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

Thesis defended by: Felicitas Mensing

Advisors: Eric Bideaux - AMPERE INSA Lyon
Rochdi Trigui - LTE/ IFSTTAR

The problem: → not sustainable

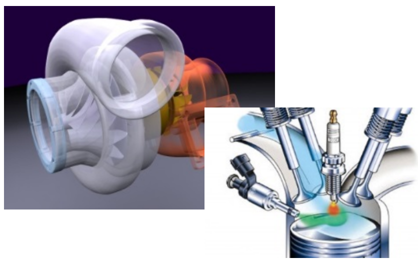
- Non-renewable fossile fuels ←→# of vehicles increases[1] + oil peak 2006[2]
- Significant contribution to global warming[3]

[1] EEA. Car Ownership rates projections, 2010. http://www.eea.europa.eu/data-and-maps/figures/car-ownership-rates-projections.
[2] The Oil Drum. Oil production in the 21st century and peak oil, 2012. http://oilprice.com/Energy/Cruide-Oil/Oil-Production-in-the-21st-Centry-and-Peak-Oil.html.
[3]EEA. Total greenhouse gas emissions by sector in eu-27,2007,www.eea.europa.eu

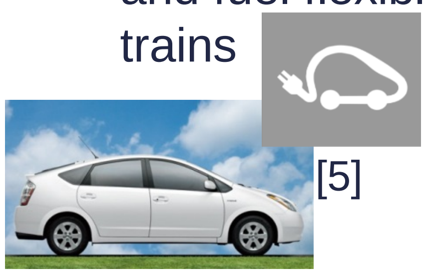
Solutions

Technical solutions

Increase component efficiency [4]



New, more efficient and fuel flexible drive trains



[5]

Vehicle utilization

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

Vehicle maintenance

Eco-driving

[4] IPPC. Climate change 2007: Working group ii: Mitigation of climate change; 5.3.1.2. Improving drive train efficiency. http://www.ipc.ch.
[5] IEA. Eight countries join IEA electric vehicle initiative, 2010. evworld.com.
[6] Lino Figueiredo, Isabel Jesus, J.A. Tenreiro Machado, Jose Rui Ferreira, J.L. Martins de Carvalho. Towards the development of intelligent transportation systems. IEEE Intelligent Transportation Systems Conference Proceedings, August 2001

What is eco-driving?

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]

PhD THESES

[9] A. B. Schwarzkopf, R.B. Leipnik. Control of highway vehicles for minimum fuel consumption over varying terrain. Transportation Research, 11(4):279-286, August 1977.

[10] J.N. Hooker, A.B. Rose, G.F. Roberts. Optimal control of automobiles for fuel economy. Transportation Science, 17(2):146-167, 1983.

[13] Spiegel Online Auto: Technische Revolution: Nissan will 2020 ein selbstfahrendes Auto anbieten. 28.08.2013

[11] A.P. Stoicescu. On fuel-optimal velocity control of a motor vehicle. International Journal of Vehicle Design, 229-256, 1995.

[14] Hornung Wirtschafts und Sozialstudien. Evaluationen von eco-drive – Ausbildungen im Ueberblick, 2004.

[12] [illegible] Optimal energy management in hybrid electric trucks using route information. Oil and Gas Science and Technology, 65(1):103-113, 2010. [illegible] Transportation Research Part C, 9(4):279-296,2001.

[15] [illegible] fuel economy driver interfaces (report task 1 and 2), August 2009.

[16] Vexia: Vexia econav, 2013. http://www.vexia.co.uk/eco-tech

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]

[22] Fiat. Fiat EcoDrive, April 2012. http://www.fiat.co.uk/ecodrive/.
[illegible] August 2008.
[illegible] information. Oil
[illegible] M.S. Young, T. Felstend, M. Fowkes. Foot-LITE: using on-board driver feedback
[illegible] and
[20] [illegible] fuel-optimal velocity control of a motor vehicle. International Journal of Vehicle Design, 229-256, 1995.
[illegible] Transportation and Air
[illegible] story/080804-02-e.html

Focus of this thesis:

