Evaluation of Transit Eco-driving in Rural, Suburban, and Urban Environments

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Problem Statement

- About 43.5% of the total transit expenses are on operations and fuel cost is a significant portion.
- Even 1% or 2% of fuel cost saving result in notable savings for operating costs.
- Transit agencies are seeking solutions to reduce fuel use, which also reduces emissions.
- In previous studies, eco-driving strategies can yield 2% to 27% fuel savings for transit fleets.
Definition of eco-driving

- **Eco-driver training**: a feasible strategy to reduce fuel consumption and emissions of all kinds of vehicle types

- **Eco-driving techniques** (*Intelligent Energy Europe, 2011*)
  - Anticipate traffic
  - Maintain a steady speed
  - Limit engine loads
  - Limit high speeds
  - Avoid hard accelerations
  - Limit idling
  - Shift to the highest possible gear with low rpm
  - Check tire pressure regularly
## Previous Research Findings

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Vehicle Type</th>
<th>Methodology</th>
<th>Estimated benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zarkadoula, et al. (2007)</td>
<td>Athens, Greece</td>
<td>Bus</td>
<td>Field measurement</td>
<td>4.35% reduction in fuel use per km</td>
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<tr>
<td>Wåhlberg (2007)</td>
<td>Uppsala, Sweden</td>
<td>Bus</td>
<td>Field measurement</td>
<td>2%- 4% fuel savings</td>
</tr>
<tr>
<td>Strömberg and Karlsson (2013)</td>
<td>Sweden</td>
<td>Bus</td>
<td>Field measurement</td>
<td>6.8% fuel savings</td>
</tr>
<tr>
<td>Carrese (2013)</td>
<td>City of Rome, Italy</td>
<td>Bus</td>
<td>Field measurement</td>
<td>Up to 27% of fuel saving</td>
</tr>
<tr>
<td>Rolim, et al. (2014)</td>
<td>Portugal</td>
<td>Bus</td>
<td>Field measurement</td>
<td>Reduced travel time under undesired driving condition</td>
</tr>
<tr>
<td>Zheng and Zhang (2015)</td>
<td>Beijing, China</td>
<td>Bus</td>
<td>Simulation</td>
<td>Reduced Vehicle STP</td>
</tr>
<tr>
<td>Xu, et al. (2017)</td>
<td>Atlanta, GA, USA</td>
<td>Bus</td>
<td>Field data and simulation</td>
<td>5% fuel saving for local transit, 7% for express bus</td>
</tr>
</tbody>
</table>
Research Gap

Study Area
• Most studies performed in urban areas
• Need to analyze rural/suburban areas

Road Grade
• Flat terrain or constant grade
• Need to consider instantaneous road grade

Local Context
• Most studies performed in European countries
• Need to consider local fuel, meteorology, and operating conditions in U.S.
Research Goal

- Assess the potential benefits of eco-driving for transit services in different areas
  - Urban, suburban, rural
- Examine the relationship between fuel saving and local transit service characteristics:
  - Travel speed
  - Road grade
  - Fuel type
  - Annual mileage
Methodology Overview

Initial GPS data collection

Data Post-process
- Remove duplicate data record
- Use Kalman filter to minimize GPS errors
- Cubic Spline to fill missing values
- Remove off route operation
- Match road grade
- Cleaned dataset

Compare operation features
- Speed-acc Plots
- Opmode bin Distribution
- Road grade

Raw cycle energy use
- Raw speed, acceleration and road grade profile
- MOVES-Matrix

ECODRIVING energy use
- ECODRIVING speed, acceleration and road grade profile
- MOVES-Matrix

Energy use before eco-driving

Energy use after eco-driving

Compare Energy use before and after eco-driving
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Energy use before ecodriving

Adjust speed-acceleration profile and match grade

Energy use after ecodriving

Compare Energy use before and after eco-driving
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Adjust speed-acceleration profile and match grade

