Longer Combination Vehicles & Road Trains for Texas?

TxDOT Project 0-6095

August 21, 2009
Objective

- consider the impact that larger, productive trucks would have if permitted on Texas highways
- trucks range from a heavier tridem semi-trailer to a variety of combination trucks, including road trains, i.e. LCVs
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Agenda

1. Introductions
2. Overview of Project
3. Project Progress-to-Date
   a. U.S. LCV Operations and Regulations
   b. Harmonization
   c. Operational Characteristics
   d. Safety Issues
   e. Large Truck Operations
   f. Environmental and Energy Issues
   g. Industry Perspectives
   h. Bridge Impacts
   i. Pavement Consumption
   j. Response
4. Next Stage of Research
   a. Case Studies
   b. Evaluation Approach
Size and Vehicle Weight Focus

- Historically, changes in motor vehicle size and weight regulations were driven by external factors
- Legal limits changed throughout development of highway system
  - System expansion
  - Improvements to vehicles and roads
  - Economic pressures to reduce costs
Size and Vehicle Weight Focus

- Governments enforce maximum weight limitations
  - Likely pay cost of road improvements and maintenance
- Concerns about incremental increase in truck size and weight limitations without corresponding increase in user fees and infrastructure investment
LCV Freeze

- ISTEA (1991) includes most recent revisions in federal truck size and weight limits
- ISTEA thus limits or “freezes” LCV operation on Interstate System to configurations authorized by state officials on or before June 1, 1991
- Allows certain exemptions (grandfather clauses: State must show higher weights would have been allowed before federal limits came into effect)
LCVs may continue to operate only if the LCV type was authorized by State officials (pursuant to State statute or regulation) and in actual lawful operation on a regular or periodic basis on or before June 1, 1991.
U.S. LCV Configurations

**Rocky Mountain Double**
- Length: 48' + 28.5'
- Max GVW: 90 - 117 kips

**Turnpike Double**
- Length: 48' + 48'
- Max GVW: 90 - 147 kips

**Triple**
- Length: 28.5' + 28.5' + 28.5'
- Max GVW: 80 - 131 kips
Major Truck Corridors

- States near Texas currently allowing LCV operations include Oklahoma, Kansas, Nebraska, Colorado, and Missouri.
- Important truck routes traverse Texas to North East, Great Lakes area, and eventually Canada or Mexico.
- Texas, Arkansas, Tennessee, and Kentucky do not permit any type of LCV operations.
U.S. LCV Operations

- Other U.S. states allow operation according to configuration
  - Oregon
    - 6,000 miles open to RMDs
    - Only 3,500 miles open to Triples
Proposals for changes in federal regulation governing vehicle size and weight are always controversial

- Increased highway construction/maintenance costs
- Divert freight from railroads to highways
- Safety concerns
Harmonization
NAFTA Regional Issues

- Truck size and weight regulations important in region
  - > 2/3 of all merchandise traded between three economies moved by truck
NAFTA Region: Canada

- LCVs usually defined as tractor/trailer combinations using
  - Two/ three semitrailers or
  - Trailers with a total vehicle length exceeding normal limit of 82 feet

- In Canada - 10 provinces and 2 territories have authority to establish weight and dimensions

- LCVs currently operate in AB, SK, MB, QC, and Northwest Territories
NAFTA Region: Canada

- National MOU
  - All provinces allow vehicles complying with national weight and dimension standards

- LCVs not covered by MOU
  - Each province has own regulations

- LCVs operate under special permits
  - Specific safety requirements
  - Other restrictions: only certain routes, at certain times or seasons, and speed restrictions
NAFTA Region: Canada

