Optimal Energy Utilization in Conventional, Electric and Hybrid Vehicles and its Application to Eco-Driving

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           Rochdi Trigui - LTE/ IFSTTAR

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The problem: **not sustainable**

- Non-renewable fossil fuels ↔ # of vehicles increases\(^1\) + oil peak 2006\(^2\)
- Significant contribution to global warming\(^3\)

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\(^3\) EEA. Total greenhouse gas emissions by sector in eu-27,2007,www.eea.europa.eu
Introduction

Solutions

Technical solutions

Increase component efficiency [4]

New, more efficient and fuel flexible drive trains [5]

Vehicle utilization

Vehicle routing, infrastructure, traffic management, car sharing [6]

Vehicle maintenance

Eco-driving

References:
What is eco-driving?

- Fuel: 31.6g
- 16%
- Fuel: 26.5g

Vehicle speed [km/h]

Distance [m]

Time [s]
How to implement eco-driving?

1. Determine optimal vehicle operation
   - Rule based (sub-optimal)
     - Intuition (tire pressure, anticipate, weight)[7]
     - Experience[8]
   - Mathematical optimization with vehicle model[9]-[12]
     Numerous studies exist varying in:
     - Optimized mission
     - Vehicle model
     - Optimization method

2. Apply the optimal operation to vehicle
   - Autonomous (driverless) vehicle (Google, Nissan)[13]
   - Eco-driving classes (short-term)[14]
   - Driver Assist system for eco-driving (long-term)[15],[16]

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[7] ACEA. Eco-driving is easy to apply and has significant, long-term effects, 2013
State of the art:

Velocity trajectory optimization:
• On one specific vehicle (drive train)[17]-[19]
• For a specific situation (driving over hills,…)[19],[20]
• Ideal, theoretical studies
• Cost == Fuel consumption (only one study on eco-driving & emissions[21])

ADAS systems:
• Several reportive systems ➔ trip and/or vehicle information BUT information given after trip [22],[23]
• Advisory (real-time) systems ➔ mostly use simple algorithm, rule-based optimization (sub-optimal)[24]-[26]

Focus of this thesis:

1. Potential gains of eco-driving: Identification of **vehicle specific optimal operation** for **various vehicle architectures** (CV, EV, HEV)

2. Limitations of eco-driving due to constraints: **Traffic and emissions**

3. Integration of numerical optimization algorithm in the development of an **effective advanced driver assist system (ADAS)** for eco-driving
Outline

Introduction

System modeling

Inverse versus direct modeling

The vehicle chassis

The vehicle drive train

Optimization

Problem definition

Dynamic Programming Optimization Method

Application of DP to our problem

Is eco-driving environmentally friendly?

Advanced Driver Assist System (ADAS)

Development of ADAS system

Experimentation

Experimental setup

Economic vehicle operation

Ecologic (eco2) vehicle operation

Conclusion
System Modeling

System modeling
Inverse versus direct modeling

**Inverse modeling:**
- eliminate driver BUT make hypothesis on some inputs
The vehicle chassis

Vehicle inertia:

\[ J_{veh} = M_{veh} R_{tire}^2 + 2J_{tire} \]

Assumption: no slipping

\[ \dot{\omega}_{wheel} = \frac{a}{R_{tire}} \]

Drive torque

\[ J_{veh} \dot{\omega}_{wheel} = T_{drive} - F_{res} R_{tire} \]

Inversion

\[ F_{res} = F_{roll} + F_{aero} + F_{grade} \]

Vehicle forces:

\[ F_{roll} = C_r M_{veh} g \cos(\alpha) \]

\[ F_{aero} = \frac{1}{2} \rho C_s A v^2 \]

\[ F_{grade} = M_{veh} g \sin(\alpha) \]

\[ T_{drive} = f(v, a) = J_{veh} \frac{a}{R_{tire}} + F_{res}(v) R_{tire} \]
The vehicle drive train

- Instantaneous gear engagement
- No losses in clutch unless shaft below idle
- Constant auxiliary power

Engine operation for gears 2-5 at 50km/h, 0.2m/s²

\[ \dot{m}_{\text{fuel}} = f(v, a) \]

For the same power output less fuel is used for in higher gears!!

