EVS27: Real-time Electric Vehicle Mass Identification

Erik Wilhelm, Singapore University of Technology and Design
Raffaele Bornatico, ETH-Zurich
Lennon Rodgers, MIT

Motivation
- Estimate vehicle mass in real-time
- Improve vehicle dynamics
- Improve EV range estimation

Identification Methods
- Optimization
- (Naïve) Signal analysis
- Model-based signal analysis

Identification Results
- Optimization
- (Naïve) Signal analysis
- Model-based signal analysis
- LQR signals with F-ima
- Mass optimization

Implications for Range Estimation
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Identification Methods
- Optimization
- Model-based signal analysis
- (Naive) Signal analysis

Identification Results
- Optimization
- Identification
- (Naive) Signal analysis

Implications for Range Estimation
- LQI signals with F-ma
- Mass optimization

Precedents
Motivation

Estimate vehicle mass in real-time

Monitor assets

Save energy

Improve service quality

Enable autonomy

Improve EV range estimates
Precedents

Coast-down
Slow
GPS-based
Inaccurate

Accelerometer
Expensive
Wheels speed
Inaccurate
Identification Methods

Optimization
Complex, correct, and robust, but not efficient

(Noëve) Signal analysis
Simple, correct, and efficient, but not robust

Model-based signal analysis
Simple, correct, efficient, and robust (we hope)
\[ f = \sum_{k=1}^{n} \sqrt{(P(t_k)_{sim} - P(t_k)_{meas})^2} \]
\[ f = \sum_{k=1}^{n} \sqrt{(P(t_k)_{\text{sim}} - P(t_k)_{\text{meas}})^2} \]
Identification Methods

Optimization
Complex, correct, and robust, but not efficient

(Naïve) Signal analysis
Simple, correct, and efficient, but not robust

Model-based signal analysis
Simple, correct, efficient, and robust (we hope)
1. Synchronize and filter data
2. Synchronize events
3. Identify events
4. Calculate Physical Parameters
5. Eliminate Outliers
6. Calculate Cumulative Mean

Model-based...
Synchronize and filter data
Identify events
Synchronize events
Calculate Physical Parameters

Time-series Data - Driver Only

- tau (N-m)
- spd (km/h)
- mass/100 (kg)
- force/100 (N)
- accel (m/s²)
- torq/10 (N-m)
- error (%)

\[ F_{\text{net}} = \frac{m \cdot a}{g} \]
\[ F_{\text{fric}} = \frac{F_{\text{net}}}{g} \]
\[ F_{trac} = \frac{\tau \cdot G}{r_w} \]

\[ m_{ident} = \frac{F_{trac}}{\ddot{x}} \]
Calculate Physical Parameters
Eliminate Outliers

Filtered mass identification - Driver Only

- Plausible Mass
- Ident. Mass
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration (m/s^2)</td>
<td>2.7</td>
<td>0</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>Torque (N-m)</td>
<td>220</td>
<td>0</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1520</td>
<td>1125</td>
</tr>
<tr>
<td>Apparent mass (kg)</td>
<td>(1958)</td>
<td>(1450)</td>
</tr>
</tbody>
</table>
Eliminate Outliers

Filtered mass identification - Driver Only

Mass (Kg)
3000
2500
2000
1500
1000

Time (s)
45
50
55
60
65

Plausible Mass
Ident. Mass
Calculate Cumulative Mean

![Graph showing identified mass for driver only]
Identification Methods

Optimization
Complex, correct, and robust, but not efficient

(Naïve) Signal analysis
Simple, correct, and efficient, but not robust

Model-based signal analysis
Simple, correct, efficient, and robust (we hope)
Model-based signal analysis

Simple, correct, efficient, and robust (we hope)

Data from: Wilhelm, Rodgers & Bornatico EVS27
\[ u_0; \]

road force [N];
\[
\begin{align*}
x_1 &= \dot{x} \\
x_2 &= \ddot{x} \\
\dot{x}_1 &= x_2 \\
\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} &= \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{n}{m} \end{bmatrix} u(k)
\end{align*}
\]
Kalman Filter

\[ H = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \]

\[ P_0 = Q = \begin{bmatrix} \sigma_{\text{proc}}^2 & 0 \\ 0 & \sigma_{\text{proc}}^2 \end{bmatrix} \]

\[ R = \begin{bmatrix} \sigma_{\text{meas}}^2 \end{bmatrix} \]
Identification Methods

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Model-based signal analysis
Simple, correct, efficient, and robust (we hope)
Identification Results