- **Rocky Mountain Double**
  - Length: 53' + 28'
  - Max GVW: 118 - 133 kips*

- **Triple**
  - Length: 28' + 28' + 28'
  - Max GVW: 118 kips

- **Turnpike Double**
  - Length: 53' + 53'
  - Max GVW: 90 - 137.8 kips*

- **B Train Double**
  - Length: 53' + 53'
  - Max GVW: 137.8 kips

- **Queen City Triple**
  - Length: 48' + 28' + 28'
  - Max GVW: 118 kips

*Varies by Number-of-Axles
NAFTA Region: Mexico

- Federal government set truck size, weight, and dimension limits
  - Apply to federal highways
- 31 state governments
  - Can establish truck size and weight limits on roads under their jurisdiction
  - No state has exercised authority to date
In April 2008 - after 14 years of resistance from trucking and industrial organizations - new Mexican Official Norm (NOM-012-SCT-2-2008) enacted

New NOM encompasses 25 configurations of commercial vehicles

- Half can be considered LCVs with 6, 7, 8 or 9 axles
NAFTA Region: Mexico

- New NOM presents major changes to LCV usage, operational issues, and extensive restrictions on 9 axle LCVs - commonly known as *fulls* (T3-S2-R4)

- **T3-S3**
  - Length: 75.5 ft (23 m)
  - Max GVW = 105.8 kips (48 tons)

- **T3-S2-R4**
  - Length: 102 ft (31 m)
  - Max GVW = 146.6 kips (66.5 tons)
Harmonization Challenges

- Lack of political will
  - History of disputes between U.S. and Mexico regarding cross border trucking

- Technical and stakeholder issues
  - Railroad lobby
  - Safety advocacy groups
  - Engineering assumptions about heavy truck impacts on bridges and pavements
Harmonization Challenges

- Jurisdictional complexity
  - U.S. western states want to maintain “grandfather” rights
  - Others wanted the LCV freeze lifted

- Mexican trucks having to adapt to lower weights
Operational Characteristics
Operational Issues

- Roadway geometric design changes may be required to accommodate LCVs
- LCV characteristics (e.g., stability and acceleration speed) may impact traffic operations and safety
- Vehicle weights, dimensions, and connection types may impact basic traffic maneuvers
### Effects of Vehicle Features

<table>
<thead>
<tr>
<th>Vehicle Features</th>
<th>Traffic Congestion</th>
<th>Vehicle Offtracking</th>
<th>Traffic Operations</th>
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<tbody>
<tr>
<td></td>
<td>Low Speed</td>
<td>High Speed</td>
<td>Passing</td>
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<tr>
<td>Size</td>
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<td>Design</td>
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<td>Number of Axles</td>
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<td>Loading</td>
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<td>Gross vehicle weight</td>
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<tr>
<td>Center of gravity height</td>
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<tr>
<td>Operation</td>
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<tr>
<td>Speed</td>
<td>+ E</td>
<td>+ E</td>
<td>- E</td>
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<tr>
<td>Steering input</td>
<td>---</td>
<td>- E</td>
<td>- E</td>
</tr>
</tbody>
</table>

**Source:** FHWA, 2000

 +/- As parameter increases, the effect is positive or negative.

E = Relatively large effect. e = relatively small effect. -- = no effect.
Roadway Geometric Design Impacts

- Lane width
- Turning radius
- Primary vehicle characteristics
  - Wheel base length
  - Number of articulation points

<table>
<thead>
<tr>
<th></th>
<th>5 Axle Semi-Trailer</th>
<th>Turnpike Double</th>
<th>Triple Trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Turning Radius (ft)</td>
<td>45</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Center-line Turning Radius (ft)</td>
<td>41</td>
<td>56</td>
<td>41</td>
</tr>
<tr>
<td>Minimum Inside Radius (ft)</td>
<td>4.4</td>
<td>19.3</td>
<td>9.9</td>
</tr>
</tbody>
</table>

Source: AASHTO, 2004
**Offtracking**

- Low-speed offtracking
- High speed offtracking
- Dynamic high speed offtracking

