Impact Analysis of Roadway Surface and Vehicle Conditions on Fleet Formation for Connected and Automated Vehicles

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Outline

• Background

• Objectives

• Research Focus
  (1) Issue 1: understanding of the impact of roadway surface, vehicle, and other environmental factors on skid resistance
    • pavement friction behavior for in-service roads
    • other vehicle and tire conditions on skid resistance
  (2) Issue 2: time dependent dynamic fleet model
    • introducing base model
    • impact analysis due to disturbances

• Conclusion and Further Work
Background:

- Over 6.7 million crashes reported by Police in 2018. Nearly 37,000 people died in 2018.
- Over 52,000 vehicles involved in fatal crashes in 2018.

Source: (FHWA-Safety, 2019)
Background:

- Economic cost of all motor vehicle traffic crashes in the U.S in 2010 was estimated $242 billion, as tangible losses.

- When intangible costs such as the quality of life valuations are considered, the total cost of societal harm due to traffic crashes in 2010 was estimated $836 billion.
How to set car following spacing in a CAV Fleet?
Objective

To investigate the impact of roadway, vehicle, and other environmental conditions on safe formation of CAV fleets.
Issue 1 – Roadway Surface Skid Resistance

It is understood that…

• Roadway surface must have an appropriate level of pavement friction to be able to keep vehicles safely in the lane;

  ➢ Poor pavement conditions (such as worn surface in wet condition) is one of the major contributing factors in roadway departure crashes;

• FHWA indicates that about 70 percent of wet pavement related crashes may be prevented by improved pavement friction.

Source: (FHWA-Safety, 2016)
HOW TO assess roadway friction-related safety?

1. field measurement and monitoring
   - expensive and time consuming

2. modeling and estimation
   - laboratory test + field sampling
   - computer modeling and validation
Laboratory work to prescreen polishing susceptibility

- short and simple laboratory tests
e.g., versatility of testing different HMA specimens
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Short-term field sampling at limited locations
Friction is affected by two opposing actions in real world:
- Surface polishing due to traffic load
- Roughening action due to rainfall and environmental factors
Implication of Friction on Stopping Sight Distance

• According to FHWA and NTSB a significant proportion of traffic crashes directly or indirectly related to inadequate stopping sight distance.

If we isolate surface friction as a focus in the analysis…
• A commonly used formula to derive stopping sight distance (SSD) is based on well-established fundamental principles of mechanics.

\[
SSD = V_t_r + D_B
\]

\[
D_B = \frac{v^2}{2g(\mu+G)}
\]

• SSD consist of two parts:
  - Reaction distance due to human driver, \( V_t_r \)
  - Braking distance due to mechanical process, \( D_B \)
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- $D_B$ is the focus of discussion in the CAV environment
- $D_B$ can be measured based on AASHTO recommended Coefficient of Friction. For example,

<table>
<thead>
<tr>
<th>Design Speed</th>
<th>Running Speed</th>
<th>1990 and 1994 AASHTO Coeff. of Friction for $f_{WET}$</th>
<th>AASHTO Coeff. of Friction for trucks, $f_{TR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(20 mph)</td>
<td>(20 mph) 30 kph</td>
<td>(20 mph) 32 kph</td>
<td>0.40</td>
</tr>
<tr>
<td>(30 mph)</td>
<td>(28 mph) 50 kph</td>
<td>(28 mph) 45 kph</td>
<td>0.35</td>
</tr>
<tr>
<td>(40 mph)</td>
<td>(36 mph) 65 kph</td>
<td>(36 mph) 58 kph</td>
<td>0.32</td>
</tr>
<tr>
<td>(50 mph)</td>
<td>(44 mph) 80 kph</td>
<td>(44 mph) 71 kph</td>
<td>0.30</td>
</tr>
<tr>
<td>(60 mph)</td>
<td>(52 mph) 100 kph</td>
<td>(52 mph) 84 kph</td>
<td>0.29</td>
</tr>
<tr>
<td>(70 mph)</td>
<td>(58 mph) 115 kph</td>
<td>(58 mph) 93 kph</td>
<td>0.28</td>
</tr>
</tbody>
</table>
NCHRP report 400

Instead of specifying the coefficient of friction AASHTO recommend using the following equation

$$D_B = \frac{V^2}{2(a+gG)}$$

- $a$ is the recommended deceleration rate, 3.4 m/s$^2$
- $V$ is design speed (not vehicle running speed)
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Consumer Report Braking Distance vs. AASHTO
Different vehicles at same speed on same road may require different Braking Distances ($D_B$).