Eco-driver always chooses most efficient gear
The vehicle drive train

\[ P_{batt} = f(v, \alpha) \]
The vehicle drive train

- Multiple power sources
- Modeling of energy management

\[ \dot{m}_{fuel} = f(v, a, SOC) \]

Summary:

- Inverse vehicle model
  - Conventional vehicle (Peugeot 308)

- Electric vehicle (Aixam Mega City)

- Hybrid vehicle (Toyota Prius)

- Direct dynamic vehicle simulation (VEHLIB)

\[
\dot{m}_{fuel} = f(v, a)
\]

\[
P_{batt} = f(v, a)
\]

\[
\dot{m}_{fuel} = f(v, a, SOC)
\]
Optimization

Results/ Analysis

Constraint integration
Problem definition

Find optimal velocity trajectory which covers same distance, in similar time, while respecting the same speed limitations and stops and results in the lowest possible energy consumption.
Problem definition

Equation of motion:
2 state variables \((d,v)\)

\[
\frac{d}{dt} \begin{bmatrix} d \\ v \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} d \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} a
\]

\[
d_{i+1} = d_i + v_i \Delta t + \frac{1}{2} a_i \Delta t^2
\]

\[
v_{i+1} = v_i + a_i \Delta t
\]

Cost function

\[
\Gamma_1 = \int_t \gamma_{veh}(t) dt \approx \sum_{i=1}^{n} \gamma_{veh_i}(t_i \rightarrow t_{i+1}) f(v,a)
\]

\[
\gamma_{veh}^{conv}(t) = \dot{m}_{fuel}(t_i \rightarrow t_{i+1}) \Delta t_i
\]

\[
\gamma_{veh}^{elec}(t) = P_{batt}(t_i \rightarrow t_{i+1}) \Delta t_i
\]

\[
\gamma_{veh}^{hyb}(t) = \dot{m}_{fuel}(t_i \rightarrow t_{i+1}) \Delta t_i - \alpha \Delta SOC \Delta t_i
\]
Problem definition

- **Trip constraints**
  \[ d(0) = d_0 \quad d(t_f) = d_f \]
  \[ v(0) = v_0 \quad v(t_f) = v_f \]
  \[ t_f = T \]

- **Road constraints**
  \[ v(d_i) < v_{\text{max}}(d_i) \]

- **Other constraints**
  - Traffic
  - Emissions
  - …
Dynamic Programming Optimization

Heuristic methods (ex: genetic algorithm)[29]
- Global optimal is not always identified
- Dependent on initialization parameter → local minimum

Deterministic methods
- Pontryagin’s maximum principle[30]
  - Algebraic equation → fast
  - Constraint integration is not trivial
- Bellman principle (ex: Dynamic Programming (DP))[31],[32]
  - Computational effort grows with dimensions
  - Complex problems are easily integrated

Literature review
- Used for problems with simple constraints
- Used when discrete problem with complex constraints

Our problem: complex constraints, varying cost function (conventional, electric hybrid)


Dynamic Programming Optimization Method
Application of DP to our problem

Equations of motion

\[ d_{i+1} = d_i + v_i \Delta t + \frac{1}{2} a_i \Delta t^2 \]

\[ v_{i+1} = v_i + a_i \Delta t \]

2 state variables

Objective

\[ \Gamma_2 = \int \gamma_{veh}(d)dt + \beta \Delta t(d) \approx \sum_{i=1}^{n} \gamma_{veh}(t_i - t_{i+1}) \Delta t_i + \beta \Delta t_i \]

Constraints

- Constraints in three dimensions (d,v,t)
- Constraints in two dimensions (d,v)

DP in 3 dimensions with weighting factor

DP in 2 dimensions


[37] F. Mensing, E. Bideaux, R. Trigui, B. Jeanneret. Trajectory optimization application driving during OBD vehicle verified optimization method, Int. J. Vehicle Systems Modelling and Testing, accepted for publication

\[ t_f = T \]
Application of DP to our problem

Mission

\[ d(0) = d_0 \quad d(t_f) = d_f \]
\[ v(0) = v_0 \quad v(t_f) = v_f \]
\[ v(d_i) \leq v_{\text{max}}(d_i) \]
\[ t_f \leq T \]
\[ \text{gravity}(d_i) \]

How to identify β?

