Using Autonomous and Connected Trucks to Extend Flexible Pavement Life – Challenge to Opportunity

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Importance of Truck Freight in the US

- In 2019, trucks hauled 11.4 billion tons of cargo (72.5% of US freight by weight) at $72B, 80.4% of transportation revenue (ATA).
- By 2040, it is projected to increase to 15 billions tons (BTS).
- 177 million miles travelled by combination trucks in 2020 (BTS)
Issues in Truck Freight

Cost of Trucking:
- Cost of trucking was $1.7 per mile in 2019 (ATA)
- 15.6 cents per ton compared to 5.1 cents for rail (CBO)
- Driver wages and fuel are the largest items

Congestion:
- $75 billion added operation cost in 2018 in the U.S. (ATRI)
- In Chicago alone, 50 miles of congested roadways resulted in $300 million delay cost (FHWA)

Safety:
- Large trucks account for 10% of all fatal accidents in 2019 (NHTSA)
- 4,100 fatal truck accidents in 2019 (FARS)

Driver Shortage:
- 61,000 (2021)
- 90,000 (by 2025) (ATA)

High Fuel Consumption:
- 5% of total vehicle population, consumes 24% of total transportation fuel in 2021. (EPA)
- Transportation sector is responsible for 30% of US emissions in 2021 (EIA)
CAV/T - Truck Platoons

- Vehicles travelling at highway speed and at close-proximity (as close as 10ft)
- Vehicles save fuel due to air drag reduction (5-15%)
- Level 3 connected platoons have already been tested in the field, level 4 is under testing

Slowik and Sharpe, 2018
Benefits to Truck Freight Using Platoons

Cost of Trucking:
- Autonomous trucking could reduce costs by up to 45% (Engholm et al., 2020)

Congestion:
- Platoons increase traffic capacity by 2%-25%. (Wang et al., 2019)

Safety:
- 94% of accidents are due to human error (NHTSA).
- Automation decreases the accidents caused by human drivers.

Driver Shortage:
- Later stages of platooning could be driverless

High Fuel Consumption:
- Platooning saves 5%-15% fuel (Muratori et al., 2017)

Introduction
Pavement Damage and Platoons

Scenario - Channelized Traffic
- Trucks always follow the same path on the pavements
- Most damaging to the system because of load concentration
- In this scenario, platooning is more damaging than traditional traffic
Reduction of Drag Forces

**Concept**

\[ C_{D,\text{tot}} = C_p + C_{f_{sf}} - C_{p_f} \]

**No lateral shift**

- \( C_{D,\text{lead}} \): 0.29
- \( C_{D,\text{trail}} \): 0.21

**Shifted**

- \( C_{D,\text{lead}} \): 0.29
- \( C_{D,\text{trail}} \): 0.27

She et al. 2018, CDF Analysis and Prediction Model for Air Resistance on Platooned Freight Trucks

*Introduction*
Modelling Truck Aerodynamics

Drag ratio v.s Position

Drag ratio v.s Inter-vehicle separation

Introduction
Pavement Damage and Platoons

Distributed Traffic

- Each platoon follows a specified path
- Optimized fuel usage and minimized pavement damage at the same time
How do Platoons Interact with Infrastructure?

1. How do we identify platoonable segments of a highway system?

2. What is the impact of following distance \((s)\), or rest period, impact on pavement performance?

3. What is the impact of lane positioning \((l)\) on pavement performance?

4. How does platoons change the life-cycle impacts of the pavement system?
Autonomous Platooning and Roadways

Platoonable Segments

Impact of Spacing

Impact of Lane Position

Life Cycle Impacts

Platooning Levels:
1. 1
2. 2
3. 3
4. 4
5. 5

Impact of Spacing:
- Spacing Impact
- Spacing Distribution

Impact of Lane Position:
- Lane Position Impacts
- Lane Position Efficiency

Life Cycle Impacts:
- Trade-Offs
- Fuel Efficiency
- Pavement Life Cycle

"Where Excellence and Transportation Meet"
Road Conditions Suitable for Platooning

Regular Traffic Need to
• Change lanes when needed
• Maintain accessibility (Take exits when needed)
• Freely control speed

Platoons need to
• Have high truck volume on a road to justify platooning
• Freely control speed for fuel efficiency
• Remain continuous
Potential Challenges

- Vehicle density may compromise free flow speeds

*Platooning is most efficient near free flow operation*
Potential Challenges

- Possible conflicts near entry and exit ramps
Finding Platoonable Roadways

1. Vehicle density may compromise free flow speeds needed for platooning (V/C)

2. Possible conflicts near entry and exit ramps may reduce efficiency and affect safety

3. Every 20-mile segment with high truck volume in IDOT GIS data is analyzed considering traffic density and possible conflicts.
Finding Platoonable Roadways

4. Roads are divided into five platoonability levels (PL) with level 3 being the threshold for platoonability. For a platoon of 5 trucks, 83% of interstates are platoonable during peak hours.
Autonomous Platooning and Roadways

