rating of systems
- Observations
  - Errors, comments, body language
- Measurements
  - Position, velocity

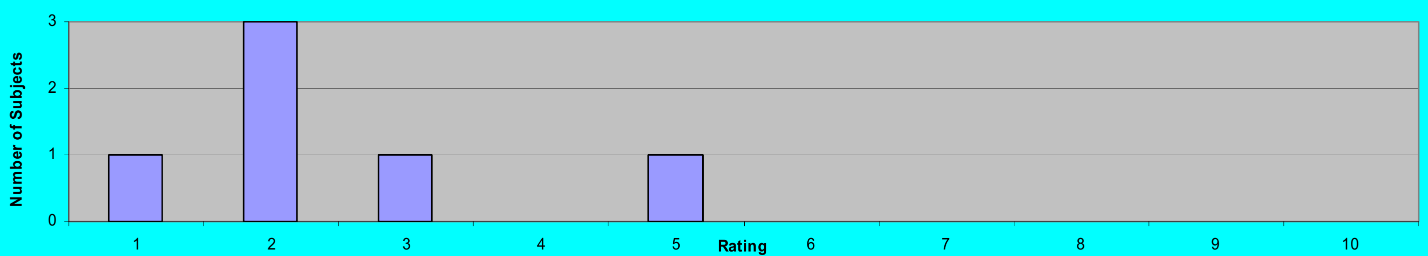
Error Example:
Jamaica Pond Trajectory



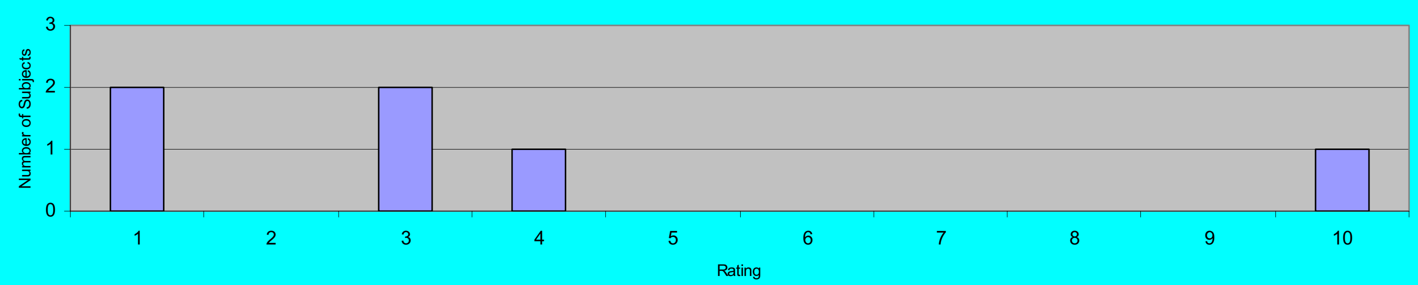
Results: System Ratings



K2



Carin



Map

Obstacle Collision Alerting System Example

- Examine effect of design parameters on performance
  - sensor accuracy
  - operator response
  - braking deceleration

- Performance shown using SOC curves

- Monte Carlo simulation used to estimate probabilities
  - v = 35 mph (56 km/hr)
  - Safety evaluation
    - Avoidance trajectory:
      - variable delay, 16 ft/s^2 deceleration (0.5 g)

False Alarm Estimation

- Was an alert unnecessary?
- What would have happened without the alert?
  - Require Nominal trajectory
  - Definition of false alarm is situation- and operator-specific
  - Baseline:
    - If collision would occur after
      1.5 s delay, 10 ft/s^2 deceleration (1/3 g),
      then an alert is necessary
    - Otherwise, an alert is a false alarm

Implications

- A single decision threshold for all users will not be acceptable
  - uncertainties in response time and braking dominate
  - some users will experience apparent false alarms
  - some users will experience apparent late alarms
- Automating the braking response could improve safety
  - less uncertainty in response delay and deceleration profile
  - may still be prone to perceived false alarms
  - may encourage complacency, over-reliance

What Will Ultimately Control Secondary Task Levels ?