1. Chosen by driver
   Time constraint!!
2. Look-up table
   \[ \beta = f(T_f, d_{\text{trav}}) \]

Optimal trajectory with some final time \( T_f \)

\[ T_f = f(\text{mission}, \beta) \]
Application of DP to our problem

How to identify $\beta$?

1. Chosen by driver
2. Look-up table $\beta = f(T_f, d_{trav})$
3. Nested Solution with root-finding methods

Solution: Optimal trajectory

Vehicle mission

Dynamic Programming Optimization
- 3 dimensions
- 2 dimension
- With weighting factor (time constraint)

Optimal vehicle operation

Optimization
- Constraints

Results/Analysis

Introduction

System modeling

Conclusion
Optimization

Results/ Analysis

Constraint integration
## Potential gains of eco-driving

<table>
<thead>
<tr>
<th>Cycle</th>
<th>max speed</th>
<th>stop frequency</th>
<th>distance</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEDC</td>
<td>120km/h</td>
<td>1.1 per km</td>
<td>11km</td>
<td>887sec</td>
</tr>
<tr>
<td>Urban</td>
<td>58km/h</td>
<td>1.1 per km</td>
<td>3.5km</td>
<td>560sec</td>
</tr>
<tr>
<td>Extra-urban</td>
<td>103km/h</td>
<td>0.1 per km</td>
<td>11.2km</td>
<td>754sec</td>
</tr>
<tr>
<td>Freeway [38]</td>
<td>138km/h</td>
<td></td>
<td>46.2km</td>
<td>1741sec</td>
</tr>
</tbody>
</table>

**Conventional vehicle**

---

Potential gains of eco-driving

Experimental validation (HIL)

HIL

Data Acquisition

Testbed Regulation

Injection/load torque demand

Torque and speed measurement

Injection demand

Speed/Load demand

DYNO APA AVL

ICE EP 6

VEHIL [Matlab/Simulink]

DSpace


[40] Dspace MicroAutoBox http://www.dspace.com/de/gmb/home/products/hw/micautob.cfm

[41] AVL. https://www.avl.com

Vehicle [39]

simulation

Hardware:

EP6 engine

EM simulates load on engine

Fuel consumption

$T_{eng}, \omega_{eng}$

Fuel consumption

Clutch

Gear Box

ICE

FD
Potential gains of eco-driving

Significant reductions in fuel consumption

<table>
<thead>
<tr>
<th>drive cycle</th>
<th>original [L/100km]</th>
<th>eco [L/100km]</th>
<th>reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEDC</td>
<td>6.7</td>
<td>5.5</td>
<td>17.9</td>
</tr>
<tr>
<td>HYZURB</td>
<td>9.76</td>
<td>7.11</td>
<td>27.2</td>
</tr>
<tr>
<td>HYZROUTE</td>
<td>7.22</td>
<td>5.41</td>
<td>25.1</td>
</tr>
<tr>
<td>HYZAUTO</td>
<td>6.92</td>
<td>6.37</td>
<td>7.9</td>
</tr>
</tbody>
</table>

urban and extra-urban area

Highway/ freeway driving

HOW???
Optimal vehicle operation

Potential gain: 18%

1. Component operation

Efficiency changes minimal

NEDC

fuel consumption EP6 [g/kWh]

speed [rpm]

torque [Nm]

original cycle

eco cycle
Optimal vehicle operation
**Optimal vehicle operation**

**Conventional vehicle:**

1. **Transmission:**
   - High gear → increase engine efficiency

2. **Velocity**
   - Low constant speed → reduce resistance forces (aerodynamic drag)

3. **Acceleration**
   - High, short acceleration → save time, rapidly approach cruising speed (time constraint!!)

4. **Deceleration**
   - 2 phases:
     - cruising (engine breaking)
     - hard breaking (friction break)

**Electric vehicle:**

1. **Transmission:**
   - No influence

2. **Velocity**
   - Low constant speed → reduce resistance forces (aerodynamic drag)

3. **Acceleration**
   - High, short acceleration → save time, rapidly approach cruising speed (time constraint!!)

