Impact of Wide-Base Tires on Pavement and Trucking Operation

Imad L. Al-Qadi
Founder Professor of Engineering
Illinois Center for Transportation

Outline

- Current Knowledge of Wide-base Tire
- Impact of “Old” Wide-base Tires on Pavements
- Impact of Wide-base Tires on Trucking Operation
- New Generation of Wide-base Tires
- Analytical Considerations
- Three-Dimensional Finite Element Model
- Pavement Response Analysis
- Summary and Future Research

Tire Development
Wide-base Tire

Dual 275, 295


385 425 445/45R22.5 495

445/45: North America; 495: European Union

Tire Dimension

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>Tire Size</th>
<th>Contact Width (mm)</th>
<th>Rim-Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual (one tire)</td>
<td>11R22.5</td>
<td>184</td>
<td>1054</td>
</tr>
<tr>
<td></td>
<td>12R22.5</td>
<td>201</td>
<td>1085</td>
</tr>
<tr>
<td></td>
<td>255/60R22.5</td>
<td>235</td>
<td>1059</td>
</tr>
<tr>
<td>Wide-base</td>
<td>385/55R22.5</td>
<td>329</td>
<td>958</td>
</tr>
<tr>
<td></td>
<td>385/65R22.5</td>
<td>385</td>
<td>1071</td>
</tr>
<tr>
<td></td>
<td>425/65R22.5</td>
<td>385</td>
<td>1126</td>
</tr>
<tr>
<td></td>
<td>445/65R22.5</td>
<td>340</td>
<td>1155</td>
</tr>
<tr>
<td></td>
<td>465/45R22.5</td>
<td>427</td>
<td>1013</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>Tire Pressure (kPa)</th>
<th>Contact Width (mm)</th>
<th>Axle load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>275/60R22.5</td>
<td>720</td>
<td>37.8</td>
</tr>
<tr>
<td></td>
<td>445/55R22.5</td>
<td>720</td>
<td>37.8</td>
</tr>
<tr>
<td></td>
<td>455/55R22.5</td>
<td>720</td>
<td>37.8</td>
</tr>
</tbody>
</table>

Dual vs. Wide-Base Tires

- Wide-base tires have been used in Europe since the early 1980's
- In 1997, 65% of trailers in Germany used wide-base tires
- Earlier generation of wide-base tires were proven more detrimental to flexible pavement systems than regular dual tires
Impact of Early Wide-Base Tire

• Early generations are 385/65R22.5, 425/65R22.5, and 445/65R22.5:
  – Required high inflation pressure (790 to 890kPa – smaller contact area).
  – Significantly increased pavement damage compared to dual tires:
    • Damage ratios ranged between 1.31 and 4.30.

Christison et al. (1980)
– In-field measured pavement responses
– Conventional wide-base tire induces more damage than dual-tire
  ➔ 1.2~1.8 times more fatigue damage

Akram et al. (1992)
• Multi-Depth Deflectometer at a speed of 90km/h
• Conventional wide-base tire
  ➔ Pavement life reduced by a factor of 2.5~2.8 when wide-base tire is used

Sebaaly et al. (1989)
• Comparison between Dual and Wide-base Tires:
  • 11R22.5, 245/75R22.5
  • 385/65R22.5, 425/65R22.5
  • Testing speed: 58 km/hr
• Pavement Damage Evaluation:
  • 10 and 45% fatigue damage model (Finn et al.1986)
  • Wide-base tire induces significantly more damage than dual tire (1.5 times more fatigue damage)
Huhtala et al. (1992)
- Comparison between Dual and Wide-base Tires
  - 11R22.5, 265/70R19.5
  - 355/75R22.5, 385/65R22.5, 425/65R22.5
  - Test speed: 76 km/hr
- Pavement Damage Evaluation
  - Steering axle is the most detrimental
  - A drive axle equipped with wide-base tires is more damaging than dual-tires by a factor of 2.3 ~ 4.0.