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

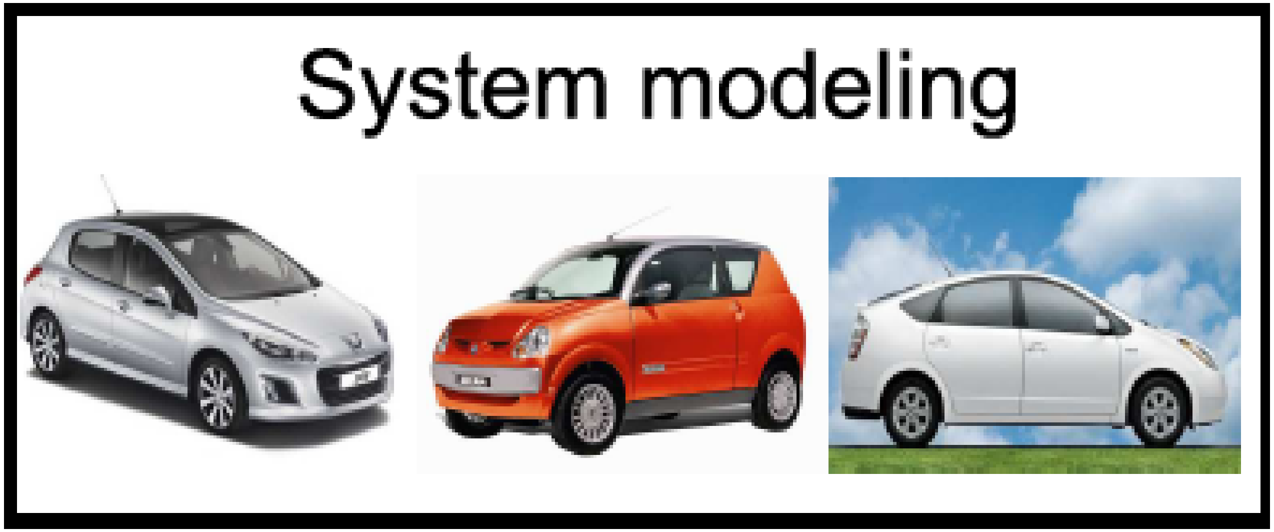
2. Limitations of eco-driving due to constraints:
   Traffic and emissions

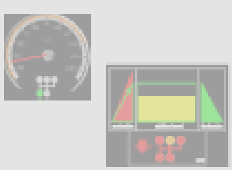
3. Integration of numerical optimization algorithm in the development of an **effective advanced driver assist system (ADAS) for eco-driving**