<table>
<thead>
<tr>
<th></th>
<th>Maximum Offtracking (ft)</th>
<th>Maximum Swept Path Width (ft)</th>
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</thead>
<tbody>
<tr>
<td>Turn Radius (ft)</td>
<td>100</td>
<td>150</td>
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<tr>
<td>Vehicle Type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48 ft Semi-Trailer</td>
<td>10.1</td>
<td>18.4</td>
</tr>
<tr>
<td>53 ft Semi-Trailer</td>
<td>12.1</td>
<td>20.3</td>
</tr>
<tr>
<td>STAA Double</td>
<td>6.3</td>
<td>14.6</td>
</tr>
<tr>
<td>RMD</td>
<td>12.7</td>
<td>21.0</td>
</tr>
<tr>
<td>TPD – 48 ft</td>
<td>17.1</td>
<td>25.3</td>
</tr>
<tr>
<td>TPD – 53 ft</td>
<td>17.9</td>
<td>26.1</td>
</tr>
</tbody>
</table>

Source: TRB, 2003
Acceleration

- Require more power to accelerate
- Intersections
  - Decreased capacity
  - Increased exposure
- Passing
  - Larger gaps to change lanes
  - Longer passing sight distances (8% on 2-lane)
  - Increased exposure
- Larger speed differentials (accident severity)
Braking and Traction

- Braking performance should not be affected
- Heavier trucks may experience traction problems in slippery conditions
  - Can be mitigated through tandem drive axles, automated traction control
Stability

- Steady state induced rollover
  - Centrifugal force exceeds truck’s ability to counteract
  - Static roll stability
  - Primary factors
    - Height of cargo center of gravity
    - Vehicle track width
    - Suspension
    - Tire properties
Stability

- Evasive maneuver induced rollover
  - Truck traveling at high speed must abruptly steer side to side
    - Lateral acceleration amplified at each trailer
  - Rearward amplification and load transfer ratio
  - Primary factors
    - Number of articulation points
    - Length of wheelbase
    - Static roll stability of trailers
Connection Types

- **A Dolly**
  - Tandem-axle dolly connected to preceding semi-trailer by single drawbar; drawbar connected by “hook” and “eye” can pivot on transverse horizontal axis and on longitudinal axis

- **B Train**
  - Second trailer connected directly to first at fifth-wheel mount; better dynamic roll stability; higher payload

- **C Train**
  - Dolly connected by two drawbars; prevents rotation about vertical axis; better dynamic roll stability
Safety Issues
by Avinash Unnikrishnan & Kara Kockelman
LCV Safety Studies

- **Operational Attributes**
  - Studies compare LCV operational needs to roadway designs & speeds.

- **Crash Data Analysis**
  - Comparisons of actual crash rates (per VMT & by outcome) to identify general trends, across vehicle classes.
Operational Attributes
(Harkey et al. 1996)

- **Speed & Acceleration**: Induce speed differentials which may create unsafe conditions.
- **Off-tracking & Encroachment**: 12’ lanes allow for high-speed (high-radius) off-tracking.
- **Trailer Sway**: Not expected to pose significant hazard as long as AASHTO lane width guidance met.
- **Rollover** tendencies: Reduced by decreasing number of articulation points & using longer trailers.
- **Rearward Amplification**: A problem for triple-trailer LCVs.
Operational Characteristics (2)
(Knight et al., 2008)

- LCV safety from perspective of maneuverability, field of view, braking & stability.

- **Recommend technology** to improve safety:
  - Mirror configurations & camera technology to identify blind spots;
  - ABS & electronically-controlled braking systems (EBS) to prevent wheel locking;
  - Steered axles & electronic stability controls to reduce stability risks.

Note: Many have concluded that LCVs do *not* result in additional maneuverability issues, as compared to other combination vehicles.
Operational Characteristics (3)

Overall Conclusions, across multiple studies:

- Do not recommend LCV use on routes with multiple at-grade intersections, railway crossings or single lanes.
- Recommend LCV usage on motorways & freeways with strict enforcement of speed limits & load distribution rules.
Crash Involvement

- Difficult to identify trends from LCV crashes due to a lack of data involving LCVs.