Bonaquist et al. (1993)
- Comparison between dual and wide-base tires
  - 11R22.5
  - 425/65R22.5
- Pavement Damage Evaluation:
  - Wide-base tire induces significantly more damage than dual tire:
    - 3.5 times more fatigue damage
    - 1.9 times more rutting damage

Early Studies on Wide-base Tire

<table>
<thead>
<tr>
<th>Study</th>
<th>Tires Description</th>
<th>Damage Potentials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penn State (1989)</td>
<td>Wide-base (385, 425/65R22.5)</td>
<td>1.5 times more damage</td>
</tr>
<tr>
<td>Huhtala et al. (1992)</td>
<td>Wide-base (385, 425/65R22.5)</td>
<td>2.3 - 4.0 times more damage</td>
</tr>
<tr>
<td>FHWA (1993)</td>
<td>Wide-base (425/65R22.5)</td>
<td>1.9 - 3.5 times more damage</td>
</tr>
<tr>
<td>Cost 334 (1997-2001)</td>
<td>Wide-base (445/50R22.5)</td>
<td>1.2 - 1.6 times more damage</td>
</tr>
</tbody>
</table>

*Other studies at Canada, Europe, South Africa, and UC Barkley

- Code: 445/50R22.5
  - Tire width (mm)/ Tire aspect ratio(%)/ Radial ply (R)/ Rim diameter (in)
Dual vs. Wide-Base Tires

- Earlier generation of wide-base tires were detrimental to flexible pavement
- A new generation of wide-base tires has recently been introduced:
  - Legalized in all states for 355.8kN GVW trucks
  - 16-18% wider than the first generation:
    - Makes use of a new crown architecture that allows wider widths at low aspect ratios
    - Designed based on inch/width principle
  - More uniform tire-pavement contact stress:
    - Reduced tire pressure (690kPa) at high loads (151kN)
  - Potential economic advantages to trucking industry

New vs. Old - Design

Unique Infini-Coil™ technology.
1/4 mile of continuous steel cable to help eliminate casing growth

New Generation of Wide-Base Tires

- New vs. Conventional Wide-base (Footprint width and Tire diameter)
Why Wide-Base Tires NOW?

- Substantial savings to truck freight transportation:
  - Fuel economy
  - Increase hauling capacity (increase payload)
  - Reduced tire cost and repair
  - Ride and comfort
  - Reduced emission and noise
  - Reduced recycling impact of scrap tires
  - Better handling, braking, and safety
Where Does the Fuel Go?

- Aerodynamic drag: At 60 mph (100 kmh), aerodynamic drag consumes approximately 40% of the fuel.
- Mechanical losses: Mechanical losses consume approximately 25% of the fuel.
- Rolling resistance: Rolling resistance accounts for approximately 35% of the fuel consumed.

Fuel Economy/ Hauling Capacity

- Tire rolling resistance accounts for 35% of truck energy consumption.
- Using the new generation of wide-base tires reduces rolling by 12%:
  - Reduction fuel consumption by an average of 4%
  - Savings of fuel per year:
    - A truck that uses 6.5 mpg on duals will be at 6.76 mpg or better with new wide-base generation
    - At 120,000 miles/year, the saving is 710 gallons (3230 liters) per vehicle per year
- Reduces truck weight by 410kg:
  - Increases hauling capacity by 2%
Tire Cost and Repair, Truck Safety, and Ride Comfort

- Requires only one rim compared to two for dual tires
- Requires half the repair time needed for dual tires
- Handling is maintained even when two tires blow out
  - Requires regular monitoring of tire pressure (good practice for all tire types)
- Ride quality is improved by 12% compared to dual tires

Environmental Impact

- Reduced gas emission: Reduction of 1.1 million metric tons of carbon equivalent by 2010 (assuming current market share, 5%)
- Reduce recycling impact of scrap tires:
  - 72.5kg of residual materials for dual tires vs. 53.6kg for a wide-base tire assembly.

Effect of Tires on Track Width

- 0” offset: 95.6”
- 2” offset: 91.9”
- 71.5”
- 74.6”
Implementation of Wide-base Tires in Canada!