Platoonable Segments

Impact of Spacing

Impact of Lane Position

Life Cycle Impacts

Impact of Spacing
Minimum Spacing

- Will the **pavement recover** before the application of the next load?
- What is the impact of **speed and pavement temperature** on recovery?
- What is the **critical spacing** between platooning trucks?
Finite Element Simulations

- Temperature – 70°F
- Loading – 12 kips (Steering) and 34 kips (Tandem)
- Tire type – DTA (Tandem), Steering
- Structure – Thin (70 mph) and Thick (70 mph)
- Materials – Strong and Weak

Wheel Path: 13.3 ft
Finite Element Simulations
Rest Period

50 °F - % Recovery at 10 ft

Rear axle of front truck

Steering axle of following truck

Strain
= Actual Strain
+ Strain(RP, Spacing)
Response Recovery

- For fatigue and rutting, transverse and compressive strains at bottom and middle of AC, respectively, were used as proxy.
- Pavement responses were extended using Gaussian mixture functions.
- FEM indicates that pavement responses recover fully for platoon spacing > 10 ft.
Experimental Results on Rutting

- Experimental results of permanent deformation could be incorporated to reflect platoon rest period conditions.
- Experimental tests are undergoing

From Alrajhi, Ozer, ASU
Minimum Spacing due to Braking

- If the platoon breaks, will there be an **increase in shear stress** at the surface due to overlapping responses?
Minimum Spacing due to Braking

- Spacing – 200ft
- Scenarios – Braking and Turning
- Contact stress database
- Tire pressure (S3) = 110psi
- Loading (P3) = 10kip
- Speed (V3) = 70mph
- Slip ratio (B4, FR6) = 7% (Braking) and 6% (turning)
Minimum Spacing due to Braking

Axle spacing – 4.5 feet
Minimum Spacing

- FEM indicates that pavement responses recover fully for platoon spacing > 10 ft
- Minimum spacing of a platoon is independent of braking and turning conditions
- Influence of rest period is negligible for both fatigue and rutting based on FEM simulations
Autonomous Platooning and Roadways

Platoonable Segments

Impact of Spacing

Impact of Lane Position

Life Cycle Impacts

Levels

Impact of Lane Position

\[ E(e_{UL}) = \int_{LL}^{UL} f(x - s)g(x, \theta)dx \]
Quick Detour #1 - How Do We Design Pavements?

- 95% of all pavements in US have flexible/Asphalt Concrete surface (AC)
- They usually have an AC layer, a granular aggregate base layer and compacted/treated soil, subgrade layer
How Do We Design Pavements?

- Most Common truck type in the US is Class-9 trucks
- 1 single axle and two tandem axles
How Do We Design Pavements?

Pavement Responses

Viscoelastic responses of pavements (finite element, layered elastic etc.)

Pavement Distresses

Damage we see in the field.
(Cracking, permanent deformation etc.)

Mechanistic-Empirical Pavement Design (MEPDG)

Gamez et al 2018

Illinois Center for Transportation
University of Illinois at Urbana-Champaign

“Where Excellence and Transportation Meet”
Lateral Position and Responses

- A shift in the wheel position will result in a shift in pavement responses.

\[ \epsilon_v = f(x) \]

\[ \epsilon_v = f(x - s) \]

x, Lane position (in)
Describing lane position \( s \) as a mixed random variable. Any mix of autonomous and human driven traffic can be represented as \( g(s, \theta) \).
Probabilistic Responses

Impact of Lane Position

Where Excellence and Transportation Meet
Example Section

- N = 1000 trucks per day
- Lane width = 12ft, truck width = 8ft
- Various platooning schemes
  - Human Driven Trucks
  - Channelized Trucks
  - Mixture of Human Driven and Connected Trucks
  - Fully Connected Trucks
Human Driven

Trucks follow a normal distribution

Channelized

All Trucks at the center of the lane

40% Conn.

40% of trucks shifted 12 in. Remaining is human driven

100% Conn.

All trucks are distributed across the lane
Results for 10 Years

Rutting

Cracking Percentage

Impact of Lane Position
Optimization of Lateral Position

- Which platooning scheme minimizes cracking, rutting or pavement roughness?
- Does more sublanes always reduce damage?
- Should sublanes have equal traffic?
Optimization of Lateral Position

- Example of an optimum scheme for seven sublanes
- Outer sublanes carry more traffic than inner sublanes
Autonomous Platooning and Roadways

Platoonable Segments

Impact of Spacing

Impact of Lane Position

Life Cycle Impacts

Levels

1 2 3 4 5

Overlap

Overlap

P

\[ E(\epsilon_1) = \int_{\text{UL}}^{\text{LL}} f(x-s)g(x,\theta)dx \]