- Market Forces tend to increase complexity
  - *Market Values functionally >> complexity*
- Industry Practice
- Regulatory Action
- Litigation
- Insurance
- Public Awareness

- *Pressure for action*
- *We don’t have sufficient data to support rational action at this point*

Transportation Systems Level

- Fleet management
  - Monitoring
  - Dispatch
  - Reporting
  - Support
- Personal vehicle management
  - Teenage driver monitoring
  - Transponders “fast pass”
  - Enforcement
- Passenger vehicle as part of distribution network
  - Low end e-commerce
    - Drive through pick-up
      - Food
      - Retail
      - Services
    - Active ride share matching

Careful Formatting Turns Data Into Information

Information distinguished by:

- **Location**
- **Labeling**
- **Shape coding**
- **NOT color**

To help pilots identify information:

- **Consistent use of shading**
- **Consistent use of color**

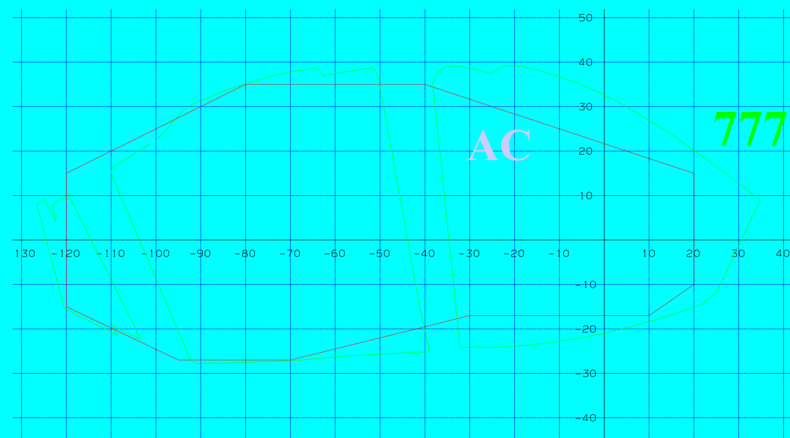
Every pixel earns its way on the display

Formatting, not color, used to distinguish information …
Surprising thing is NOT color
Originally, in the early days of CRTs, we did not use color because one failure mode of the CRT is reversion to B&W. But we liked the human factors benefit we received from the additional clarity so we kept the philosophy on the LCD. We don't use color as the only means to distinguish information. Color helps the pilot locate information but not to distinguish it.
Shading is also used to help pilots identify certain information.
So on these altitude tapes notice:
- Boeing tape does not use white outlines because they are not necessary
- The box shape is as simple as possible
- Gaps between numbers and lines are intentional, to separate the information
- color is used sparingly and consistently

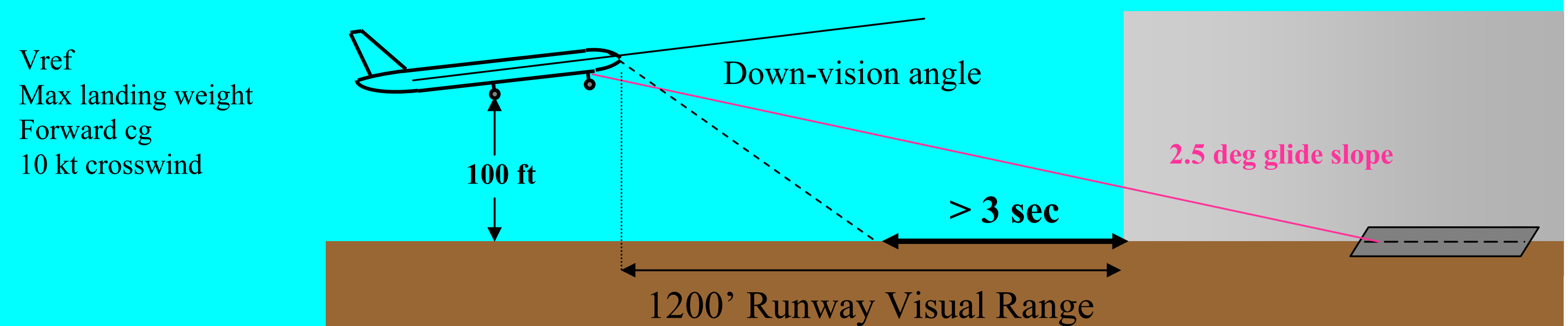
I have a couple slides on shading,
And a couple slides on color.

