16.422 Information & Signal Detection Theory

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Acknowledgements to Profs Tom Sheridan and Jim Kuchar whose notes are the core of this lecture
Outline

- Information Theory
- Signal Detection Theory
- Alerting Introduction
Information Theory

- What is information?

- Control Theoretic View
  - Lines in Control Block Diagram

- Bayesian View
  - Information is something which reduces uncertainty in a world model
Bayes Theory

H = Hypothesis, D = Data

\[ p(H \mid D) = p(D \mid H) \frac{p(H)}{p(D)} \]

With new data

\[ p(H \mid D_1, D_2) = p(D_2 \mid H) \left[ \frac{p(D_1 \mid H) \frac{p(H)}{p(D_1)}}{p(D_2)} \right] \]

With 2 hypotheses

\[
\begin{align*}
p(H_1 \mid D_1, D_2) &= \frac{p(D_2 \mid H_1) \ p(D_1 \mid H_1) \ p(H_1)}{p(H_2 \mid D_1, D_2) \ p(D_2 \mid H_2) \ p(D_1 \mid H_2) \ p(H_2)} \\
\text{Posterier odds ratio} & \quad \text{prior odds ratio}
\end{align*}
\]
- Shannon Information Theory
  - Bell Labs
  - Telephony

- Tom Sheridan Notes

(Courtesy of Thomas Sheridan. Used with permission.)
• **Bit view of Information**
  - # of bits to disambiguate
  - Bit = binary discrimination
  - Drive uncertainty to zero

(Courtesy of Thomas Sheridan. Used with permission.)
Info Transmission
H = information, D = Data

How to measure info. transmitted?

X1 → H1 → D1 → Y1
X2 → H2 → D2 → Y2
X3 → H3 → D3 → Y3

Known a priori p(Hk) → p(Hk | Dk)

Criteria for a good measure

1) What measure T = f[p(xc), p(xc | yj)]

2) Info. gained by knowing Y1 adds to info. gained by knowing Y2, etc.

T[p(xa), p(xa | Yk)] + T[p(xb), p(xb | Yk)]
= T[p(xa xb), p(xa xb | Yk Yl)]

T must be of form [log p(xc | yj) - log p(xc)]
= log p(xc | yj) / p(xc)

Simplest examples

H(x) = Σi p(x_i) log2 1 / p(x_i)
= .5 (log2 2) + .5 (log2 2) = 1

p(yj)

p(xc)

p(yj | xc)

p(xc | yj)

(0 .5)

0 .5

1 0

Same as

p(xc)

p(yj | xc)

p(xc | yj)

p(yj)

(0 .5)

0 .5

.5

.5

Same

X1 → Y1
T1 = log2 p(x1 | y1) - log2 p(x1)
= log2 (1) - log2 (.5) = 1

X2 → Y2
T2 = same = 1

Tave = .5(T1) + .5(T2) = 1

(Courtesy of Thomas Sheridan. Used with permission.)
MULTIPLY NUMERATOR AND DENOMINATOR BY \( p(y_j) \). THEN

\[
\mathcal{T}(x:y) = \sum_i \sum_j p(x_i | y_j) \log \frac{p(x_i | y_j)}{p(x_i)} \mathcal{H}(x) - \mathcal{H}(x | y)
\]

\[
- \sum_j p(x_j | y_j) \log \frac{p(y_j)}{p(y_j)}
\]

\[
\mathcal{H}(x) + \mathcal{H}(y) - \mathcal{H}(x, y)
\]

\[
\mathcal{I} = \mathcal{I}^{(i)} + \mathcal{I}^{(o)} - \mathcal{I}^{(j)}
\]

If \( x \) and \( y \) are uncorrelated, from general eqn.

\[
p(x_i | y_j) = p(x_i) \quad \Rightarrow \quad \mathcal{T} = 0
\]

If \( x \) and \( y \) perfectly correlated

\[
p(x_i | y_j) = p(x_i) = p(y_j)
\]

\[
\mathcal{T}(x:y) = \mathcal{H}(x) = \mathcal{H}(y)
\]