Energy use before eco-driving
Compare Energy use before and after eco-driving

Energy use after eco-driving
Vehicle Operations Data Collection

MARTA
(urban + suburban)

Apple Country Transit
(rural)
Vehicle Fleet

MARTA

CNG

Diesel

Apple Country Transit

CNG
Post-processing of On-road Data

1. **Remove duplicated data records:**
   Remove cycle data written twice on the server

2. **Kalman filter data smoothing:**
   Modify the erroneous GPS points

3. **Cubic spline to fill missing value:**
   Interpolate missing values (less than 5 seconds)

4. **Remove off-route operations:**
   Remove non-revenue operations and terminal idling

5. **Attach road grade:**
   Second-by-second road grade profile by route*

*Liu, Haobing, Hanyan Li, Michael Rodgers, Randall Guensler. (2018). Development of Road Grade Data Based On USGS Digital Elevation Model. 97th Annual Meeting of the Transportation Research Board. Washington, DC.*
## Transit Service Statistics

<table>
<thead>
<tr>
<th>Service</th>
<th>Downtown</th>
<th>Suburban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Agency</strong></td>
<td>MARTA</td>
<td>MARTA</td>
<td>Apple Country Transit</td>
</tr>
<tr>
<td><strong>Number of routes</strong></td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total distance (mile)</strong></td>
<td>407.94</td>
<td>129.44</td>
<td>178.78</td>
</tr>
<tr>
<td><strong>Total duration (h)</strong></td>
<td>4774.95</td>
<td>2190.78</td>
<td>3574.96</td>
</tr>
<tr>
<td><strong>Average speed (mph)</strong></td>
<td>11.71</td>
<td>16.93</td>
<td>20.00</td>
</tr>
<tr>
<td><strong>2.5th percentile grade (%)</strong></td>
<td>-5.04</td>
<td>-4.29</td>
<td>-6.03</td>
</tr>
<tr>
<td><strong>50th percentile grade (%)</strong></td>
<td>0.36</td>
<td>0.00</td>
<td>-0.17</td>
</tr>
<tr>
<td><strong>97.5th percentile grade (%)</strong></td>
<td>4.99</td>
<td>7.71</td>
<td>6.02</td>
</tr>
</tbody>
</table>
Operation Patterns

- Apply EPA’s MOVES scaled tractive power (STP) to observed onroad activity
- STP is a function of speed, acceleration, and road grade

\[ STP = \left(\frac{A}{M}\right)V + \left(\frac{B}{M}\right)V^2 + \left(\frac{C}{M}\right)V^3 + \left(\frac{m}{M}\right)(a + g \times \sin\theta)V \]

- Using MOVES pre-2014 transit bus parameters
Eco-driving strategy

- **Determine STP upper limit (STP<sub>L</sub>)**
  - If current STP< STP<sub>L</sub>, maintain operation quo
  - If current STP>= STP<sub>L</sub>, adjust acceleration using until reach the top speed limit:
    
    \[
    acc_L = \frac{STP_L \times M}{mV} - g \times \sin \theta - \left( \frac{A}{m} \right) - \left( \frac{B}{m} \right) V - \left( \frac{C}{m} \right) V^2
    \]

- **Add additional cruising to match speed**

![Graph showing speed over time with labels for maintain operation quo, smooth acceleration curve, add cruising to match distance, and maintain operation quo.]
Eco-driving strategy – max acceleration

Maximum acceleration under different speed and grade

![Graph showing maximum acceleration under different speed and grade]
Eco-driving Strategy – Cycle Comparison

Eco-driving without grade ($\text{STP}_L = 6$)

Eco-driving with grade ($\text{STP}_L = 6$)
Performance Metrics

- **Speed-acceleration distribution**: idling truncated
- **Operating Mode (OpMode) bin distribution**: fraction of different operation condition, including idling, braking, different speed levels and power levels
- **Energy consumption**: energy consumption in MJ per mile for raw driving cycle and eco-driving cycle, CNG fuel and diesel fuel, with and without grade
- **On-time performance**: travel time after eco-driving compared to bus schedule
- **Cost**: total fuel cost saving and fuel cost saving per mile, based on 2017 summer local fuel cost.
Rural Speed-Acceleration Distribution