External Vision – AC 25.773-1

- Vision Polar



- 3-Second "Rule"



Also:

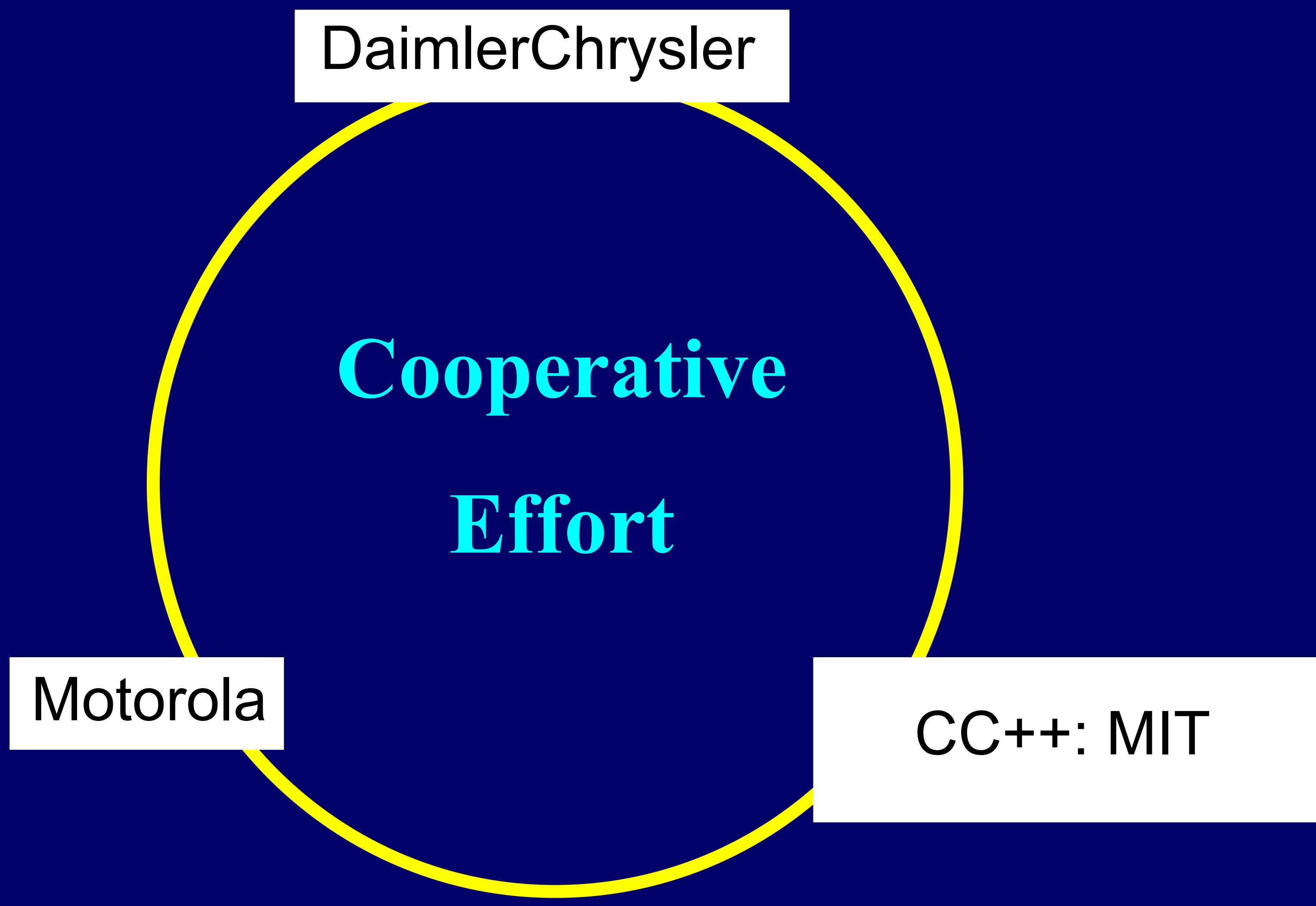
- Precipitation clearing
- Post widths
- other details