Trade-Off

Fuel Efficiency

Pavement Life Cycle

"Where Excellence and Transportation Meet"
Quick Detour #2 - Sustainability

All projects must be sustainable
- Environmentally
- Economically
- Socially

Typical Energy Consumption

- Use (50-85%)
- Materials & Construction (10-40%)
- Maintenance (5-25%)

Tire-Pavement interaction may be modeled to predict fuel consumption, pavement damage, future performance

Advanced technologies like autonomous and connected vehicles may be used to improve sustainability

Life Cycle Impacts

- Material Acquisition, Production
- Construction
- Use
- End of Life
- Maintenance
LCA/LCCA Case Study

- All stages of LCA were considered, including platoon fuel savings
- 4 different structures were selected

Life Cycle Impacts
Traffic Regimes

Channelized

All Trucks at the center of the lane

Human Driven

Trucks follow a normal distribution

50% Con.

50% of trucks channelized. Rest is human driven

100% Con.

All trucks are distributed across the lane

A: Channelized Platoon

B: Human Driven

C: Mixed Platoon with Human Driven

D: Optimized Platoon

All Trucks at the center of the lane

Trucks follow a normal distribution

50% of trucks channelized. Rest is human driven

All trucks are distributed across the lane
Pavement Condition – Structure 1

- Optimizing the lateral position of the vehicles preserve pavement condition longer
- Channelized traffic accelerates damage
Life Cycle Cost Analysis

- Fuel consumption due to roughness follows IRI progression
- Aerodynamic savings are a function of platooning
- Agency costs are constant because of regular intervals
- Optimizing lateral position reduces overall cost

![Life Cycle Impacts Diagram]

**Maintenance at Regular Intervals**

- Human
- Mixed
- Channel
- Optimized

<table>
<thead>
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<th>Energy Consumption (MJ)</th>
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<tr>
<td>Fuel Roughness</td>
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Life Cycle Cost Analysis

- Agency costs are constant because of regular intervals
- Platooning improves fuel consumption
- Optimizing lateral position saves further fuel by reducing roughness related fuel consumption
Life Cycle Assessment

- Agency impacts are constant because of regular intervals
- Platooning improves fuel consumption
- Optimizing lateral position saves further fuel by reducing roughness related fuel consumption
Summary

- Autonomous platooning can be used to improve freight efficiency.
- Platoonability depends on vehicle density and number of interactions between vehicles.
- Probabilistic strains can be used to predict pavement distresses for any traffic mixture.
- Optimum platooning scheme could reduce life cycle costs and environmental impacts (e.g., 46% and 36% for the given example, respectively).
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THANK YOU
Any Questions?

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Reduction of Drag Forces

Concept

\[ C_D,_{tot} = C_p + C_f - C_p_r \]

No lateral shift

\[ C_{D,lead} = 0.29 \]
\[ C_{D,trail} = 0.21 \]

Shifted

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Modelling Truck Aerodynamics

Drag ratio v.s Inter-vehicle separation

Drag ratio v.s Position

x – Lateral displacement
s – Inter-vehicle separation

K(x) = K_{0.1}

Drag ratio, CD/CD_0

index of vehicle within a platoon, i

inter-vehicle distance, s

She et al. 2018, CDF Analysis and Prediction Model for Air Resistance on Platooned Freight Trucks
The Concept of Controlling Pavement Damage Accumulation

Channelized

Optimized

Wheel wander changes magnitude and shape of accumulated damage

Initial Work on Pavement Damage and Platoons

Local Optimization

- Trucks follow each other with slight offset
- Reduced damage due to decreased load concentration
- However, relatively increases fuel consumption by increasing drag
Platoonability of Illinois Roads

Roads are divided into 5 platoonability levels with level 3 being the threshold for platoonability. 89% of interstates are platoonable during peak hours.
Minimum Spacing due to Braking

- If the platoon breaks, will there be an increase in shear stress at the surface due to overlapping responses?
Minimum Spacing due to Braking

- Spacing – 200ft
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- FEM indicates that pavement responses recover fully for platoon spacing > 10 ft
- Minimum spacing of a platoon is independent of braking and turning conditions
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Life Cycle Cost Analysis

Maintenance at Threshold

Present Cost ($M)

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<tr>
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<th>Agency Cost</th>
<th>User Cost</th>
<th>Total</th>
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<tr>
<td>Mixed</td>
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<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Channel</td>
<td>0.5</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Optimized</td>
<td>0.5</td>
<td>2.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Life Cycle Cost Analysis

Maintenance at Threshold

Present Cost ($M)

Human  | Mixed  | Channel | Optimized

Agency Cost  | User Cost  | Total

"Where Excellence and Transportation Meet"
Life Cycle Assessment

![Energy Consumption (MJ) vs. Use and Mat, Const, Maint for different channels: Human, Mixed, Channel, Optimized. The graph shows the energy consumption at maintenance threshold with values for each category: 29.9, 27.9, 25.7, and 22.9.]