Raw Cycle

Eco Cycle (No Grade)
Avg speed: 19.38 mph

Eco Cycle (with Grade)
Avg speed: 19.08 mph
Suburban Speed-Acceleration Distribution

Raw Cycle

Eco Cycle (No Grade)

Eco Cycle (with Grade)
Urban Speed-Acceleration Distribution

Raw Cycle

Eco Cycle (No Grade)

Eco Cycle (with Grade)
Raw Cycle (No Grade) OpMode Bin Distribution

- Raw Cycle (No Grade)

![Graph showing distribution of operating modes based on speed and STP categories for different areas: Rural, Suburban, Urban.](image-url)
Eco Cycle (No Grade)
OpMode Bin Distribution

- Eco Cycle (No Grade)
Raw Cycle (with Grade) OpMode Bin Distribution

- Raw Cycle (with Grade)
Eco Cycle (with Grade)

OpMode Bin Distribution

- Eco Cycle (with Grade)
## Energy Consumption Model Input Data

<table>
<thead>
<tr>
<th>ITEM</th>
<th>MARTA</th>
<th>APPLE COUNTRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>County</td>
<td>Fulton, GA</td>
<td>Henderson, NC</td>
</tr>
<tr>
<td>Calendar year</td>
<td>2017</td>
<td>2017</td>
</tr>
<tr>
<td>Season</td>
<td>Summer</td>
<td>Summer</td>
</tr>
<tr>
<td>Temperature</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Humidity</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Fuel</td>
<td>Diesel CNG</td>
<td>Diesel CNG</td>
</tr>
<tr>
<td>IM program</td>
<td>MOVES default</td>
<td>MOVES default (no IM)</td>
</tr>
<tr>
<td>Vehicle type</td>
<td>Transit bus (42)</td>
<td>Transit bus (42), scaled by real world fuel economy</td>
</tr>
<tr>
<td>Model year</td>
<td>2011</td>
<td>2011</td>
</tr>
<tr>
<td>Cycle</td>
<td>• MARTA CYCLE</td>
<td>• RURAL CYCLE</td>
</tr>
<tr>
<td></td>
<td>• ECO CYCLE</td>
<td>• ECO CYCLE</td>
</tr>
<tr>
<td>Grade</td>
<td>• Real-world grade</td>
<td>• Real-world grade</td>
</tr>
<tr>
<td></td>
<td>• No grade</td>
<td>• No grade</td>
</tr>
<tr>
<td>Road type</td>
<td>Local</td>
<td>Local</td>
</tr>
</tbody>
</table>
Energy Consumption (CNG)

![Bar chart showing energy consumption for CNG in rural, suburban, and urban areas with different grades and no grades.](chart.png)
Energy Consumption (Diesel)

The diagram illustrates the raw cycle energy consumption (MJ/mile) and ecodriving energy consumption (MJ/mile) for different regions and conditions:

- **Rural**:
  - Grade Diesel: 16.77 MJ/mile
  - Nograde Diesel: 15.98 MJ/mile

- **Suburban**:
  - Grade Diesel: 32.55 MJ/mile
  - Nograde Diesel: 30.87 MJ/mile

- **Urban**:
  - Grade Diesel: 39.6 MJ/mile
  - Nograde Diesel: 37.61 MJ/mile

The diagram also highlights the percentage difference between Grade and Nograde Diesel in each category:

- Rural Grade Diesel: -4%
- Rural Nograde Diesel: -3%
- Suburban Grade Diesel: -5%
- Suburban Nograde Diesel: -4%
- Urban Grade Diesel: -5%
- Urban Nograde Diesel: -4%
On-schedule Check

