A Class Note for Traffic Flow Theory (Human Factors)

Professor Gang-Len Chang
Some important performance characteristics can be identified to aid in the formulation of a comprehensive transfer function for the driver. Even if a comprehensive transfer function for the driver has not yet been formulated,

Salient performance aspects of the human in the vehicle or an individual human-vehicle comprises analysis.

Development of a molecular model of traffic flow can be identified to aid in the formulation.
Those will be described...

- Perception-reaction time
- Control movement time
- Response Distances and Times to Traffic Control Devices
- Response to Other Vehicle Dynamics
- Specific Maneuvers at the Guidance Level
- Obstacle and Hazard Detection, Recognition, and Identification
- Individual Differences in Driver Performance
- Braking, speed and acceleration Performance
- Continuous Driver Performance
- Gap Acceptance and Merging
- Stopping Sight Distance
- Intersection Sight Distance
- Speed Limit Changes
- Distractors On/Near Roadway
The Driving Task

- A knowledge-based behavior: Route planning and guidance while en route
- How enroute diversion and route changes brought about by ITS technology affect traffic flow
- A rules-based: maintenance of a safe speed and proper path relative to roadway and traffic elements. (dynamic inputs)
- A skill-based control: second-by-second exchange of information and control inputs between the driver and the vehicle.
- Most control activities are performed "automatically," with little conscious effort
The Driving Task

Intersection Layout (Illustrating Concepts of Clarify and Simplify)

- Given the short time drivers have to process a large amount of information
- Providing clear and accurate information can help drivers navigate
- The ability for a driver to successfully accomplish that task is greatly impacted by their expectancies
- Reinforced expectancies: drivers respond quickly and correctly and in predictable ways
- Encounter unfamiliar situations: responses may take longer to initiate and errors may result

It is essential to design consistency into intersections to minimize the likelihood of errors

Human Factors Issues in Intersection Safety, November 2009, United States Department of Transportation, Federal Highway Administration (FHWA-SA-10-005)
Factors directly or indirectly affect the control level of performance.

Rules & knowledge govern driver decision making.

Inputs enter the driver-vehicle system from other vehicles, the roadway, driver.
Lag in time between detection of an input (stimulus) and the start of initiation of a control or other response.

- Reaction time (sec)
- Minimum reaction time for that modality
- Empirically derived slope, around 0.13 (sec)

\[ PRT = a + bH \] (Hick-Hyman "Law")

- More decisions to be made on a busy urban facility
- Each of those added factors increase PRT
- Time for the driver to move foot from the accelerator to the brake pedal for brake application

<table>
<thead>
<tr>
<th>Component</th>
<th>Time (sec)</th>
<th>Cumulative Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Perception</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>Eye Movement</td>
<td>0.09</td>
<td>0.4</td>
</tr>
<tr>
<td>Fixation</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Recognition</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2) Initiating Brake Application</td>
<td>1.24</td>
<td>2.74</td>
</tr>
</tbody>
</table>

(Hooper-McGee 1989)
Lognormal Distribution of Perception-Reaction Time

- There cannot be a negative reaction time.
- Time starts with onset of the signal with no anticipation by the driver.
- Actual shape of the distribution has a marked positive skew.

There is a positive skew in the probability density function. It cannot be 0 (negative reaction time) or greater than 6.3 (impossible reaction time).

The Log-normal probability density function is defined as follows:

\[ f(t) = \frac{1}{\sqrt{2\pi \xi^2}} \exp \left( -\frac{(\ln(t) - \lambda)^2}{2\xi^2} \right) \]

where: \( \lambda \) is the mean of the distribution, \( \xi \) is the standard deviation of the distribution, and \( t \) is the reaction time.

Two parameters define the shape of the distribution:

- LN(t) for such percentile levels as 0.50 (the median), the 85th, 95th, and 99th can be obtained by Z score of 0.00, 1.04, 1.65, and 2.33 and then solving for t.