(Courtesy of Thomas Sheridan. Used with permission.)
\[ T(x;y) = \sum_i \sum_j p(x_i y_j) \log \frac{p(x_i y_j)}{p(x_i)} - \sum_i p(x_i) \log p(x_i) \]

\[ = H(y) - H(y|x) \]

\[ T = \text{INPUT - EQUIVOCATION} \]

CAN ALSO REWRITE GENL. EQN.
MULT. NUM. AND DENOM. BY \( \frac{p(y_j)}{p(x_i)} \)

\[ T(x;y) = \sum_i \sum_j p(x_i y_j) \log \frac{p(x_i y_j)}{p(y_j)} \]

\[ = \sum_i \sum_j p(x_i y_j) \log p(y_j | x_i) \]

\[ - \sum_i p(x_i) \log p(y_j) \]

\[ = H(y) - H(y|x) \]

\[ T = \text{OUTPUT - NOISE} \]

(Courtesy of Thomas Sheridan. Used with permission.)
Supervisory Control Computer Interface Display Control Sensors

\[ H(x) = \sum_i p_i \log \frac{1}{p_i} \quad \text{INPUT INFO.} \]
\[ H(y) = \sum_j p_j \log \frac{1}{p_j} \quad \text{OUTPUT INFO.} \]
\[ H(x/y) = \sum_i \sum_j p(x_i, y_j) \log \frac{1}{p(x_i | y_j)} \quad \text{EQUINOCATION} \]
\[ H(y/x) = \sum_i \sum_j p(x_i, y_j) \log \frac{1}{p(y_j | x_i)} \quad \text{NOISE} \]

Remember - info is uncertainty! (To be reduced)

(Courtesy of Thomas Sheridan. Used with permission.)
Assessing the Benefit of Providing Information

Average benefit from having perfect information (indicative of true state $x_i$), where one can select $u$ to optimize for each $x_i$ is

$$V_p = \sum_i p(x_i) \max_j \left[V(x_i|u_j)\right].$$

The best one can ever do from just knowing the a priori statistics is

$$V_0 = \max_j \left[\sum_i p(x_i) \, V(x_i|u_j)\right].$$

The difference $(V_p - V_0)$ is the net benefit of having the information if it were free.

As a first approximation, the cost (in complexity of hardware/software) of providing and/or of accessing the information (in computer or human time/distraction) is

$$C = \sum_i p(x_i) \, c(x_i) \, \log_2[1/p(x_i)].$$

Then should provide the information IFF $(V_p - V_0) < C$

Information may become imperfect, e.g., state $x$ changes with probability $q$ to each other state before $u$ takes effect. Then

$$V_1 = \sum_i p(x_i) \cdot \left[ (1-q) \max_j \left[V(x_i|u_j)\right] + \right.$$

$$\left. q \cdot \sum_{k \neq i} \left[V(x_k|u_j) \text{ selected for } i \right) \right]$$

Then should provide information IFF $(V_1 - V_0) < C$

(Courtesy of Thomas Sheridan. Used with permission.)
System
Supervisory
Control
Computer
Interface
Display
Control
Sensors
Direct Observation

\[ \text{INFO. RATE} \]

\[ H(Y) \]
\[ T(x:y) \]
\[ H(x) \]
Information Bandwidth

- **Information Rate**
  - Bits/Sec

- **Information Density**

- **Raster Example**
  - (# Pixels) (# Bits/ Pixel) (Update Rate)
Diagram from Sheridan, *Teleoperation*
Signal Detection Theory

- Originally Developed for Radar Threshold Detection
- Becomes the Basis for Alerting Theory
- Signal versus Noise
- A-Scope Example
Given a payoff matrix:

<table>
<thead>
<tr>
<th></th>
<th>$H_1$</th>
<th>$H_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td></td>
<td>$C_1$</td>
</tr>
<tr>
<td>$C_2$</td>
<td></td>
<td>$V_2$</td>
</tr>
</tbody>
</table>

Consider case of only 2 $H_k$.

Using Bayes' Theorem, we updated our estimate of $p(H_1)$ and $p(H_2)$ as new $d_j$ were observed.

In Signal Detection Theory (or more generally, maximum likelihood decision theory), we have a more mercenary basis for decision on $H_1$ or $H_2$—namely, which would yield the greatest payoff.

This is called an "ideal observer." (Typically American!)