4. **Deceleration**
   - 2 phases:
     - maximum electric motor capacity, hard breaking (friction break)

**Hybrid vehicle:**

1. **Transmission:**
   - No influence

2. **Velocity**
   - Low constant speed → reduce resistance forces (aerodynamic drag)

3. **Acceleration**
   - High, short acceleration → save time, rapidly approach cruising speed (time constraint!!)

4. **Deceleration**
   - 2 phases:
     - electric motor capacity, hard breaking (friction break)

**Factors dependent on**

- **Chassis**
- **Performance of components**

**Factors dependent on**

- **Drive train** ➔ optimal energy regeneration
Constraint Integration

- Traffic
- Emissions
Is eco-driving environmentally friendly?

Eco-driving

Economic advantages (energy, fuel ($\approx$CO$_2$))

$$\Gamma_{veh1} = \int \gamma_{fuel}(t)dt$$

Ecologic advantages (energy+pollutant emissions)

$$\Gamma_{veh2} = \int (\gamma_{fuel}(t) + \lambda_{emission})dt$$


[42]
Perfect combustion:
Fuel + oxygen $\rightarrow$ energy + water vapor + carbon dioxide (CO$_2$)

Real combustion:
Fuel + air $\rightarrow$ energy + water vapor + carbon dioxide (CO$_2$) + hydrocarbon (HC) + carbon monoxide (CO) + nitrogen oxides (NO$_x$) …

Economic vehicle operation

85% of max

Max torque

fuel consumption [l/100km]

9.0
27.8%
6.5

Eco cycle

engine speed [rad/sec]
Ecologic (eco2) vehicle operation

\[ \Gamma_{veh2} = \sum_i (\gamma_{fuel}(t_i) + \lambda_i) \]

\[ \lambda_i = \begin{cases} 
\lambda_0 & \text{if } T_{eng} > \chi T_{eng_{max}}(\omega_{eng}) \\
0 & \text{if } T_{eng} \leq \chi T_{eng_{max}}(\omega_{eng}) 
\end{cases} \]

Emissions as soft constraint: \( \chi = 0.85 \)

Constraint integration
Ecologic (eco2) vehicle operation

Optimization

Constraints

\[ \Gamma_{veh2} = \sum_i (\gamma_{fuel}(t_i) + \lambda_i) \]

\[ \lambda_i = \begin{cases} 
\lambda_0 & \text{if } T_{eng} > \chi T_{engmax}(\omega_{eng}) \\
0 & \text{if } T_{eng} \leq \chi T_{engmax}(\omega_{eng}) 
\end{cases} \]

Dynamic optimal gear identification using vehicle model

- maximum/minimum torque

- upshift

- downshift

- speed [km/h]

- time [sec]

- gear changes too frequent for direct vehicle simulation (calculation with inverse model)

- Original cycle
- Eco cycle
- Eco² cycle

- engine speed [rad/sec]
- engine torque [Nm]
Ecologic (eco2) vehicle operation

<table>
<thead>
<tr>
<th>Emission in g/km</th>
<th>CO2</th>
<th>CO</th>
<th>NOx</th>
<th>HC</th>
<th>fuel consumption [l/100km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Cycle</td>
<td>206.96</td>
<td>2.06</td>
<td>0.0055</td>
<td>0.068</td>
<td>9.0</td>
</tr>
<tr>
<td>Eco Cycle</td>
<td>140.96</td>
<td>5.78</td>
<td>0.0046</td>
<td>0.12</td>
<td>6.5</td>
</tr>
<tr>
<td>Eco^2 Cycle</td>
<td>151.51</td>
<td>2.18</td>
<td>0.0025</td>
<td>0.063</td>
<td>6.7</td>
</tr>
</tbody>
</table>
• Eco-driving can be economic and ecologic:
  ➔ Emissions need to be taken into account

• Vehicle operation ➔ optimal energy consumption

• Component operation/ transmission ➔ reduce emissions
Advanced Driver Assist System (ADAS)
Development of ADAS system

Vehicle speed, distance, gear, engine speed, engine torque
+ preceding vehicle speed, preceding vehicle distance

Advanced driver assist system for eco driving

3 Optimization algorithms:
- Continuous gear optimization
- Pre-segment optimization
- Post-segment optimization

Driver’s trade-off time vs energy

GPS or road mapping:
Segment information (road number, distance on road) ➔ vehicle position

