Eco-driving by replicating best driving practices

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Agenda

- Introduction
- Methodology
- Experimental work
- Results
- Conclusions
Introduction

Operational cost share in Mexican transit companies

Mexico:

- >114,000 km paved roads.
- Transit transportation moves 95% of domestic passengers in 2015.
- 83% Freight transportation: by road.
- Road: 92% energy consumption of transportation sector.
- 61% of total world transportation energy consumption: passenger mobility (2012).

US: >15% of operational costs of urban transit industry: fuel consumption (FC).

High altitudes: 68/100 Top highest cities in the world are in LA, all of them above 3000 masl\(^1\).

High slopes (>7%): e.g. long sections >13% in Colombia

Low average speed: e.g. 40 km/h freight transport in Colombia\(^2\).

Fixed routes covered by the same fleet.

- 0-20%: FC reductions controlled by drivers\(^2\).
- Eco-driving training effects: short-lived. Need for continuous monitoring of driver behavior\(^3\).
- Distraction due to eco-driving messages to the drivers: not riskier than other activities\(^4\).
- Dynamic eco-driving: FC savings up to 40% \(^5\).

Eco-driving: restrict engine to work within recommended operational ranges (max energy efficiency)

The engine RPM green band concept of eco-driving can be extended to an *engine load-RPM green area*

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**Figure 1.** Definition of green band and green area. 2D (a) and 3D (b) representations of isopleths of specific fuel consumption expressed in kg of fuel per kW h of energy delivered by the engine on an engine load vs. RPM plot.
Eco-driving by replicating best practices

- Substantial differences in fuel consumption
- Drivers can control vehicle speed and engine RPM.
- Dynamic
  - External variables (e.g. on-road traffic) can keep away from the green area.
  - Gear change and pedal position combination: not always possible.
  - Smooth transitions.

Hypothesis

The best drivers, after years of driving on the same routes, being trained on eco-driving have developed intuitively the driving parameters that get closer to the green area.
Methodology

- **Route:** Toluca – Mexico City
  - Different LoS
  - Different altitude
- **Fleet:**
  - Hilly and flat segments
  - Same technology and age
  - Same maintenance program
- **Drivers:**
  - Usual drivers
  - Same (eco-) driving training
- **Monitoring campaign:**
  - Long period to include seasonal and traffic variations

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# Road Characteristics

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Urban 1</th>
<th>Urban 2</th>
<th>Uphill</th>
<th>Downhill</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>—</td>
<td>Mexico City</td>
<td>TOL</td>
<td>—</td>
<td>—</td>
<td>TOL—MEX</td>
</tr>
<tr>
<td>Facility</td>
<td>—</td>
<td>Local roadway</td>
<td>Arterial</td>
<td>Freeway</td>
<td>Freeway</td>
<td>Combined</td>
</tr>
<tr>
<td>Level of traffic</td>
<td>—</td>
<td>Heavy</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low-Heavy</td>
</tr>
<tr>
<td>LoS*</td>
<td>—</td>
<td>F</td>
<td>E</td>
<td>C</td>
<td>B</td>
<td>B-F</td>
</tr>
<tr>
<td>Speed limit</td>
<td>km/h</td>
<td>60</td>
<td>60</td>
<td>80</td>
<td>110</td>
<td>60—110</td>
</tr>
<tr>
<td>Number of lines</td>
<td>—</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3—4</td>
</tr>
<tr>
<td>Length</td>
<td>km</td>
<td>11.5</td>
<td>18.8</td>
<td>16.1</td>
<td>25.2</td>
<td>71.6</td>
</tr>
<tr>
<td>Max road grade</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Altitude</td>
<td>masl</td>
<td>2,255/2,258</td>
<td>2,611/2,637</td>
<td>2,611/3,313</td>
<td>2,200/3,313</td>
<td>2,200/3,313</td>
</tr>
</tbody>
</table>

*LoS: Level of service. Level of quality of a traffic facility representing a range of operating conditions generally in terms of service measures such as speed and travel time, freedom to maneuver, traffic interruptions, and comfort and convenience. Classification according to the US Highway capacity manual (Transportation Research Board, 2010).
Fleet:
- 16 buses

Size: 12.85 x 3.6 x 2.6 m
Capacity: 49 passengers
Fuel: Diesel
Gross vehicle weight: 13850 kg
Engine: Cummins ISM 425, 6 cil, 10.8 l, 16.3 of compression ratio, 425 HP, 2102 Nm.
Transmission: ZFS8 2100
Meritor differential pitch: 14/45
Tires: 305 / 75 / R24.5
Model: 2012-2014
Km traveled: 100,000-200,000 km
Methodology ...