Smaller data sets will benefit more from a tolerance interval approach to approximate percentiles (Odeh 1980).
Brake PRT (Log Normal Transformation)

The driver does not know when or even if the stimulus for braking will occur

The driver is aware that the signal to brake will occur

<table>
<thead>
<tr>
<th></th>
<th>&quot;Surprise&quot;</th>
<th>&quot;Expected&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.31 (sec)</td>
<td>0.54</td>
</tr>
<tr>
<td>Standard Dev</td>
<td>0.61</td>
<td>0.1</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.17 (no unit)</td>
<td>-0.63 (no unit)</td>
</tr>
<tr>
<td>$\xi$</td>
<td>0.44 (no unit)</td>
<td>0.18 (no unit)</td>
</tr>
<tr>
<td>50th percentile</td>
<td>1.18</td>
<td>0.53</td>
</tr>
<tr>
<td>85th percentile</td>
<td>1.87</td>
<td>0.64</td>
</tr>
<tr>
<td>95th percentile</td>
<td>2.45</td>
<td>0.72</td>
</tr>
<tr>
<td>99th percentile</td>
<td>3.31</td>
<td>0.82</td>
</tr>
</tbody>
</table>

95th percentile value is very close to the AASHTO (2.5 sec) estimating both stopping sight distance and other kinds of sight distance (Lerner et al. 1995)
None of the age differences were statistically significant.

Case 1. Closed Course, Test Vehicle

12/ Older: Mean = 0.82 sec; SD = 0.16 sec
10/ Young: Mean = 0.82 sec; SD = 0.20 sec

Case 2. Closed Course, Own Vehicle

7/ Older: Mean = 1.14 sec; SD = 0.35 sec
3/ Young: Mean = 0.93 sec; SD = 0.19 sec

Made stopping maneuvers in response to the emergence of the barrier.

Case 3. Open Road, Own Vehicle

5/ Older: Mean = 1.06 sec; SD = 0.22 sec
6/ Young: Mean = 1.14 sec; SD = 0.20 sec

Approximate real-world driving conditions.
One driver failed to notice the barrel, or at least made no attempt to stop or avoid it.

One out of 12 of the drivers in the open road barrel study (Case 3) did not appear to notice the hazard at all.

Thirty percent of the drivers confronted by the artificial barrier under closed-course conditions also did not respond appropriately.

How generalizable percentages to driver population remains an open question.
Control Movement Time

*AASHTO Braking Distance Formula (AASHTO 1990)

$$MT = a + b\sqrt{A}$$ (a variant of Fitts' Law)

- Movement time (sec)
- Minimum response time lag (no movement)
- Empirically derived slope
- Distance from the starting point to end point

Braking Inputs: sensitive to age, condition of the driver, and circumstances such as degree of workload, perceived hazard or time stress, and preprogramming by the driver

- Greatly influenced by vertical separation of the pedals (Hoffman 1991)
- Ballistic model in which amplitude A does make a difference (Berman 1994)

Steering Response Times: latency, deviation from the pre-event pathway->

Not dependent upon the car's prior position with respect to the opening car door

*AASHTO (American Association of State Highway and Transportation Officials)
Traffic Control Device (TCD) Information Processing

Among many variables, we’ll see the following major concerns:

- **Detect**
  - Size
  - Shape
  - Color
  - Complexities of Surroundings
  - Brightness Contrast

- **Understand**
  - Illumination
  - Visual Acuity
  - Symbol or Letter Characteristics
  - Word Meaning
  - Color Meaning

- **Conspicuity**
- **Legibility**
- **Coding System**

Drivers' Workload

**SIGNAL VALUE**
- Perceived Risk
- Social Customs and Norms
- Background Experience

**Field Dependency**
- Motivation
- Probability of Punishment
- Enforcement Efforts

**Amount of Information**
- Uncertainty
- Individual Differences

**Level of Exposure**
- Length of Exposure

**INFORMATION PROCESSING CAPABILITIES**

Traffic Signal Change

- Sign Visibility and Legibility
- Real-Time Displays and Signs
- Reading Time Allowance

**EDUCATION**
- Level of Education
- Driver Education
- Defensive Driving Course
Drivers response lag to signal change \( \text{time of change to onset of brake lamps} \)

Inelastic with respect to distance from the traffic signal at which signal state changed

PRT Averaged 1.3 sec, 85th percentile 1.9 sec, 95th percentile at 2.5 sec
\((\text{Chang et al. 1985})\)

PRT Averaged 1.5 sec, 85th percentile 2.34 sec, 95th percentile at 2.77 sec
\((\text{Wortman and Matthias 1983})\)
The psychophysical limits to legibility and identification sign legends are the resolving power of the visual perception system.