- Longer trucks do not increase accident risk (Vierth et al., 2008), but result in higher casualty ratios (Vierth et al., 2008; Zaloshnja et al. 2004).

- Combination-trucks have significantly lower crash rates, as compared to passenger vehicles & single-unit trucks (Wang et al., 1999, Woodroofe, 2001; Montufar et al. 2007, Abdel-Rahim 2006).
Crash Involvement (2)

- **Under difficult driving conditions** multiple unit trucks have a higher likelihood of crash involvement (Forkenbrock et al., 2003).

- Crash rates are lower for multiple trailer trucks (vs. single-trailer trucks) on interstates & urban roads, but **higher on rural roads** (USDOT 2004).
Data Analysis

- Large Truck Crash Causation Study (LTCCS) Data, 2001-2003
- 785 crashes with 1+ truck over 10,000 lbs (GVWR)
- Regression analyses using ordered probit & heteroscedastic ordered probit models.
- $Y = 0$ to $4$ (no injury, no visible injury/only pain reported, non-incapacitating injury, incapacitating injury, & death)
Two Models...

- $Y = \text{maximum injury severity in a crash}$
- $Y = \text{injury severity (for each involved person)}$

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Max Injury Severity</th>
<th>Injury Severity</th>
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<tbody>
<tr>
<td></td>
<td>Count</td>
<td>%</td>
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<tr>
<td>No Injury ($Y=0$)</td>
<td>10</td>
<td>1.3%</td>
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<tr>
<td>No visible injury (1)</td>
<td>100</td>
<td>12.7</td>
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<td>Non-Incapacitating Injury (2)</td>
<td>262</td>
<td>33.4</td>
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<tr>
<td>Incapacitating Injury (3)</td>
<td>262</td>
<td>33.4</td>
</tr>
<tr>
<td>Death (4)</td>
<td>151</td>
<td>19.2</td>
</tr>
</tbody>
</table>
Likelihood of death rises...

- as the number of lanes falls (by 28%),
- when (largest) involved truck is not an LCV (by 46%),
- when roadway is not a rural freeway (53%) or not an urban freeway (57%),
- when driver unaware of his speeding (94%),
- under non-bright lighting conditions (151%).
Maximum Injury Severity (2)

- Likelihood of death *rises*...
  - with *# trailers* on the largest truck,
  - when *drugs* are involved (by 82%),
  - when driver of largest truck is "emotionally stressed" (48%),
  - on *undivided two-way* facilities (52%),
  - in presence of *sag or crest* curve (54%), &
  - under *non-bright lighting* conditions (by 151%).
Maximum Injury Severity (3)

- Greater uncertainty in crash outcome with…
  - Non-bright conditions,
  - Freeway crash locations,
  - More lanes,
  - Higher truck counts,
  - Fewer trailers,
  - Unstressed driver, &
  - No vertical curvature in alignment.
Model 2: Injury Severity
(all involved parties)

- Likelihood of fatal & severe injury reduced significantly with use of **ITS equipment** (32%) & for males (66%), **but increases when** largest truck is an LCV.

- Presence of **flow restrictions & wet conditions** reduce likelihood of severe injuries by 52% & 38%, respectively.

- As in the max-severity model, likelihood of death **increases on vertical curves, under inadequate lighting, with more involved HDTs, & off freeways.**
Injury Severity (2)

- Greater **uncertainty** in crash outcome with…
  - Male drivers,
  - More ITS equipment on board,
  - Largest truck is not an LCV, &
  - Non-freeway crash location.
Conclusions

- LCVs appear to enjoy significantly lower crash rates, but higher crash costs.
- LCVs are less likely to be involved in fatal crashes, but involve more persons (& more fatal injuries, for severe crashes).
- Can recommend LCV use on freeways (with proper speed & other enforcement), but not on roadways with at-grade intersections.
Large Truck Operations
LCV Operator Surveys

- Objective
  - Insight into LCV use in the U.S. (operator perspective)

- Questions
  - Operations
  - Vehicles
  - Drivers
  - Vehicle Performance/Safety
LCV Operator Surveys

- Conducted telephone surveys
  - Summer 2009

- FMCSA database
  - Separate operators by LCV type
  - Include range of operators
    - Owner operators and larger companies
    - Commodities (harvesters, concrete companies, etc.)