(E. 1 ff $E(H_1) = p(H_1) V_1 - p(H_2) C_1$
$E(H_2) = p(H_2) V_2 - p(H_1) C_2$)

Decide $H_1$ if $[p(H_1)V_1 - p(H_2)C_1] \geq [p(H_2)V_2 - p(H_1)C_2]$

i.e., 1 ff

$$\frac{p(H_1)}{p(H_2)} \geq \frac{V_1 + C_1}{V_2 + C_2}$$

Let $p(H_1)$ and $p(H_2)$ be prior probabilities.

Then, after one observation $d_1$, criterion becomes

Decide $H_1$ if $\frac{p(H_1 | d_1)}{p(H_2 | d_1)} \geq \frac{V_1 + C_1}{V_2 + C_2}$

(Courtesy of Thomas Sheridan. Used with permission.)
Consider two distributions:

\[
\frac{p(H_i | x_i)}{p(H_j | x_i)} = \frac{p(x_i | H_i) p(H_i)}{p(x_i | H_j) p(H_j)}
\]

or

\[
\frac{p(x_i | H_i)}{p(x_i | H_j)} = K_0 \quad \text{or} \quad \frac{p(H_i)}{p(H_j)} = \text{cutoff value} \quad \text{also called } \beta
\]

Better to make likelihood ratio monotonic by reordering!
System Supervisory Control Computer Interface Display Control Sensors

IF CUTOFF K IS HERE

\[ \frac{d_j}{H_2} \]

FOR THESE \( d_j \)

\[ \text{DECIDE } H_1 \]

\[ \text{INCORRECT, PAY } C_1 \]

\[ \text{CORRECT, COLLECT } V_i \]

\[ \text{HIT} \]

\[ \frac{d_j}{H_2} \]

\[ \text{DECIDE } H_2 \]

\[ \text{INCORRECT, PAY } C_2 \]

\[ \text{FALSE ALARM} \]

\[ \text{FALSE ALARM RATE} \]

\[ d' \] distance between means

RECEIVER OPERATING CHARACTERISTIC

PERFECT CORRELATION \( f(d_j | H_0) \) FROM RIGHT SIDE

\[ \frac{1}{p(H_1 | H_1)} \]

\[ \text{HIT RATE} \]

FOR CUTOFF AT \( k \)

\[ \frac{1}{p(H_1 | H_0)} \]

\[ \text{FALSE ALARM RATE} \]

\[ f(d_j | H_1) \] FROM RIGHT SIDE

ROC CURVE IS WHAT HAPPENS AS SLIDE CUTOFF LINE FROM RIGHT TO LEFT AND INTEGRATE TWO AREAS TO ITS RIGHT

(Courtesy of Thomas Sheridan. Used with permission.)
EXPERIMENT: PRESENT SUBJECT WITH SIGNAL OR NOISE ALONE

EXPERIMENTAL PROCEDURE BASED ON

SUBJECTIVE CONFIDENCE SCALE OF SIGNAL PRESENCE

SURE $H_L$

SURE $H_I$

DECIDE

$P(H_I | \text{noise only})$

$P(H_L | \text{signal + noise})$

DECIDE

$P(H_I | \text{signal only})$

INTEGRATE FROM RIGHT, OBTAIN ROC FOR SUBJECT

ALTERNATIVE EXPERIMENT IS TO OBTAIN ONE POINT ON ROC BASED ON $H_L, H_I, \text{dist. and k}$ DETERMINED BY:

1) Payoff Matrix (Regret Ratio)

\[ \frac{V_L + C_L}{V_I + C_L} \]

2) Prior Odds

\[ \frac{P(H_I)}{P(H_L)} \]

(Courtesy of Thomas Sheridan. Used with permission.)
Consider Sensor System

- Radar
- Engine Fire Detection
- Other
Threshold Placement

Ideal Alerting System

Example Alerting Threshold Locations

Probability of Successful Alert $P(SA)$

Probability of False Alarm $P(FA)$

(Courtesy of James Kuchar. Used with permission.)
Threshold Placement

- Use specified \( P(FA) \) or \( P(MD) \)

- Alerting Cost Function: Define \( C_{FA}, C_{MD} \) as alert decision costs

\[
J = P(FA) \ C_{FA} + P(MD) \ C_{MD} \\
= P(FA) \ C_{FA} + (1 - P(CD)) \ C_{MD}
\]