HMI
Development of ADAS system - Algorithm

Road number =x_3
\[ d_{\text{road}0}, d_{\text{road}f} \]
\[ v_{\text{max}}(d_{\text{road}}) \]
\[ v_{\text{des}}(d_{\text{road}f}) \]

Road number =x_2
\[ d_{\text{road}0}, d_{\text{road}f} \]
\[ v_{\text{max}}(d_{\text{road}}) \]
\[ v_{\text{des}}(d_{\text{road}f}) \]

Road number =x_1
\[ d_{\text{road}0}, d_{\text{road}f} \]
\[ v_{\text{max}}(d_{\text{road}}) \]
\[ v_{\text{des}}(d_{\text{road}f}) \]

Road number =z?
Road number =y?

Pre-segment optimization

Post-segment optimization

Gear optimization

Pre-segment optimization

NOT ON SEGMENT

ON SEGMENT

ON SEGMENT

ON SEGMENT
Development of ADAS system - HMI

- Educational display
- Continuous display
Continuous display

Without advice

With advice
Results

Average Gain: 11%

Gain:
- Urban: 8.74%
- Extra-Urban: 15.25%

Fuel consumption [L/100km]
- Baseline
- Assisted
• Inverse model of three vehicles (conventional, electric and hybrid)

• Dynamic programming optimization $\Rightarrow$ energy optimal vehicle operation for given mission (3D $\Rightarrow$ 2D + weighting factor)

• Analysis/ Comparison of optimal vehicle operation

• Eco-driving with constraints
  Traffic and emissions

• Integration of algorithms in ADAS
Communications

Conference papers


Journal papers


Journal papers in progress


Vehicle model of electric and hybrid vehicle

Optimization (Multi-Obj)

Results Electric

Results (Optimization) Hybrid

Traffic constraint study
System Modeling – Chassis/Aero

\[ F_{aero} = \frac{1}{2} \rho C_x S_x v^2 \]
Hypotheses:
- Instantaneous gear engagement
- No losses in clutch unless shaft speed below idle
- Constant auxiliary power ($P_{aux} = 300W$)
The conventional vehicle (inverse)

Engine operation → Fuel consumption (== energy consumption)

Engine map: Instantaneous fuel consumption in g/kWh

Assumption: eco-driver always chooses optimal (most efficient) gear

For the same power output less fuel is used in higher gears!!

Energy consumption as a function of vehicle speed and acceleration

1.6L gasoline engine

\[ T_{\text{max}}: 160\text{Nm}(4250\text{rpm}) \]
\[ P_{\text{max}}: 88\text{kW}(6000\text{rpm}) \]

Engine map: Instantaneous fuel consumption in g/kWh
Electric vehicle (inverse)

AIXAM Mega City
M=750kg
CC EM: Tmax=60Nm
Pmax=14kW (3000rpm)
Lead acid battery (Capacity=76Ah)

\[
\omega_{EM} = \omega_{wheel} R_{FD}
\]

\[
T_{driveEM} = T_{wheel} \frac{\eta_{FD}}{R_{FD}} \quad \psi = \begin{cases} 
1 & \text{if } T_{drive} \text{ is positive} \\
-1 & \text{if } T_{drive} \text{ is negative}
\end{cases}
\]

\[
J_{EM} \dot{\omega}_{EM} = T_{wheel} - T_{driveEM} \quad \Rightarrow \quad T_{EM} = T_{wheel} \frac{\eta_{FD}}{R_{FD}} - J_{EM} \omega_{wheel} R_{FD}
\]
System Modeling - Electric vehicle

Electric vehicle (inverse)

\[ P_{battout} = T_{EM} \omega_{EM} + P_{lossEM} + P_{aux} \]

\[ P_{battout} = V_{OCV} I_{batt} - I_{batt}^2 R \]
\[ = U_{batt} I_{batt} \]
\[ P_{batt} = V_{OCV} I_{batt} \]

\[ P_{batt} = f(v, a) \]
\[ \Delta SOC = -\eta_{far} \frac{I_{batt}}{C_{ah}/100} \]
Hybrid Vehicle (inverse) - general