Optimization

(Naïve) Signal analysis

Model-based signal analysis

LQE signals with F=ma

Mass optimization

Average ~10% error

Average 3% error

relative mass of passenger
absolute mass of full vehicle

<table>
<thead>
<tr>
<th>Mass</th>
<th>Relative</th>
<th>Absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>2</td>
<td>30%</td>
<td>40%</td>
</tr>
<tr>
<td>3</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>50%</td>
<td>60%</td>
</tr>
</tbody>
</table>
Average 3% error
Identification Results

Optimization

Average ~10% error

Model-based signal analysis

(Laïve) Signal analysis

Average 3% error

LQE signals with F=ma

Mass optimization

<table>
<thead>
<tr>
<th>Case</th>
<th>Relative mass of passenger</th>
<th>Absolute mass of full vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25%</td>
<td>75%</td>
</tr>
<tr>
<td>2</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td>3</td>
<td>35%</td>
<td>65%</td>
</tr>
<tr>
<td>4</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>5</td>
<td>45%</td>
<td>55%</td>
</tr>
<tr>
<td>6</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Average Error
LQE signals with $F=ma$

Relative = mass of passenger
Absolute = mass of full vehicle

<table>
<thead>
<tr>
<th>Passengers</th>
<th>Relative Error</th>
<th>Absolute Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N/A</td>
<td>4.4%</td>
</tr>
<tr>
<td>1</td>
<td>-24%</td>
<td>4.4%</td>
</tr>
<tr>
<td>2</td>
<td>-23%</td>
<td>4.4%</td>
</tr>
<tr>
<td>3</td>
<td>-47%</td>
<td>3.6%</td>
</tr>
<tr>
<td>4</td>
<td>-78%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
$v \text{(m/s)}$

$a \text{(m/s}^2\text{)}$

$t \text{(s)}$
4 People: 1780, -46% relative, 3.6% absolute error
relative = mass of passenger
absolute = mass of full vehicle

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Mass optimization

Average 8% error
Average 8% error
Identification Results

Optimization

Average ~10% error

Model-based signal analysis

LQE signals with F=ma

Mass optimization

(Naïve) Signal analysis

Average 3% error

<table>
<thead>
<tr>
<th>Relative mass of passenger</th>
<th>Absolute mass of full vehicle</th>
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<tbody>
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</tr>
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<td>20%</td>
</tr>
<tr>
<td>3</td>
<td>20%</td>
</tr>
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Implications for Range Estimation
$DTE_{ideal}$ represents iMiEV range claim

$DTE_{long} = \frac{E_{batt}}{\bar{p}_{300km}(t)}$

$DTE_{blended} = \frac{E_{batt}}{\mu \cdot \bar{p}_{300km}(t) + (1 - \mu) \cdot \bar{p}_{300km}(t)} \quad \mu_{default} = 0.9$

$DTE_{feedback} = \frac{E_{batt}}{\bar{p}_{P1}(t)}$, \quad \dot{p}_{P1}(t) = K_P (p_{act}(t) - \dot{p}_{P1}(t)) + K_I \int_0^t (p_{act}(t) - \dot{p}_{P1}(t))$

$DTE_{blended+model} = \frac{E_{batt}}{\mu \cdot \bar{p}_{300km}(t) + (1 - \mu) \cdot \bar{p}_{300km}(t) + \Delta m \cdot E_{inc}} \quad E_{inc} \sim 6 \frac{Wh}{100km \cdot kg}$
Various Distance to Empty predictors

- $DTE_{ideal}$ represents IMEV range claim
- $DTE_{long} = \frac{E_{max}}{P_{max}(t)}$
- $DTE_{predicted} = \frac{E_{max}}{P_{max}(t) + (1 - \beta) \cdot P_{range}(t) \cdot \rho_{eff}(t)}$
- $DTE_{feedback} = \frac{E_{max}}{P_{max}(t) + (1 - \beta) \cdot P_{range}(t) \cdot \rho_{eff}(t)}$
- $DTE_{blend} = \frac{E_{max}}{P_{max}(t) + (1 - \beta) \cdot P_{range}(t) \cdot \rho_{eff}(t)}$
- $DTE_{blend+model} = \frac{E_{max}}{P_{max}(t) + (1 - \beta) \cdot P_{range}(t) \cdot \rho_{eff}(t)}$

- actual
- ideal
- Plong
- Feedback
- Pblend
- Pblend+model
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Motivation
- Estimate vehicle mass in real-time
- Improve vehicle's safety
- Enhance vehicle's performance

Identification Methods
- Optimization
  - Design of experiment
  - Model-based signal analysis
- (Naive) Signal analysis

Implications for Range Estimation

Identification Results
- Optimization
- Model-based signal analysis
- LQR signals with F-max
- Mass optimization

Precedents