Areas of Research

- Dynamic impact of the tire (25% less than dual tires?).
- Recapping of wide-base tires vs. dual tires
- Impact on road Infrastructure

Cost 334 Action in Europe (1997~2001)

- APT and instrumented pavement (17 tire assemblies)
- Intensive research on the effect of wide-base tires
  - Tire type, axle load, tire pressure, and pavement design
- Pavement Damage Evaluation:
  - Developed Tire Configuration Factor (TCF) by stepwise regression analysis
  - Suggested the use of wide-base tires on the steering axle
- Top-down cracking was not considered
**The COST Action (2001)**

- Introduced the concept of tire configuration factor (TCF):

  \[
  \text{TCF} = \left( \frac{\text{width}}{470} \right)^{1.68} \left( \frac{\text{length}}{198} \right)^{-0.85} \left( \text{pres. ratio} \right)^{0.81}
  \]

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>W (mm)</th>
<th>D (mm)</th>
<th>TCF</th>
<th>Wide-base vs. dual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual (275/80R22.5)</td>
<td>368</td>
<td>1054</td>
<td>1.52</td>
<td>----</td>
</tr>
<tr>
<td>Wide (445/50R22.5)</td>
<td>380</td>
<td>947</td>
<td>1.56</td>
<td>2.7%</td>
</tr>
<tr>
<td>Wide (455/55R22.5)</td>
<td>380</td>
<td>998</td>
<td>1.47</td>
<td>-3.1%</td>
</tr>
</tbody>
</table>

**Al-Qadi et al. (2000-)**

- Heavily Instrumented Virginia Smart Road
- Comparison between dual and wide-base tires
  - 445/50R22.5, 455/55R22.5
  - Test parameters: speed, axle load, tire pressure
- Pavement Damage Evaluation:
  - Various transfer functions
  - Steering axle is the most detrimental
  - Wide-base is more fatigue damaging by a factor of 1.35.
  - Equivalent rutting damage
  - Wide-base is less damaging than dual in surface initiated top-down cracking by a factor of 0.45

**Prophète et al. (2003)**

- Instrumented Pavement: Laval University
- Comparison between dual and wide-base tires
  - 385/65R22.5, 455/55R22.5
  - 50km/hr, axle load, tire pressure
  - Wide-base (455) is more fatigue damaging by a factor of 1.54
  - Wide-base (455) is less rutting damaging by a factor of 0.17
  - Surface initiated top-down cracking is less damaging by 0.87 times
NCAT Experimental Study (2005)
• Compared field responses of new generation of wide-base tires to dual tires
• Measurements conducted at 72.4km/h
• Used measured strains at the bottom of HMA and vertical stress on top of subgrade (reported rutting only)
• Both dual and wide-base tires configurations causes the same pavement damage

Current Knowledge of Wide-base Tire

<table>
<thead>
<tr>
<th></th>
<th>Wide-base Tires</th>
<th>Damage Potentials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost 334 (1997-2001)</td>
<td>Wide-base (445/50R22.5)</td>
<td>1.2 - 1.6 times more damage</td>
</tr>
<tr>
<td>Prophète et al. (2003)</td>
<td>New Gen. Wide-base Tire (455/55R22.5)</td>
<td>Less damage in rutting (0.17) and Top-down cracking (0.87)</td>
</tr>
</tbody>
</table>

Code: 445/50R22.5
Tire width (mm)/ Tire aspect ratio(%)/ Radial ply (R)/ Rim diameter (in)

Impacts on Road Infrastructure
• Only a few studies on new wide-base tire
• What do we know:
  – The steering axle is the most damaging
  – Significantly less damage than the first wide-base tire generations
  – Impact on the subgrade is similar to dual tires
  – The layered theory can not be used to quantify tire damage
  – Focus has been on primary roads
Field Testing

• Full-scale pavement testing at the Smart Road

• 12 different flexible pavement sections and a continuously reinforced concrete section.

• The flexible pavement sections were instrumented during construction with a complex array of pressure cells, strain gages, thermocouples, moisture probes, and frost probes.