Minimize Cost:

\[
dJ = dP(FA) \ C_{FA} - dP(CD) \ C_{MD} = 0
\]

\[
\frac{dP(CD)}{dP(FA)} = \frac{C_{FA}}{C_{MD}}
\]

Slope of SOC curve = cost ratio

(Courtesy of James Kuchar. Used with permission.)
Engine Fire Alerting

- C(FA) high on takeoff
- Alerts suppressed during TO

Now let's take a quick look at non-normal checklists. The 777 EICAS message list is similar to other Boeing EICAS airplanes. [For 747-400 operators: It doesn't use the "caret" symbol to indicate a checklist with no QRH items, like the 747-400s do.] But it has an additional feature, called the "checklist icon". The icon is displayed next to an EICAS message whenever there is an ECL checklist that needs to be completed. Once the checklist is fully complete, the icon is removed from display next to the message. This helps the crew keep track of which checklists remain to be completed.
## Crew Alerting Levels

### Non-Normal Procedures

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time Critical</strong></td>
<td>Operational condition that requires immediate crew awareness and immediate action</td>
</tr>
<tr>
<td><strong>Warning</strong></td>
<td>Operational or system condition that requires immediate crew awareness and definite corrective or compensatory action</td>
</tr>
<tr>
<td><strong>Caution</strong></td>
<td>Operational or system condition that requires immediate crew awareness and possible corrective or compensatory action</td>
</tr>
<tr>
<td><strong>Advisory</strong></td>
<td>Operational or system condition that requires crew awareness and possible corrective or compensatory action</td>
</tr>
</tbody>
</table>

### Alternate Normal Procedures

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comm</strong></td>
<td>Alerts crew to incoming datalink communication</td>
</tr>
<tr>
<td><strong>Memo</strong></td>
<td>Crew reminders of the current state of certain manually selected normal conditions</td>
</tr>
</tbody>
</table>

Source: Brian Kelly Boeing

Don't have time to discuss these levels.

Important thing to know is that we rigorously define and defend these levels.

We apply them across all the systems.

The indications are consistent for all alerts at each level.

Thus the pilots instantly know the criticality and nature of an alert even before they know what the problem is.
## Boeing Color Use Guides

<table>
<thead>
<tr>
<th>Color</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>Warnings, warning level limitations</td>
</tr>
<tr>
<td>Amber</td>
<td>Cautions, caution level limitations</td>
</tr>
<tr>
<td>White</td>
<td>Current status information</td>
</tr>
<tr>
<td>Green</td>
<td>Pilot selected data, mode announcements</td>
</tr>
<tr>
<td>Magenta</td>
<td>Target information</td>
</tr>
<tr>
<td>Cyan</td>
<td>Background data</td>
</tr>
</tbody>
</table>

Again, we don’t have time to describe these definitions in detail. The important thing to note is that our philosophy is definite, and as simple as practical. It fits on one page, in big font no less.
Access To Non-Normal Checklists

- Prevents choosing wrong checklist

When an alert message is displayed, the pilot simply pushes the CHKL button and the correct non-normal checklist is displayed. This prevents the crew from accidentally choosing the wrong checklist. The non-normal checklists have priority over the normal checklists.
Non-Normal Checklists

- Checklist specific to left or right side
- Exact switch specified
- Memory items already complete
- Closed-loop conditional item
- Page bar

This is what a typical normal checklist looks like. This is the Preflight checklist. There are two kinds of line items, which we call open-loop and closed-loop items. The open-loop items have a gray check-box in front of them. These are items that the airplane systems cannot sense. The pilot determines whether the items have been completed and clicks the CCD thumbswitch when each item is complete. Closed-loop items are for switches and selectors that are sensed by the airplane systems. They automatically turn green when the switch has been positioned correctly. If the crew actuates the wrong switch, the closed-loop item will not turn green and the crew will catch their error. In this example, the procedure was already complete, so the last two items are shown in green as soon as the checklist is displayed.