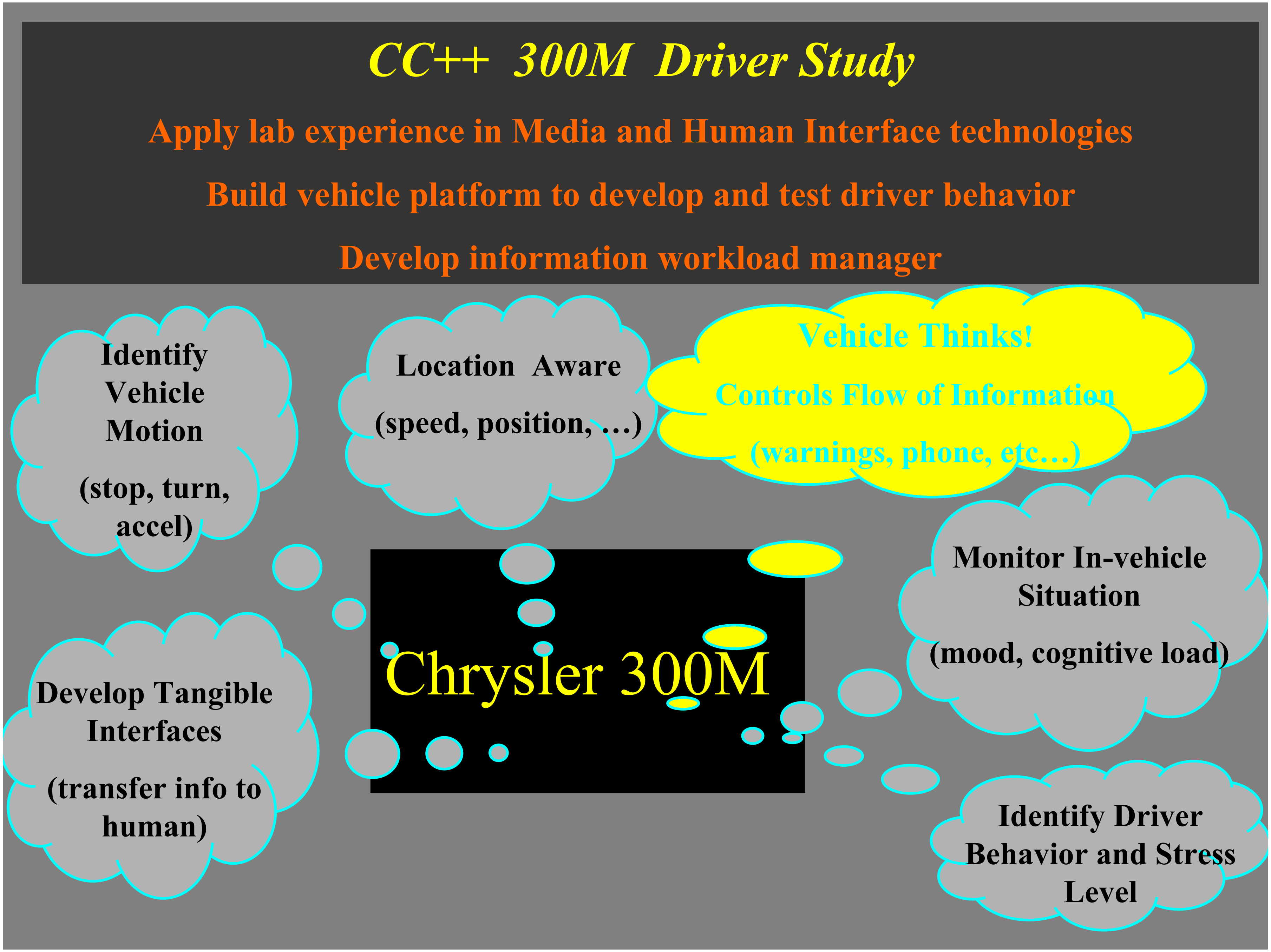
Vision polar and 3 second rule drive airplane configuration (approach attitude and speed)

Synthetic Vision

Picture of the outside world created by combining precise navigation position with databases of comprehensive geographic, cultural and tactical information.

Chrysler 300M Research Platform




CC++ 300M Driver Study
Apply lab experience in Media and Human Interface technologies
Build vehicle platform to develop and test driver behavior
Develop information workload manager
Identify Vehicle Motion
(stop, turn, accel)
Location Aware
(speed, position, …)
Vehicle Thinks!
Controls Flow of Information
(warnings, phone, etc…)
Chrysler 300M
Monitor In-vehicle Situation
(mood, cognitive load)
Develop Tangible Interfaces
(transfer info to human)
Identify Driver Behavior and Stress Level