Smart Road Pavement Design

Al-Qadi and Co-Workers

• Testing at the Virginia Smart Road (2000-2002):
Conclusions of the Exp. Program

- The steering axle is the most detrimental of all tire configurations (small contact area with respect to the carried load)
  - Fatigue Failure: slightly greater for the wide-base tire configuration
  - Subgrade Rutting: approximately equal for the wide-base and dual tires configurations
- Recommendation: Address a broader range of failure mechanisms (i.e., HMA rutting, top-down cracking) using FEM.
Accelerated Loading Facility Testing

Loading matrix
Response testing (20 passes in each case)

<table>
<thead>
<tr>
<th>Tire load (kips)</th>
<th>Speed (mph)</th>
<th>Tire pressure (psi)</th>
<th>Tire configuration</th>
<th>Offset (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6, 8, 10, 12 &amp; 14</td>
<td>5, 10</td>
<td>80, 100 &amp; 110</td>
<td>Dual, WB-455 &amp; WB-425</td>
<td>0</td>
</tr>
</tbody>
</table>

Tire-pressure differential in dual tire (20 passes in each case)

<table>
<thead>
<tr>
<th>Tire load (kips)</th>
<th>Speed (mph)</th>
<th>Control tire pressure (psi)</th>
<th>Variable tire pressure (psi)</th>
<th>Offset (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6, 10 &amp; 14</td>
<td>10</td>
<td>110</td>
<td>30, 50, 70 &amp; 90</td>
<td>0, 6 &amp; 6</td>
</tr>
</tbody>
</table>

Full Depth HMA Test Sections

<table>
<thead>
<tr>
<th>Section A</th>
<th>Section B</th>
<th>Section D</th>
<th>Section F</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA - 2in</td>
<td>Poly. Binder 2.25m</td>
<td>Poly. Binder 2.25m</td>
<td>Poly. Binder 2.25m</td>
</tr>
<tr>
<td>Standard Binder 3.5in</td>
<td>Standard Binder 3.5in</td>
<td>Standard Binder 3.5in</td>
<td>Poly. Binder 2.25m</td>
</tr>
<tr>
<td>Standard Binder 2.5in</td>
<td>Standard Binder 2.5in</td>
<td>Poly. Binder 2.25m</td>
<td>DG Surface 2in</td>
</tr>
<tr>
<td>Lime Modified Subgrade 12in</td>
<td>Lime Modified Subgrade 12in</td>
<td>Lime Modified Subgrade 12in</td>
<td>Lime Modified Subgrade 12in</td>
</tr>
</tbody>
</table>

Thermocouple

Strain gauge
Peak Response Ratio
The ratio of measured peak longitudinal strain between wide-base tire and dual-tire assembly:

$$RR_i = \frac{\varepsilon_w}{\varepsilon_d}$$

At 16km/h and various load and pressure levels:

<table>
<thead>
<tr>
<th></th>
<th>Section A</th>
<th>Section B</th>
<th>Section D</th>
<th>Section F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>Standard deviation</td>
<td>average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>W445</td>
<td>1.28</td>
<td>0.05</td>
<td>1.19</td>
<td>0.05</td>
</tr>
<tr>
<td>W455</td>
<td>1.19</td>
<td>0.05</td>
<td>1.12</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Pavement Thickness Effect
Strain differences between dual-tire assembly and wide-base tire diminish as pavement thickness increases.

Load Effect
- Longitudinal strain at bottom of HMA linearly increases with load.
Experimental Findings

- Ratios of longitudinal strain at bottom of HMA between W-425 tire and dual-tire: 1.12-1.47; between W-455 tire and dual tires: 1.06-1.35 (at 16km/h).
- Higher strain ratios than smart road study, probably not considering reduction in dynamic forces induced by wide-base tires.
- The strain differences between dual-tire assembly and wide-base tire diminish as pavement thickness increases.
- Fatigue damage ratios between wide-base and dual tires is reduced when wander effect is considered. This effect diminishes for thick pavement.
Analytical Model