- **Visual acuity** is 20/20 if a person can recognize 1/3 in letter at a distance of 20ft.
- **Visual acuity** is 20/x if a person can recognize the letters at the distance 20/x times the distance required by a person with visual acuity 20/20.
- **Visual acuity** is worse when an object is moving.
Visual acuity ratings are related to the size of objects in terms of visual arc, radians and legibility indices

\[ \Delta = 2 \arctan \left( \frac{L}{2D} \right) \]

\( L = \text{diameter of the target (letter or symbol)} \)
\( D = \text{distance from eye to target in the same units} \)

The best visual acuity that can be expected of drivers under optimum contrast conditions so far as static acuity is concerned

Sizable numbers of older drivers is considered

(O’Leary and Atkins 1993)

<table>
<thead>
<tr>
<th>Snellen Acuity</th>
<th>Visual angle of letter or symbol</th>
<th>Legibility Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/3 (20/10)</td>
<td>2.5</td>
<td>13.7</td>
</tr>
<tr>
<td>6/6 (20/20)</td>
<td>5</td>
<td>6.9</td>
</tr>
<tr>
<td>6/9 (20/30)</td>
<td>7.5</td>
<td>4.6</td>
</tr>
<tr>
<td>6/12 (20/40)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>6/15 (20/50)</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>6/18 (20/60)</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

“Best case”
With the advent of Intelligent Transportation Systems, traffic flow modelers must consider the effects of changeable message signs on driver performance in traffic streams.

Depending on the design of such signs, visual performance to them may not differ significantly from conventional signage.
Reading speed is affected by a host of factors such as the type of text, number of words, sentence structure, information order, whatever else the driver is doing, the purpose of reading, and the method of presentation (Boff and Lincoln 1988).

"Exposure time" / "reading time" used in estimating how long drivers will take to read and comprehend a sign with a given message (Dudek 1990).
The Vehicle Ahead

- As the rate of change of visual angle becomes geometric, the perceptual system triggers a warning that an object is going to collide with observer/ pulling away from observer (Schiff 1980)

The Vehicle Alongside

- Radial motion (car alongside swerving toward or away from the driver) detection would follow the same pattern as the vehicle ahead case
- No study concerned with measuring this threshold directly was found
Hazard Detection

- An object subtending less than 5 minutes of arc will be detected by all but 1 percent of drivers under daylight conditions provided they are looking in the object's direction (Picha 1992)

- After nightfall, such targets with similar contrast subtend around 2.5 times the visual angle

Recognition and Identification

- **Recognition**: decide if the object, whatever it is, is a potential hazard
- **Identification**: a driver actually can tell what the object is

If the decision is made that the object is too large to pass under the vehicle, then either evasive action or a braking maneuver must be decided upon
**Gender**

- Fine finger dexterity and color perception are areas in which women perform better than men, but men have an advantage in speed.
- Reaction time tends to be slightly longer for women than for men the recent popular book and PBS series, *Brain Sex* *(Moir and Jessel 1991)* has some fascinating insights into why this might be so. This difference is statistically but not practically significant.
- For the purpose of traffic flow analysis, performance differences between men and women may be ignored *(Kroemer, Kroemer, and Kroemer-Ebert 1994)*.

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**Driver Impairment**

- **Drugs**
  Alcohol abuse in isolation & combination with other drugs, legal has a generally deleterious effect on performance *(Hulbert 1988; Smiley 1974)*.

- **Medical Conditions**
  Driver's performance of *medical conditions* is indistinguishable from the general driving population *(Koppa et al. 1980)*.
Although a number of aspects of human performance related to driving change with the passage of years age is a poor predictor of performance. The cognitive trends are very variable in incidence and in their actual effect on driving performance.

**VISUAL PERCEPTION CHANGE**

- **Loss of Visual Acuity (static)**
  not a very significant factor in discerning path guidance devices and markings

- **Light Losses & Scattering in Optic Train**
  a given level of contrast of an object has to be increased by a factor of anywhere from 1.17 to 2.51 for a 70 year old person to see it, as compared to a 30 year old (Blackwell & Blackwell 1971)

- **Glare Recovery**

- **Figure/Ground Discrimination**

**COGNITIVE PERFORMANCE CHANGE**

- **Information Filtering Mechanisms**
  Older drivers reportedly experience problems in ignoring irrelevant information and correctly identifying meaningful cues (McPherson et al. 1988)