System Modeling - Hybrid Vehicle

Series

Parallel

Power split (Toyota Prius)
Hybrid Vehicle (inverse) - Prius

Toyota Prius II
M=1360kg
Permanent magnet synchronous AC motors
NiMH battery (1.3kWh)
1.5L gasoline engine (Atkinson cycle)

$$\omega_{ring} = \omega_{EM1} = \omega_{wheel} R_{FD}$$
$$T_{ring} = (T_{drive} - T_{brakemech}) \frac{\eta_{FD}}{R_{FD}} - T_{EM1}$$

$$\omega_{sun} = R_g \omega_{ring} + (1 - R_g) \omega_{planet}$$
$$T_{sun} = -\frac{1}{1 - R_g} T_{planet} = \frac{1}{R_g} T_{ring}$$

Static modeling of planetary
System Modeling - Hybrid vehicle

Hybrid Vehicle (inverse)

\[ P_{battout} = T_{EM1}\omega_{EM1} + P_{lossEM1} + T_{EM2}\omega_{EM2} + P_{lossEM2} + P_{aux} \]

\[ P_{battout} = V_{OCV}I_{batt} - I_{batt}^2R \]
\[ = U_{batt}I_{batt} \]
\[ P_{batt} = V_{OCV}I_{batt} \]
Hybrid Vehicle (inverse) – Control Strategy

Optimization of vehicle operation ≠ Control strategy

Hybrid mode vs Electric mode

SOC < \text{SOC}_{\text{minhyb}}, \quad v > v_{\text{vehmaxelec}}

- BMS computes \text{P}_{\text{dembatt}}
- Power losses are estimated \text{P}_{\text{loss}}
- Total power req from engine is calculated
- Engine speed, torque chosen for max efficiency

Electric mode

- EM1 provides output power

\[
\begin{align*}
\text{P}_{\text{batt}} &= f(v, a) + \text{SOC} \\
\Delta \text{SOC} &= -\eta_{\text{far}} \frac{I_{\text{batt}}/3600\Delta t}{C_{\text{ah}}/100}
\end{align*}
\]
Dynamic Programming Optimization Method

\[
J^*_{i_1, N-k} = \min_{i_2} (J_{i_1, N-k} \rightarrow i_2, N-k+1) + J^*_{i_2, N-k+1} \\
J_{i_1, N-2} = \min_{i_2} (J_{i_1, N-2} \rightarrow i_2, N-1) + J^*_{i_2, N-1}
\]
Root finding methods
Multi-objective optimization:

\[ \gamma_{21} = \sum_{i=d_0}^{d_f} \gamma_{veh_i}(d_i) \]

\[ \Gamma_{22} = \sum_{i=d_0}^{d_f} \Delta t_i(d_i) \]

Pareto optimal:

- On front if \( p \) satisfies \( J_n(p) < J_n(i) \) for all points \( i \) and at least one objective \( n \)
- \( Q \) not on front if there exist a \( p \) s.t. \( J_n(p) < J_n(q) \) for all \( n \)
Multi-objective optimization (Dynamic Programming):

Optimization
Multi-objective optimization (Dynamic Programming):

![Pareto optimal front graph]

<table>
<thead>
<tr>
<th>Optimization method</th>
<th>$\Delta t$</th>
<th>$\Delta d$</th>
<th>$\Delta v$</th>
<th>trunc pts</th>
<th>computation time [sec]</th>
<th>trajectories calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Fixed time method</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>240-280</td>
<td>1</td>
</tr>
<tr>
<td>2D Flexible time method</td>
<td>-</td>
<td>5</td>
<td>0.2</td>
<td>10</td>
<td>155</td>
<td>10</td>
</tr>
<tr>
<td>2D Flexible time method</td>
<td>-</td>
<td>5</td>
<td>0.2</td>
<td>30</td>
<td>241</td>
<td>30</td>
</tr>
</tbody>
</table>
Divergence from optimal trajectory:
## Consumption in Wh