- Uniform Pressure Distribution Model:
  - Original models developed by Boussinesq (1885) and Burmisier (1954).
  - Uniform vertical pressure distribution
  - Circular areas
- Non-uniform Pressure Distribution Model
  - Nonuniform tire contact pressure model (Schapery, 1980)
  - Distributions are actually non-uniform (Tielking, 1980)
  - Depends on the size and tire type (Roberts, 1987)
    - Tensile strain at the bottom of HMA results in excess of 100% higher than those for uniform pressure

Drawbacks of Current Flexible Pavement Analysis

- Vehicular loading:
  - Stationary circular
  - Can not differentiate between wide-base tires or dual tires (i.e., 385/65R22.5 = 455/55R22.5 and 11R22.5 = 12R22.5).
- Pressure distribution:
  - Uniform vertical contact stress
  - No surface tangential contact stresses
- Effect of vehicle speed & loading:
  - Pavement response to loading is time-independent

Finite Element Approaches

<table>
<thead>
<tr>
<th></th>
<th>Asymmetric</th>
<th>2D Model</th>
<th>3D Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading</td>
<td>Static</td>
<td>Static</td>
<td>Static/Dynamic</td>
</tr>
<tr>
<td>Loading area</td>
<td>Circular</td>
<td>Line load</td>
<td>Versatile</td>
</tr>
<tr>
<td>Computational time and memory</td>
<td>Lowest</td>
<td>Middle</td>
<td>Highest intensity</td>
</tr>
<tr>
<td>Interface modeling</td>
<td>No</td>
<td>Partial</td>
<td>Yes</td>
</tr>
<tr>
<td>Pavement discontinuity</td>
<td>No</td>
<td>Partial</td>
<td>Yes</td>
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<tr>
<td>System equation</td>
<td>Static equilibrium</td>
<td>Equation of motion</td>
<td>Dynamic FE</td>
</tr>
<tr>
<td>Loading Amplitude</td>
<td>Static</td>
<td>Dynamic</td>
<td>Time-dependent</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Tangent stiffness</td>
<td>Effective stiffness</td>
<td></td>
</tr>
<tr>
<td>Loading steps intensity</td>
<td>Low</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Computing intensity</td>
<td>Low</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Residual error</td>
<td>Relatively high</td>
<td>Relatively low</td>
<td></td>
</tr>
</tbody>
</table>

Major Differences
FE model for HMA

Real and FE simulated tire foot prints for wide-base tire and dual tire assembly

Layout of the 3-D FE model

Contact Pressure Loading

Assigning pressure data to the FE of tire imprint
Material Characterization

- HMA materials: Linear viscoelastic constitutive model
  - Indirect resilient modulus and creep compliance
  - Prony Series Expansion
- Granular materials: Linear elastic constitutive model
  - Nondestructive testing (FWD)

Creep Compliance Test at Different Loading Levels

Pavement Response

Retardation of the response

Asymmetry of the response
**Surface Strain (T=25°C)**

![Graph of Surface Strain](image)

**Combined Relative Damage**
- Number of cycles till failure spread over several orders of magnitude:
  - Rutting of HMA and top-down cracking are the most critical distresses since they directly affect the pavement surface condition

\[
\text{CombinedDR} = a_{DR_{\text{rutting-HMA}}} + a_{DR_{\text{top-down}}} + a_{DR_{\text{rutting-subgrade}}} + \frac{1}{\log(N_{\text{subgrade}})} \\
\text{with} \ a_1 = \frac{1}{\log(N_{\text{rutting-HMA}})} + \frac{1}{\log(N_{\text{top-down}})} + \frac{1}{\log(N_{\text{rutting-subgrade}})} + \frac{1}{\log(N_{\text{subgrade}})} \\
\text{other terms could be added as necessary.}
\]

**Al-Qadi and Co-Workers**
- Combined Damage Ratios:

<table>
<thead>
<tr>
<th>Distress Tire</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>CDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>445/50R22.5</td>
<td>2.25</td>
<td>1.43</td>
<td>1.13</td>
<td>0.76</td>
<td>1.19</td>
</tr>
<tr>
<td>455/55R22.5</td>
<td>1.83</td>
<td>1.34</td>
<td>0.97</td>
<td>0.25</td>
<td>1.07</td>
</tr>
</tbody>
</table>