- **Forced Pacing under Highway Conditions**

- **Central vs. Peripheral Processes**
  Older driver safety problems relate to tasks that are heavily dependent on central processing
1 Human Transfer Function for Steering

- Steering can be classified as a special case of the general pursuit tracking model (after Sheridan 1962)

Mathematical Expression

\[ g(s) = Ke^{-ts} \frac{(1 + T_Ls)}{(1 + T_Ls)(1 + T_Ns)} + R \]

- Empirically derived for a given control situation

Pursuit Tracking Configuration

- Desired input forcing function
- Reaction time
- System error function
- What vehicle seems to be doing

2 Performance Characteristics Based on Models (Godthelp 1986)

- Driver starts maneuver with a lead term the curve actually begins
- This precognitive control action finishes shortly after the curve is entered
- Steady-state curve driving follows, with the driver making compensatory steering corrections
**Braking Performance**

**Open-Loop Braking Performance**

- **Inputs are specified**

- **Initial speed** (km/h)

\[ d = \frac{V^2}{257.9f} \]  
(AASHTO 1990)

- **braking distance** (meters)

- **Coefficient of friction**

**Closed-Loop Braking Performance**

- **Allow driver to adjust inputs, more representative of real world**

**Percentile Estimates of Steady State Deceleration**
(Fambro et al. 1994)

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Mean (g)</th>
<th>Standard Deviation</th>
<th>75th Percentile (g)</th>
<th>90th Percentile (g)</th>
<th>95th Percentile (g)</th>
<th>99th Percentile (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-0.55g</td>
<td>0.07</td>
<td>-0.43</td>
<td>-0.37</td>
<td>-0.32</td>
<td>-0.24</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.07</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75th Percentile</td>
<td>-0.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90th</td>
<td>-0.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95th</td>
<td>-0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99th</td>
<td>-0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- unexpected obstacle or object encountered on a closed course
- expected braking, but unsure when the signal would come

The ratio of unexpected to expected closed-loop braking effort: **1.22** under the same pavement conditions

* *AASHTO (American Association of State Highway and Transportation Officials)*
Steady-State Traffic Speed Control

- Drivers perform a tracking task with the speedometer as the display, and the accelerator position as the control input.
- Driver response to the error between the present indicated speed and the desired speed is to change the pedal position in the direction opposite to the trend in the error indication.
- The growing prevalence of cruise controls undoubtedly will reduce the amplitude of this speed error pattern in a traffic stream by half or more.

Acceleration Control

- The actual acceleration rates are typically much lower than the performance capabilities of the vehicle *(particularly a passenger car)*.
- If the driver removes his or her foot from the accelerator pedal drag and rolling resistance produce deceleration at about the same level as "unhurried" acceleration, approximately 1 m/sec at speeds of 100 km/h or higher. *(ITE 1992)*
Gap Acceptance

The driver entering or crossing a traffic stream must evaluate the space between a potentially conflicting vehicle and himself or herself and make a decision whether to cross or enter or not.

**Time gap:** The time between the arrival of successive vehicles at a point is the time gap.

**Critical time gap:** The least amount of successive vehicle arrival time in which a driver will attempt a merging or crossing maneuver.

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**Critical Gap Values for Un-signalized Intersections (HCM 1985)**

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Control</th>
<th>Average Speed of Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50 km/h</td>
</tr>
<tr>
<td></td>
<td>Number of Traffic Lanes, Major Roadway</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>None</td>
<td>5.0</td>
</tr>
<tr>
<td>2</td>
<td>Permissive Green¹</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>Stop</td>
<td>6.5</td>
</tr>
<tr>
<td>4</td>
<td>Stop</td>
<td>6.0</td>
</tr>
<tr>
<td>4</td>
<td>Yield</td>
<td>5.5</td>
</tr>
<tr>
<td>5</td>
<td>Stop</td>
<td>5.5</td>
</tr>
<tr>
<td>5</td>
<td>Yield</td>
<td>5.0</td>
</tr>
</tbody>
</table>

- The range of gap times under the various scenarios is 4~8.5 sec
- In a stream traveling at **50 km/h (14 m/sec)**
  gap distance: 56 ~ 119m
- In a stream traveling at **90 km/h (25 m/sec)**
  gap distance: 100 ~ 213m
Theoretically as short a gap as three car lengths (14 meters) can be accepted if vehicles are at or about the same speed, as they would be in merging from one lane to another. This is the minimum, however, and at least twice that gap length should be used as a nominal value for such lane merging maneuvers.