![Graph showing travel times for different routes and conditions.](image)

- **Original Travel Time**
- **Ecodriving travel time no grade**
- **Ecodriving travel time with grade**
- **Travel time on Schedule**
- **Travel + Dwell Time on Schedule**

**Route**
- Rural
- Suburban Route
- Urban

**Travel Time (Min)**

**Bottom Line**
## Fuel Savings for Diesel

<table>
<thead>
<tr>
<th></th>
<th>Rural</th>
<th>Suburban</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual mileage</strong></td>
<td>163,373</td>
<td>981,856</td>
<td>730,005</td>
</tr>
<tr>
<td><strong>Before Fuel rate (Mile/GGE)</strong></td>
<td>7.3</td>
<td>3.8</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Before fuel usage (DGE)</strong></td>
<td>19,686</td>
<td>229,601</td>
<td>207,688</td>
</tr>
<tr>
<td><strong>After Fuel rate (Mile/GGE)</strong></td>
<td>7.7</td>
<td>4.0</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>After fuel usage (DGE)</strong></td>
<td>18,759</td>
<td>217,702</td>
<td>197,237</td>
</tr>
<tr>
<td><strong>Fuel saving (DGE)</strong></td>
<td>927</td>
<td>11,899</td>
<td>10,451</td>
</tr>
<tr>
<td><strong>Unit price ($/DGE)</strong></td>
<td>2.1</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Cost saving ($)</strong></td>
<td>$1,946</td>
<td>$27,367</td>
<td>$24,037</td>
</tr>
<tr>
<td><strong>Unit saving ($/Mile)</strong></td>
<td>$0.012</td>
<td>$0.028</td>
<td>$0.033</td>
</tr>
</tbody>
</table>
# Fuel Savings for CNG

<table>
<thead>
<tr>
<th>CNG</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Service</td>
<td>Rural</td>
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<tr>
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<td>163,373</td>
<td>981,856</td>
<td>730,005</td>
</tr>
<tr>
<td>Before Fuel rate (Mile/GGE)</td>
<td>6.3</td>
<td>3.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Before fuel usage (GGE)</td>
<td>25,971</td>
<td>303,298</td>
<td>278,241</td>
</tr>
<tr>
<td>After Fuel rate (Mile/GGE)</td>
<td>6.5</td>
<td>3.3</td>
<td>2.8</td>
</tr>
<tr>
<td>After fuel usage (GGE)</td>
<td>25,140</td>
<td>295,434</td>
<td>264,402</td>
</tr>
<tr>
<td>Fuel saving (GGE)</td>
<td>830</td>
<td>7,864</td>
<td>13,840</td>
</tr>
<tr>
<td>Unit price ($/GGE)</td>
<td>2.1</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Cost saving ($)</td>
<td>$1,741</td>
<td>$18,874</td>
<td>$33,215</td>
</tr>
<tr>
<td>Unit saving ($/Mile)</td>
<td>$0.011</td>
<td>$0.019</td>
<td>$0.045</td>
</tr>
</tbody>
</table>
Conclusions

- Eco-driving cycles provide different benefits:
  - CNG: 1-5% saving with grade, 2-4% without grade
  - Diesel: 4-5% saving with grade, 3-4% without grade
- The energy saving and cost saving results vary by service type and road grade conditions
- Overall, the eco-driving strategy can help reduce fuel use by 1% to 5% for these transit agencies
  - $0.011 to $0.045 savings in operating cost per mile
- Eco-driving can help agencies reduce fuel use, but the magnitude of the savings depends on local conditions
Future Work

- Assess routes that include highway operations
- Additional service parameters, such as signal timing, passenger load and drivers’ acceptance to eco-driving guidance, should be incorporated
- Field studies are needed with ecodriving intervention to assess the variance in eco-driving benefits across vehicles and drivers
  - Proposals submitted to MARTA and Tech Trolley
THANK YOU!