- 65 completed telephone surveys
LCV Operator Surveys

- LCV operators in nine states
  - Northeast
  - Northwest
  - Midwest
  - Southeast

Number of Respondents = 65
Significant Benefits

Number of Responses = 139
Major Costs

- Other: 15%
- Drivers: 11%
- Trailers: 23%
- Permits/Licensing/Training: 23%
- Maintenance: 11%
- Fuel: 46%
- Initial Purchase/Tractors: 18%
- Tires: 38%

Number of Responses = 113
Major Commodities

Number of Responses = 72

- Other: 12%
- Dirt/Rocks/Aggregate: 15%
- Fuel/Oil: 9%
- LTL: 5%
- Lumber/Wood Products: 9%
- Food/Grocery/Beverage: 8%
- General Commodities/Freight: 11%
- Unspecified Bulk: 6%
- Grains/Feed/Fertilizer: 35%
Percentage of Fleet (LCV)

Number of Responses = 49
Percentage Reduction in Truck Loads

Number of Responses = 32
Major Challenges

- Other: 29%
- Highway Restrictions: 10%
- Permits/Licensing/Weight Limits: 14%
- Infrastructure/Maneuverability: 10%
- Freight Volume/Density: 10%
- Varying States' Regulations: 29%
- Qualified Drivers/Training: 30%

Number of Responses = 82
LCV Driver Training

- 58% of respondents provided additional training
  - Written test
  - Driving test with experienced driver
  - Equipment “walk-thru” check
  - Refresher courses
  - Combination of above

- Larger companies had safety instructors/directors
LCV Driver Compensation

Number of Respondents = 46
LCV Driver Compensation

Number of Respondents = 55
Number of Accidents

Number of Respondents = 58

- None: 53%
- Yes, minor incident: 19%
- Yes, major - weather: 10%
- Yes, major - driver error: 16%
- Yes, major - other roadway user at fault: 9%
- Yes, other: 3%
Preliminary Conclusions

- Major benefit
  - Potential for increased payload, yielding productivity gains, and higher revenues

- Major costs
  - Fuel and tires
  - Initial equipment investment

- Commodities varied by region
  - Tend to be bulk commodities
  - “Weigh out” rather than “cube out”
Preliminary Conclusions

- Major challenges
  - Qualified drivers
  - Varying LCV regulations by state
- Major costs
  - Tires and brakes
  - Fuel (initially)
  - Equipment investment
- Driver training varied
  - Function of company size
Preliminary Conclusions

- Compensation structures varied
  - Per mile
  - Per hour
  - Per ton/%
- 62% of respondents pay LCV drivers more
- ~ 50% of respondents LCVs not involved in accidents
  - Cause of accidents varied
    - Weather, driver error, other road users
Environmental and Energy Issues
Increased Congestion

- Congestion increased substantially from 1982 to 2003
  - While largest cities are most congested, congestion occurs (and has increased) in cities of every size

- Liberalizing limits and authorizing LCVs could reduce congestion
  - Fewer truck trips could possibly reduce traffic congestion
Fuel Efficiency

- After driver compensation, fuel costs are typically largest expenditure for heavy-duty vehicle operators.