The white current line item box leads the pilot through the checklist and prevents accidentally skipping a line item. Color is used to indicate line item status. Incomplete items are displayed white and complete items are displayed green. Cyan (or blue) indicates an inapplicable item, or an item that has been intentionally overridden by the crew using the ITEM OVRD button. In this example, the flight is dispatching with autobrakes inoperative, so the crew has overridden the AUTOBRAKE item. Overriding the item allows the checklist to be completed.
Internal vs External Threat Systems

- **Internal**
  - System normally well defined
  - Logic relatively static
  - Simple ROC approach valid
  - Examples (Oil Pressure, Fire, Fuel, ...)

- **External**
  - External environment may not be well defined
    - Stochastic elements
  - Controlled system trajectory may be important
    - Human response
  - Need ROC like approach which considers entire system
  - System Operating Characteristic (SOC) approach of Kuchar
  - Examples (Traffic, Terrain, Weather, ...)

---

Diagram:
- System
- Supervisory
- Control
- Computer Interface
- Display
- Control Sensors
- Direct Observation

Analysis:
- Internal systems are typically well defined, with stable logic and simple ROC approaches.
- External systems face uncertain environments with stochastic elements, requiring more holistic ROC approaches.

Examples:
- Internal: Oil Pressure, Fire, Fuel
- External: Traffic, Terrain, Weather
Decision-Aiding / Alerting
System Architecture

(Courtesy of James Kuchar. Used with permission.)
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**

(Courtesy of James Kuchar. Used with permission.)
The Alerting Decision

- Examine consequences of alerting / not alerting
  - Alert is not issued: Nominal Trajectory (N)
  - Alert is issued: Avoidance Trajectory (A)

Compute probability of Incident along each trajectory

(Courtesy of James Kuchar. Used with permission.)
System Operating Characteristic Curve

Probability of False Alarm $P(FA)$

Probability of Successful Alert $P(SA)$

Ideal Alerting System

Example Alerting Threshold Locations

(Courtesy of James Kuchar. Used with permission.)
Trajectory Modeling Methods

Nominal

Worst-case

Probabilistic

(Courtesy of James Kuchar. Used with permission.)
Nominal Trajectory Prediction-Based Alerting

- Alert when projected trajectory encounters hazard
- Look ahead time and trajectory model are design parameters
- Examples: TCAS, GPWS, AILS

(Courtesy of James Kuchar. Used with permission.)
Airborne Information for Lateral Spacing (AILS) (nominal trajectory prediction-based)

Endangered aircraft vectored away

Alert occurs with prediction of near miss in given time interval

(Courtesy of James Kuchar. Used with permission.)
Alert Trajectory Prediction-Based Alerting

- Alert is issued as soon as safe escape path is threatened
- Attempt to ensure minimum level of safety
- Some loss of control over false alarms
- Example: Probabilistic parallel approach logic (Carpenter & Kuchar)

(Courtesy of James Kuchar. Used with permission.)
Example State Uncertainty Propagation

Computed via Monte Carlo

along-track $\sigma = 15$ kt

cross-track $\sigma = 1$ nmi

(from NASA Ames)

(Courtesy of James Kuchar. Used with permission.)
Monte Carlo Simulation Structure

Current state information
(position, velocity)

Protected Zone size

Intent information:
- Waypoints (2D, 3D, 4D)
- Target heading
- Target speed
- Target altitude
- Target altitude rate
- Maneuvering limitations

Monte Carlo Simulation Engine

Uncertainties
(probability density functions)
- Current states
- Along- and cross-track error
- Maneuvering characteristics
- Confidence in intent information

Probability of conflict

Implemented in real-time simulation studies at NASA Ames
Computational time on the order of 1 sec

(Courtesy of James Kuchar. Used with permission.)
System Operating Characteristic Curve

Probability of False Alarm $P(FA)$

Probability of Successful Alert $P(SA)$

Ideal Alerting System

Example Alerting Threshold Locations

(Courtesy of James Kuchar. Used with permission.)
Aircraft Collision Avoidance

**Automation**
- GPWS alert and decision aid
- caution: “terrain”
- warning: “pull up”
- terrain data
- displays
- other info. (e.g. window view)
- other sensor information
- altitude and altitude rate

**Human**
- experience, training
- diagnosis and control

**Aircraft**
- controls
- sensors
- GPWS alert and decision aid
Fatal Accident Causes

Fatalities by Accident Categories

Note: Accidents involving multiple non-onboard fatalities are included. Accidents involving single, non-onboard fatalities are excluded.