A: Fatigue Cracking, B: Subgrade Rutting, C: HMA Rutting, D: Top-down
New Analysis Approach

Finite Element Modeling

Analysis Parameters
- Material Constitutive Models
- Loading Amplitude
- Surface Shear Forces
- Layer Interface Condition

Validation of FE Models (w/ Field Measurements)

Pavement Damage Analysis

Discretization of Tire Imprint

One of the dual tire imprint

Loading Amplitudes

- Trapezoidal amplitude
  - All tire-pavement contact stresses have same amplitude while moving.

- Continuous amplitude for moving load
  - Different amplitudes for the entrance and exit part each rib.
**Master curve for section “F”**

![Graph of Master curve for section “F”]

**Effect of Tire Loading**

![Image of tire loading effect]

**Interface Friction**

- **Simple Friction Model: Friction Coefficient Control**
  - Model characterized by the Coulomb friction coefficient, μ
  - Resistance to movement is proportional to normal pressure at interface

- **Elastic Slip Model: Max. Shear Stress Control**
  - Shear stress and displacement are linearly dependent until shear stress equals shear strength; then converted to the Coulomb friction condition
Measured vs. Calculated
- Variation in interface friction coefficients
- In case of elastic slip model, results are close to field measurement

Surface Tangential Contact Pressures
- Conventional surface tangential pressure distributions
  (Pierre et al. 2003, Tielking 1987)

Measured Tire Contact Stress
- Exit Aspect of Tire Imprint
- Entrance Aspect of Tire Imprint
- Normalized Contact Stresses
Nonuniform Vertical Contact Stress

Asymmetric Transverse Tangential Stress

Surface Tangential Stress Effect at Surface (40 °C)
Verification Results

- Measured
- Calculated-Without Tangential Pressure
- Calculated-With Tangential Pressure

Effects of Shear Forces

- Without Shear
- With Shear
- Measured

Various Dynamic Analysis Approaches

- Implicit Dynamic Analysis
  - Advantage: Unconditionally Stable/ Very Small Error
  - Disadvantage: Long Analysis Time

- Explicit Dynamic Analysis
  - Advantage: Short Analysis Time
  - Disadvantage: Conditionally Stable/ High Error

- Modal/Subspace Dynamic Analysis
  - Only Applicable to the Linear Systems
Dynamic Analysis Example with Impulsive Loading

It shows unreasonable strain oscillation at the bottom of HMA

Dynamic Analysis Example with Continuous Loading

Reasonable response at the bottom of HMA

Quasi Static vs. Dynamic Analysis

Interstate Pavement Design: 25v Degree 5 mph
Quasi Static vs. Dynamic Analysis

**Extreme Case:**
10 degree/50 MPH at bottom of 6 inch of HMA: Low Temperature

- Elastic
- Quasi-Static-Visco
- Implicit Dynamic

Quasi Static Response vs. Dynamic Response

Maximum dynamic strain is higher than that of quasi-static analysis (about 15%)

Summary

- Only a few studies on new wide-base tire
- What do we know:
  - The steering axle is the most damaging of all axles
  - Significantly less damage than the first generations
  - Impact on fatigue is a little higher than dual tires (depend on pavement structure)
  - Impact on rutting is similar to dual tires
  - Impact on surface cracking is less than dual tires
  - The layered theory with static circular loading is not appropriate to quantify tire damage
  - Focus has been given to primary roads
<table>
<thead>
<tr>
<th>Criterion</th>
<th>Dual Tire</th>
<th>Wide-base Tires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trucking Operations</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Hauling Capacity</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Tire Cost and Repair</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Truck Operation and Safety</td>
<td>→</td>
<td>→</td>
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<tr>
<td>Ride and Comfort</td>
<td>↓</td>
<td>↑</td>
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<td>Road Infrastructure</td>
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<td>Fatigue Cracking</td>
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