- Drivers:
  - Usual company’s assigned drivers
  - All drivers well trained in traditional eco-driving concepts

**Instrumentation**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position: latitude, longitude, altitude</td>
<td>GPS</td>
</tr>
<tr>
<td>Speed</td>
<td>GPS</td>
</tr>
<tr>
<td>Instantaneous fuel consumption</td>
<td>OBD</td>
</tr>
<tr>
<td>Vehicle emissions</td>
<td>PEMS</td>
</tr>
</tbody>
</table>
... Selecting the best practices

Road partition

Best drivers

1 km long

IQR of best drivers

Best quartile

Best practices

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Experimental work
Best/ worst
- Speed
- RPM
- Load
- SFC
Results

![Graph showing SFC (l/km) vs Distance (km) with arrows indicating Urban 2, Uphill, Downhill, and Urban 1 traveling directions.](image)

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Results

Recommended vehicle speed (km/h)

Recommended engine RPM

Distance (km)

Non overlapping ranges
### Results... FC reductions

<table>
<thead>
<tr>
<th>Road</th>
<th>Eco-driving $\mu_1 \pm e_1$ (l/km)</th>
<th>Potential min SFC (l/km)</th>
<th>Relative potential reductions (%)</th>
<th>Eco-driving $\mu_2 \pm e_2$ (l/km)</th>
<th>Eco-driving by using best driving practices $\mu_3 \pm e_3$ (l/km)</th>
<th>Relative reductions+ (%)</th>
<th>$p$-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban 1</td>
<td>0.344 ± 0.028</td>
<td>0.181</td>
<td>53.4</td>
<td>0.340 ± 0.016</td>
<td>0.305 ± 0.030</td>
<td>11.3</td>
<td>0.005</td>
</tr>
<tr>
<td>Urban 2</td>
<td>0.364 ± 0.028</td>
<td>0.201</td>
<td>53.8</td>
<td>0.351 ± 0.094</td>
<td>0.320 ± 0.033</td>
<td>10.0</td>
<td>0.171</td>
</tr>
<tr>
<td>Uphill</td>
<td>0.572 ± 0.019</td>
<td>0.356</td>
<td>63.8</td>
<td>0.556 ± 0.038</td>
<td>0.565 ± 0.148</td>
<td>-3.1</td>
<td>0.992</td>
</tr>
<tr>
<td>Downhill</td>
<td>0.097 ± 0.014</td>
<td>0.004</td>
<td>29.1</td>
<td>0.110 ± 0.033</td>
<td>0.059 ± 0.017</td>
<td>16.5</td>
<td>0.007</td>
</tr>
<tr>
<td>Combined</td>
<td>0.313 ± 0.017</td>
<td>0.166</td>
<td>47.2</td>
<td>0.312 ± 0.027</td>
<td>0.282 ± 0.066</td>
<td>9.6</td>
<td>0.074</td>
</tr>
</tbody>
</table>

$\mu$: Mean values for SFC obtained from the set of trips sampled during the first and second campaigns of measurements.

$E$: 95% half-confidence interval range obtained for mean values. It corresponds to the precision of the SFC measurement.

$\pm$: Reduction in SFC obtained by the best driver when he followed best driving practices compared to when he drove following his training on eco-driving, relative to the SFC of the combined road.

$^*$: $p$-values obtained for the difference of means tests between eco-driving and eco-driving by using best driving practices observed during the second monitoring campaign.
Results ...

First campaign

Eco-driving training

Best Practices

\[ \eta^* \]

\[ \overline{SFC} \]

27.6% 28.4% 28.9%

0.313 0.312 0.282

4.7% 10%
Conclusions & further work

- Eco-driving by replicating best practices
  - Dynamic green area (load vs RPM)
  - Reductions up to 10% in SFC
  - Improvements in engine efficiency
    - Closer to engine green area
  - Next step: automation
Thank you!

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Experimental work
Experimental work ...

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