<table>
<thead>
<tr>
<th>cycle</th>
<th>original cycle</th>
<th>eco cycle</th>
<th>gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIXAM1</td>
<td>872.2</td>
<td>705.56</td>
<td>19.3%</td>
</tr>
<tr>
<td>AIXAM2</td>
<td>89.4</td>
<td>85.56</td>
<td>4.5%</td>
</tr>
<tr>
<td>AIXAM3</td>
<td>283.3</td>
<td>248.89</td>
<td>12.1%</td>
</tr>
<tr>
<td>AIXAM4</td>
<td>427.78</td>
<td>386.11</td>
<td>9.4%</td>
</tr>
</tbody>
</table>
### Results Electric

<table>
<thead>
<tr>
<th>components</th>
<th>original cycle (motor/generator phase)</th>
<th>eco cycle (motor/generator phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Drive [%]</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>Electric Motor [%]</td>
<td>70.82/57.14</td>
<td>69.4/59.5</td>
</tr>
<tr>
<td>Battery [%]</td>
<td>92.8/99.31</td>
<td>92.87/99.29</td>
</tr>
</tbody>
</table>

![Graph showing energy components for original and eco cycles](image1)

![Graph showing energy recovered for original and eco cycles](image2)
Optimization forward:
Optimization forward:

\[ \gamma_{veh}^{hyb}(t) = \dot{m}_{fuel_i}(t_i \rightarrow t_{i+1}) \Delta t - \alpha \Delta SOC(\Delta t_i) \]

- Initialize optimal costs at \( k_1 = 2 \): \( J_{[2,i]}^{*} = J_{[1,i_0 \rightarrow 2,i]} \)
- Increment \( k_1 \) and find the optimal cost at each state by comparing
  \( J_{[k_1,i_2]}^{*} = \min_{i_1} (J_{[k_1-1,i_1 \rightarrow k_1,i_2]} + J_{[k_1-1,i_1]}^{*}) \) while storing the optimal indices
- Compute the optimal trajectory by retracing the stored indices
Hybrid Vehicle Consumption

- For the same battery use, more fuel consumed
- For the same battery use, less fuel consumed

Cycle evaluation
Results for different battery weighting
Results for different battery weighting (gain ~20%)
Results for different battery weighting
<table>
<thead>
<tr>
<th>components</th>
<th>original cycle (motor/generator phase)</th>
<th>eco cycle (motor/generator phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Drive [%]</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>EM1 [%]</td>
<td>86.2/87.2</td>
<td>87.2/89.4</td>
</tr>
<tr>
<td>EM2 [%]</td>
<td>88.1/88.2</td>
<td>90.8/90.7</td>
</tr>
<tr>
<td>Engine [%]</td>
<td>35.1</td>
<td>35.0</td>
</tr>
<tr>
<td>Battery [%]</td>
<td>96.3/91.4</td>
<td>96.7/94.7</td>
</tr>
</tbody>
</table>
Vehicle following situation

test vehicle x

test vehicle y

dx

dy

vx

vy
Traffic study

Optimization input

[Graph showing speed and distance to preceding vehicle over time]
Traffic study

Safety factor:

\[ TTTC = \frac{(d_y - d_x)}{(v_x - v_y)} \]
# Traffic study

## Results - Trajectory

![Graphs showing velocity over time for different cycles](image)

<table>
<thead>
<tr>
<th>cycle</th>
<th>constraint</th>
<th>fuel consumption [g]</th>
<th>gain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>original cycle</td>
<td>driver</td>
<td>97.36</td>
<td>-</td>
</tr>
<tr>
<td>eco-drive cycle</td>
<td>-</td>
<td>64.10</td>
<td>34</td>
</tr>
<tr>
<td>eco-drive cycle TTC=2sec</td>
<td></td>
<td>69.62</td>
<td>28</td>
</tr>
<tr>
<td>eco-drive cycle TTC=4sec</td>
<td></td>
<td>82.30</td>
<td>15</td>
</tr>
</tbody>
</table>
Traffic study

Results - Constraints
Emission study

Dynamic gear choice

$v_{\text{veh}} = [0, \ldots, v_{\text{max}}]$

$a_{\text{veh}} = [a_{\text{min}}, \ldots, a_{\text{max}}]$

for all $m,n$ calculate vehicle operation for $v_m, a_n$ with optimal gear

$\text{gear}(m,n)$

$\omega_{\text{eng}}(m,n)$

$T_{\text{eng}}(m,n)$

find engine operating points for each gear
Dynamic gear choice
ADAS algorithm
Result distribution