Five different gap acceptance situations.

1. Left turn across opposing traffic, no traffic control
2. Left turn across opposing traffic, with traffic control (permissive green)
3. Left turn onto two-way facility from stop or yield controlled intersection
4. Crossing two-way facility from stop or yield controlled intersection
5. Turning right onto two-way facility from stop or yield controlled intersection
A realistic worst case will have an **Stopping Sight Distance** *(at a velocity of 88 km/h)*

### Percentile Estimates of PRT

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Case 1 Test Vehicle Closed Course</th>
<th>Case 2 Own Vehicle Closed Course</th>
<th>Case 3 Own Vehicle Open Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>50th</td>
<td>0.82 sec</td>
<td>1.09 sec</td>
<td>1.11 sec</td>
</tr>
<tr>
<td>75th</td>
<td>1.02 sec</td>
<td>1.54 sec</td>
<td>1.40 sec</td>
</tr>
<tr>
<td>90th</td>
<td>1.15 sec</td>
<td>1.81 sec</td>
<td>1.57 sec</td>
</tr>
<tr>
<td>95th</td>
<td>1.23 sec</td>
<td>1.98 sec</td>
<td>1.68 sec</td>
</tr>
<tr>
<td>99th</td>
<td>1.39 sec</td>
<td>2.31 sec</td>
<td>1.90 sec</td>
</tr>
</tbody>
</table>

Adapted from Fambro et al. (1994).

### A case example

- **PRT:** \(1.57 \times 24.44 = 38.4 \text{ m}\)
- **Braking Distance:** 82.6 m
- **SSD:** \(38 + 83 = 121 \text{ m}\)

### Human Transfer Function for Steering

- **gain or sensitivity term**
- **Reaction time**

\[
g(s) = \frac{Ke^{-ts}(1 + T_Ls)}{(1 + T_Ls)(1 + T_Ns)} + R
\]

Empirically derived for a given control situation.

### standard AASHTO SSD

- **PRT:** \(2.50 \times 24.44 = 61.1 \text{ m}\)
- **Braking Distance:** 47.3 m
- **SSD:** \(61 + 47 = 108 \text{ m}\)
Case I
- No traffic control
- Initiates acceleration/deceleration based upon perceived gap
- Own vehicle/open road

Case II
- Yield control for secondary roadway
- Stretch from the time that the YIELD sign first could be recognized ~
- the time that the driver began a deceleration maneuver / speeded up to clear the intersection in advance of cross traffic.
  *(Hostetter et al. 1986)*

Case III
- Stop control on secondary Roadway
- Drivers complete monitoring of the crossing roadway before coming to a stop *(Hostetter et al. 1986)*

### Stop control on secondary Roadway

<table>
<thead>
<tr>
<th></th>
<th>4-way</th>
<th>T-Intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRT 1</td>
<td>2.2 sec</td>
<td>2.8</td>
</tr>
<tr>
<td>PRT 2</td>
<td>1.8</td>
<td>2.6</td>
</tr>
<tr>
<td>PRT 3</td>
<td>1.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**PRT1:** starts with the vehicle at rest

**PRT2:** first head movement at stop

**PRT3:** the last head movement in the opposite direction of the intended turn or toward the shorter sight distance leg

*(Hostetter et al. 1986)*
Drivers tend to **adapt to sustained speed** over a period of time, such that the perceived velocity lessens \( (G\text{stalter and Hoyos }1988) \).

When drivers go **from a lower speed to a higher one**, they also **adapt**, such that the higher speed seems higher than in fact it is, hence errors of 10 to 20 percent slower than commanded speed occur.

**Investigate the possible impact patterns of 65mph speed limit increase on interstate highway fatalities**

**Increased speed limit caused a significant increase in highway fatalities in beginning periods/decrease over time.**
Drivers passing by accident scenes, unusual businesses or activities on the roadside, construction or maintenance work, or occurrences irrelevant to the driving task tend to shift sufficient attention to degrade their driving performance.

"rubber neck" problem.

How to model the driver response to such distractions?

In the absence of specific driver performance data on distractors, the individual driver response could be estimated by injecting a sudden accelerator release with consequent deceleration from speed.
Thank you for your attention
Q & A