Adapted from The Boeing Company
Prototype MIT Terrain Alerting Displays
Enhanced GPWS Improves Terrain/Situational Awareness

EFIS map display color legend

- 2,000-ft high density (50%) red
- 1,000-ft high density (50%) yellow
- 250/-500-ft medium density (25%) yellow
- 1,000-ft medium density (25%) green
- 2,000-ft medium density (12.5%) green
- Reference altitude
Terrain Alerting

TAWS Look-Ahead Alerts
(Terrain Database)

“Terrain, Terrain, Pull Up...”
approx 22 sec.

“Caution Terrain”
approx 45 sec

Basic GPWS modes
(radar altitude)
• Threat terrain is shown in solid red
• “Pull up” light or PFD message
• Colored terrain on navigation display
Conflict Detection and Resolution Framework

(Courtesy of James Kuchar. Used with permission.)
Multiple Alerting System Conflicts

- Developing formal methods for system analysis
- Identification of conflicts and methods to mitigate
- Drivers / implications for human interaction

(Courtesy of James Kuchar. Used with permission.)
Design Principles for Alerting and Decision-Aiding Systems for Automobiles

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Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

(Courtesy of James Kuchar. Used with permission.)
Alert time: $t_{\text{alert}} = (r - d)/v$

$t_{\text{alert}} = 0 \rightarrow$ braking must begin immediately

$t_{\text{alert}} = \tau \rightarrow$ alert is issued $\tau$ seconds before braking is required

• Determine $P(UA)$ and $P(SA)$ as function of $t_{\text{alert}}$

(Courtesy of James Kuchar. Used with permission.)
Example Human Response Time Distribution

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

(Courtesy of James Kuchar. Used with permission.)
Case 3: Add Response Delay Uncertainty

(Courtesy of James Kuchar. Used with permission.)
Case 4: Add Deceleration Uncertainty

\[ \sigma_a = 3 \text{ ft/s}^2 \]

(Courtesy of James Kuchar. Used with permission.)
Conformance Monitoring for Internal and Collision Alerting

- Simple Sensor Based Collision Alerting Systems Do Not Provide Adequate Alert Performance due to Kinematics
  - SOC Curve Analysis
    - P(FA), P(MD) Performance
- Enhanced Collision Alerting Systems Require Inference or Measurement of Higher Order Intent States
  - Automatic Dependent Surveillance (Broadcast)
  - Environment Inferencing
    - Observed States

(Courtesy of James Kuchar. Used with permission.)
SURVEILLANCE STATE VECTOR

- Aircraft Surveillance State Vector, \( X(t) \) containing uncertainty & errors \( \delta X(t) \) is given by:
  - Traditional dynamic states
  - Intent and goal states

\[
X(t) = \begin{bmatrix}
\text{Position, } R(t) \\
\text{Velocity, } V(t) \\
\text{Acceleration, } A(t) \\
\text{Intent, } I(t) \\
\text{Goals, } G(t)
\end{bmatrix}
\]

\[
\delta X(t) = \begin{bmatrix}
\delta R(t) \\
\delta V(t) \\
\delta A(t) \\
\delta I(t) \\
\delta G(t)
\end{bmatrix}
\]

(Courtesy of James Kuchar. Used with permission.)
• Intent State Vector can be separated into current target states and subsequent states

\[ I(t) = \begin{cases} 
\text{Current target states} \\
\text{Subsequent planned trajectory} 
\end{cases} \quad \text{(Eqn. 3)} 

(Courtesy of James Kuchar. Used with permission.)
System Supervisory Control
Computer Interface Display Control

Sensors

Direct Observation

Automobile Lateral Tracking Loop

External Environment

Goal Selection
Route Selection
Lane/Line Selection
Lane/Line Tracking
Vehicle

Desired Line

Strategic Factors
Hazard Monitoring
Threats
Disturbances

Goal
Route

Best Line
Lane Switching
Traffic
Speed

Wheel Position (force)
Acceleration
Velocity
Position

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

(Courtesy of James Kuchar. Used with permission.)
Intent Observability States

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

(Courtesy of James Kuchar. Used with permission.)