- At first glance:
  - LCVs and trucks operating at heavier GVWs have lower fuel economy than regular 5 axle trucks at 60,000 and 80,000 lbs.
  - However, LCVs carry heavier loads.
  - More fuel efficient when loading capacity of LCV well utilized.
**ATRI Scenario**

- ATRI (2008) compares energy and emissions of RMD with conventional 5 axle truck
- Scenario - 1,000 ton shipment moved 500 miles:

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>Load (GVW in lbs)</th>
<th>No. of Trips</th>
<th>Fuel Economy (mpg)</th>
<th>Gallons Required for the Delivery</th>
<th>CO2 emissions (tons)</th>
<th>PM emissions (lbs)</th>
<th>NOx emissions (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Axle</td>
<td>80,000</td>
<td>42</td>
<td>5.4</td>
<td>3,889</td>
<td>--</td>
<td>--</td>
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<tr>
<td>RMD</td>
<td>120,000</td>
<td>27</td>
<td>4.2</td>
<td>3,215</td>
<td>- 7.5</td>
<td>- 34</td>
<td>- 0.16</td>
</tr>
</tbody>
</table>

Source: ATRI, 2008
Anheuser-Busch Scenario

Anheuser-Busch evaluated potential benefits of using 97,000 lbs (6 axle) truck instead of 80,000 lbs (5 axle) truck

<table>
<thead>
<tr>
<th>Route</th>
<th>Trucks per week at 80,000 lbs</th>
<th>Trucks per week at 97,000 lbs</th>
<th>Increase in cargo/truck (lbs)</th>
<th>Reduction in diesel fuel/week (gallons)</th>
<th>Reduction in CO2 emissions/week (lbs)</th>
<th>Reduction on roads and bridges per week (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston to San Antonio (198 miles)</td>
<td>128</td>
<td>96</td>
<td>15,000</td>
<td>807</td>
<td>17,996</td>
<td>1,120,000</td>
</tr>
<tr>
<td>Houston to Waco (219 miles)</td>
<td>1,126</td>
<td>845</td>
<td>15,000</td>
<td>7,824</td>
<td>174,475</td>
<td>9,835,000</td>
</tr>
</tbody>
</table>

Source: Jacoby, 2008
Industry Perspectives
Bridge Impacts
Bridge Cost Allocation

- Bridge Replacement, Maintenance/Rehabilitation and New Construction
  - Load related: Axle loads and configuration and GVW
  - Non-load related: Age and Environment

- Allocators
  - Load-related: Live-load bending moments
  - Non-load related: VMT,PCE

- Costs
  - TxDOT
  - 2030 Study
  - User Costs?
  - Analysis period

- Traffic
  - Forecasts
  - Economic Analysis

![Diagram](image)
Live-load Bending Moments
Route Moment Analysis

M O A N S T R
Moment Analysis of Structures

BASIC Batch Processor Menu

(1) Enter or Edit Future Traffic Loads.
(2) Include Dead Load Moments?: NO
(3) Perform Batch Moment Analysis.
(4) Save or Load Future Traffic Loads.
(5) Moment Analysis Interrupt Criteria (% Overload): 50
(6) Enter Inventory Rating Multipliers.

Select a Number (1-6) or <ESC> to Return to BASIC
### Moment Ratios

#### Axle Loads

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<th>Axle</th>
<th>Axle Loads</th>
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<td>Trailer</td>
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<tr>
<td>TOTAL</td>
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#### Axle Load Calculations

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<th>ID #</th>
<th>M 0+</th>
<th>M 0-</th>
<th>MX.RAT</th>
<th>M 1+</th>
<th>M 1-</th>
<th>MX.RAT</th>
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Level I analysis

NCHRP
REPORT 495

Effect of Truck Weight on Bridge Network Costs

$RF_{AS} = RF_{BC} \times \frac{M_{BC, \text{rating vehicle}}}{M_{AS, \text{rating vehicle}}} \times \frac{1}{AF}$

(3.5.1.1)
Bridge Fatigue

Effects of Increasing Truck Weight on Steel and Prestressed Bridges

2003-16
Final Report

Research

UTSA
GIS Data Bridges (BRINSAP/NBI)
Case Study Framework
Bridge Costs Methodology