So Pavement Friction is Not the Only major factor to consider for a safe stop.
Adhesion vs Hysteresis

- The traditional friction theory, which is accepted now, is based on metallic friction theory: $\mu = \frac{F}{W}$

- Traditional friction law doesn’t work as desired for rubber.

**Adhesion:** depends mostly on micro-level surface roughness

**Hysteresis:** depends mostly on macro-level surface roughness
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Summary

- Road surface conditions are different because construction materials vary from situation to another. Thus, tire-pavement friction varies with location and time.

- Tire tread and quality may vary from one vehicle from another.

- Vehicle braking effect and stability systems may also function differently.
1. Other factors also affect the roadway resistance and safe stopping of a vehicle.
2. A passive (pre-determined) system won’t be able to truthfully and timely describe the impact on CAV operation.
Total Resistance < Driving Force

Driving Force $\propto$ Power Produced at Engine

Power Produced at Engine $\propto$ Engine Load

Total Resistance $\propto$ Engine Load, Weight, Speed
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\[ R_T = R_R + R_C + R_G + R_{air} \]

\[ F_D > R_T \]

Driving Power \( P_D = \lambda P \)

\[ P_D = VF_D \]

\[ P_D \propto R_T \]
Resistance and Engine Power

Losses of fuel energy in a vehicle in city usage (highway usage)

[U.S. National Academy of Science, 2006]
Braking Process

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• According to Newton’s law

\[ m \ddot{x} = F - m g \sin \theta - \frac{\rho A C_d}{2} \dot{x}^2 - d_m \]  \rightarrow (1)

• The engine of vehicle is modeled as :

\[ \dot{F} = -\tau F + u \]  \rightarrow (2)
Platoon Formation

- Number of vehicles, $N$
- All vehicles with the same speed, $v_d$
- A desired minimum distance, $L$, between two successive vehicles.
String Stability:
It is required to ensure that the spacing errors do not amplify upstream from vehicle to vehicle in a platoon.
String/Platoon Stability

A sufficient condition for string stability is that the spacing error must not increase as it propagates through the platoon.

The spacing error propagation transfer function is defined by:

\[ R_i(s) = \frac{e_i(s)}{e_{i-1}(s)} \]

\[ ||R_i(s)||_\infty \leq 1 \quad \text{and} \quad R_i(t) > 0 \quad i = 1, 2, \ldots, N \]
Calculation of the Spacing Error Propagation Transfer Function

\[
R_i(s) = \frac{e_i(s)}{e_{i-1}(s)}
\]

\[
e_i(s)[S^3 + c_a S^2 + S (c_v + c_p h) + c_p] = e_{i-1}(s)[c_v S + c]
\]

\[
R_i(s) = \frac{c_v S + c_p}{S^3 + c_a S^2 + (c_v + c_p h) S + c}
\]
Performance of the Transfer Function ($G_i(s)$)

- Stability of the System (Poles)
- Performance Measures/Parameters
Performance Parameters of the Transfer Function \( (G_i(s)) \)

Second order systems

- \( t_r \): Rise time (10% - 90%)
- \( M_p \): Maximum overshoot
- \( t_p \): Time to peak
- \( t_s \): Settling time (to within a specified tolerance band)

Settling tolerance:
\[ \pm 5\% \text{ or } 2\% \text{ or } 1\% \]
Simulation Results of Base Model
Tuning of the Parameters
Trial & Error Method

- Testing with different parameter combinations
- Keeping string stability requirements when deciding on parameter values
- Evaluating testing results by looking at the risetime and settling time

```matlab
sys = 

4 s + 4
-------------------
\[ s^3 + 4 s^2 + 8 s + 4 \]

Continuous-time transfer function.

S =

struct with fields:
    RiseTime: 1.5036
    SettlingTime: 4.4157
    SettlingMin: 0.9036
    SettlingMax: 0.9988
    Overshoot: 0
    Undershoot: 0
    Peak: 0.9988
    PeakTime: 8.3283
```
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Representation of Disturbance (2)
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Work is continuing…

• To further characterize and define the impact of driving and vehicle conditions as a form of disturbance to the base model.

• To establish proper parameter ranges to cope with the above impact for safe operation of a CAV fleet.
Thank You!

Any Questions?