- Identify candidate vehicle, route and planning horizon.
- Retrieve bridge data with GIS.
- Forecast traffic based on economic inputs (volumes, classification and axle weights).
- Forecast bridge costs for route over planning horizon for LCV and no LCV and annualize.
- Allocate costs based on Cost Allocation methodologies.
Pavement Consumption
Pavement Cost Allocation

- Pavement Reconstruction, Rehabilitation and Resurfacing (3R) costs
  - Load-related: Axle loads
  - Nonload-related: Pavement age and climate

- Allocators
  - Load related: ESALs
  - Non-load related: VMT

- Costs
  - TxDOT
  - 2030 Study
  - User Costs?
  - Analysis period

- Traffic
  - Forecasts
  - Economic Analysis
Pavement Load Related ESALs
Flexible Empirical

\[
\log\left(\frac{W_{tx}}{W_{118}}\right) = 4.79 \log(18 + 1) - 4.79 \log(L_x + L_2) + 4.33 \log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad \text{(Eq. 1)}
\]

\[
G_t = \log\left(\frac{4.2 - p_t}{4.2 - 1.5}\right) \quad \text{(Eq. 2)}
\]

\[
\beta_x = 0.40 + \frac{0.081(L_x + L_2)^{3.23}}{(SN + 1)^{5.19}L_2^{3.23}} \quad \text{(Eq. 3)}
\]

where

- \(W_{tx}\) = number of applications of given axle
- \(W_{118}\) = number of standard axle passes (single 18 kip axle)
- \(L_x\) = load in kips of axle group
- \(L_2\) = axle code (1 for single axle, 2 for tandem axles, 3 for tridem axles, and 4 for quad axles)
- \(\beta_{18}\) = value of \(\beta_x\) when \(L_x = 18\) and \(L_2 = 1\)
- \(p_t\) = terminal serviceability
- \(SN\) = structural number.
Pavement Load Related ESALs
Flexible Mechanistic

- Original ESAL definition:
  \[ \text{ESAL}_x = \frac{\rho_{18}}{\rho_x} \]
  axle cycles to terminal PSI from 18 kips
  axle cycles to terminal PSI from x kips

- Fatigue life \( N_f \) as a fn of tensile strain \( \varepsilon_t \):
  \[ N_f = 0.0795 \varepsilon_t^{-3.291} E^{-0.854} \]

- Rutting life \( N_r \) as a fn of compressive strain \( \varepsilon_v \):
  \[ N_r = 1.365 \times 10^{-9} \varepsilon_v^{-4.477} \]

- Strains are computed with layered elastic analysis (e.g., *Everstress*).
Pavement Load Related ESALs Flexible Mechanistic

\[
ESAL_x = \frac{\rho_{18}}{\rho_x} = \left( \frac{\varepsilon_{t,x}}{\varepsilon_{t,18}} \right)^{3.291}
\]

\[
ESAL_x = \frac{\rho_{18}}{\rho_x} = \left( \frac{\varepsilon_{v,x}}{\varepsilon_{v,18}} \right)^{4.477}
\]
Pavement Load Related ESALs
Rigid Empirical

\[
\log \left( \frac{W_{\text{ex}}}{W_{\text{18}}} \right) = 4.62 \log(18 + 1) - 4.62 \log(L_x + L_2) + 3.28 \log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}}
\]

\[
G_t = \log \left( \frac{4.5 - p_t}{4.5 - 1.5} \right)
\]

\[
\beta_x = 1.00 + \frac{3.63(L_2 - L_2)}{(D + 1)^{8.46} L_2^{3.52}}
\]

where

- \( W_{\text{ex}} \) = number of applications of given axle
- \( W_{\text{18}} \) = number of standard axle passes (single 18 kip axle)
- \( L_x \) = load in kips of axle group
- \( L_2 \) = axle code (1 for single axle, 2 for tandem axles, 3 for tridem axles, and 4 for quad axles)
- \( \beta_{18} \) = value of \( \beta_x \) when \( L_x = 18 \) and \( L_2 = 1 \)
- \( p_t \) = terminal serviceability
- \( D \) = slab thickness in inches.
Pavement Load Related ESALs
Rigid Mechanistic

\[
\text{ESAL}_x = \frac{\rho_{18}}{\rho_x} = \frac{2.0 \left( \frac{MR}{\sigma_{18}} \right)^{1.22} + 0.4371}{10} = 10 \left[ \left( \frac{MR}{\sigma_{18}} \right)^{1.22} - \left( \frac{MR}{\sigma_x} \right)^{1.22} \right]
\]

Where \( MR \) is the Modulus of Rupture of the PC, (ASTM C 78)
# Pavement Costs

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<tr>
<th>District</th>
<th>Route</th>
<th>Lane-miles</th>
<th>Treatment</th>
<th>Trtmt Cost</th>
<th>Summary</th>
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<td>IH 30</td>
<td>140.0</td>
<td>Nothing</td>
<td>$0</td>
<td>$0</td>
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<td>Paris</td>
<td>IH 30</td>
<td>40.0</td>
<td>PM</td>
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<td>$8,000,000</td>
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<td>Light Rb</td>
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<td><strong>Total Need = $36,000,000</strong></td>
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## Costs Attributable to Non-Load Factors

### Table V-8. 2000 Proportion of Federal 3R Pavement Costs Attributable to Non-Load Factors

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<th>Functional Highway Class</th>
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<th>Rigid Pavements (percent)</th>
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<td>14.5</td>
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<td>Local</td>
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Pavement Costs Traffic

Traffic

ESAL

18 kip 18 kip 18 kip

Load Spectra

VMT

Single axle load

Tandem axle load

Tridem axle load

Quad axle load
GIS Data (PMIS, Research Data, LTPP)
Case Study Framework
Pavement Costs Methodology

- Identify candidate vehicle, route and planning horizon.
- Retrieve pavement data with GIS.
- Forecast traffic based on economic inputs (volumes, classification and axle weights).
- Forecast pavement costs for route over planning horizon for LCV and no LCV and annualize.
- Allocate costs based on Cost Allocation methodologies.
Response
Next Stage of Research
Case Studies
LCV Case Study 1

- Existing Interstate Regional Corridor
  - NAFTA
  - Segment
  - LCV Types
LCV Case Study 2

- Existing State Corridor (IH and State)
  - IH-45/IH-37/SH 281
  - Segment
  - LCV Types
LCV Case Study 3

- Toll Road (all vehicles)
  - TTC
  - NAFTA (San Antonio)
  - LCV Types
LCV Case Study 4

- Truck-only Toll Road
  - Laredo-Corpus Christi
  - ICF Study
  - LCV Types
Evaluation Approach
Draft Evaluation Model

Demand for LCV VMT

- Pavements
- Bridges
- Geometry
- Ramps

- Traffic Volumes

- Externalities

- Costs

- Benefits

Operational Productivity:
- Costs (Vehicle)
- Drivers
- Trip Reduction
Evaluation Model

- Demand – loads and trips will vary between the case studies operational benefits.
- Vehicle Operating Costs – current vehicle types/LCV selected model(s)
- Infrastructure Costs – focus on bridges and pavement use factors for geometry and ramps
- Social Costs – emissions, noise for current vehicle types/LCV selected model(s)
- Economic Analysis
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<tr>
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<td>Task 3: Highway Infrastructure for Larger Trucks</td>
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<td>Task 4: First Project Advisory Meeting</td>
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<td>Task 6: Pavement Consumption and LCV Operations</td>
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Note: A Tech Memo will be submitted to the PD & RTI at the end of each non-deliverable task.
THANK YOU!