Outline

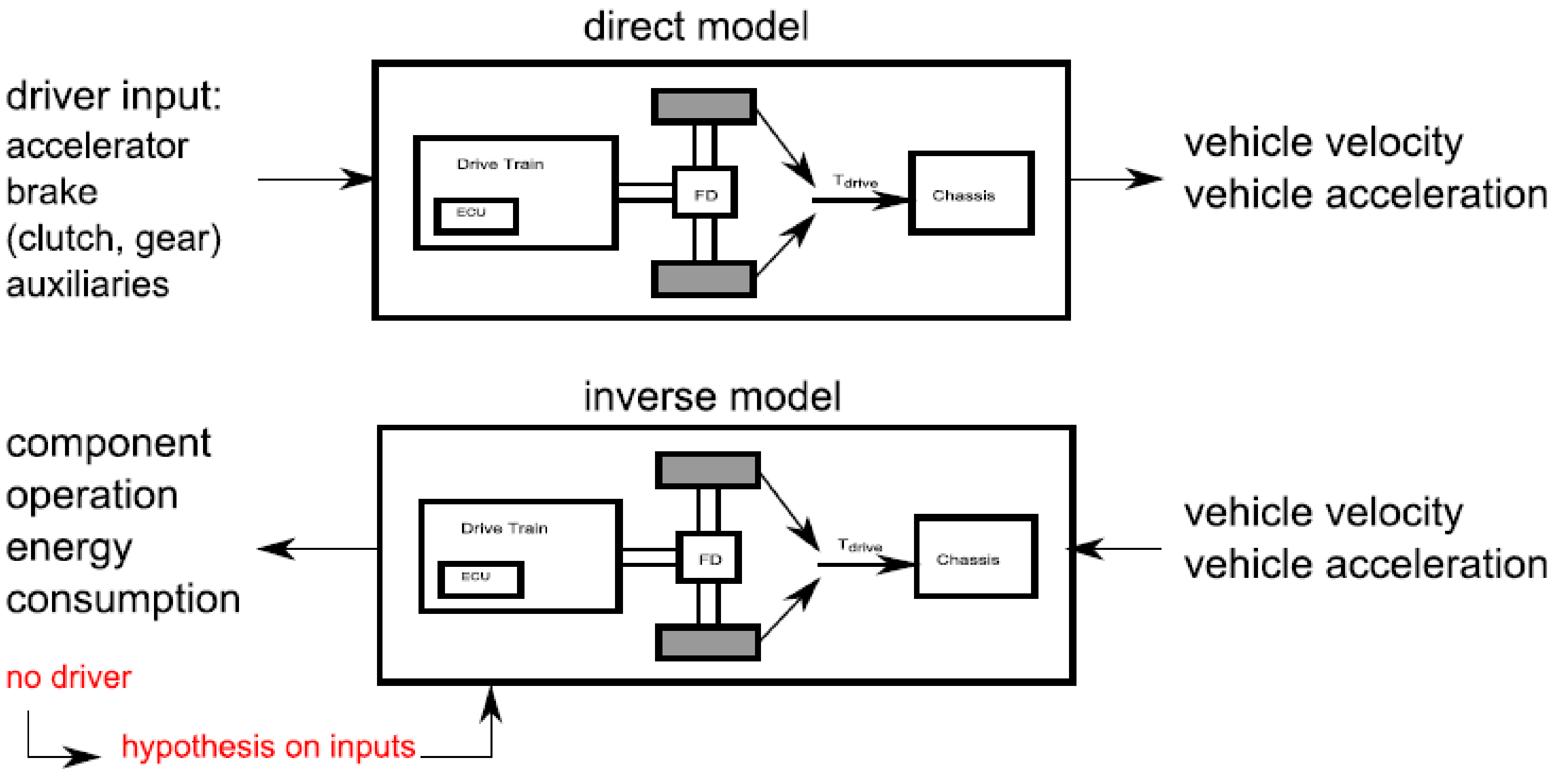
- **Introduction**
- **System modeling**
  - Inverse versus direct modeling
  - The vehicle chassis
  - The vehicle drive train
  - Introduction to VEHLIB
- **Optimization**
  - Problem definition
  - Dynamic Programming Optimization Method
  - Application of DP to our problem
- **Results/ Analysis**
  - Potential of eco-driving
  - Optimal vehicle operation
  - Is eco-driving environmentally friendly?
- **Constraint integration**
- **Advanced Driver Assist System (ADAS)**
  - Experimental setup
  - Development of ADAS system
  - Experimentation
  - Economic vehicle operation
  - Ecologic (eco2) vehicle operation
- **Conclusion**

System Modeling





Inverse versus direct modeling



Inverse modeling:

➔ eliminate driver BUT make hypothesis on some inputs

The vehicle chassis

Vehicle inertia:

$$J_{veh} = M_{veh} R_{tire}^2 + 2 J_{tire}$$

Assumption: no slipping

$$\dot{\omega}_{wheel} = a / R_{tire}$$

Drive torque

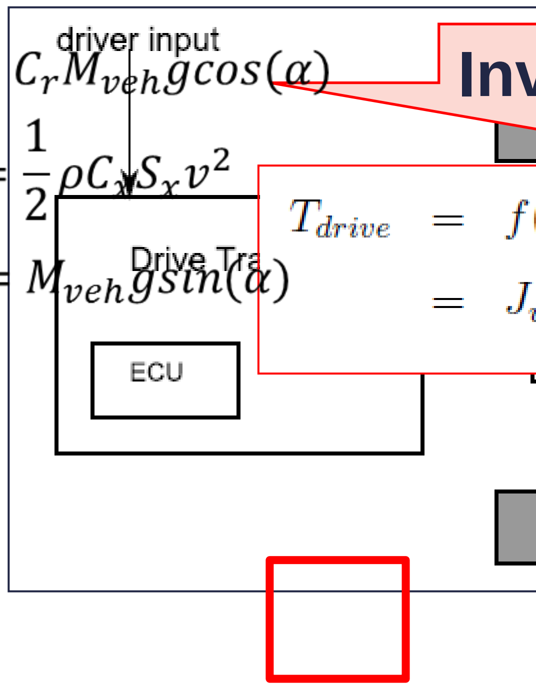
$$J_{veh} \dot{\omega}_{wheel} = T_{drive} - F_{res} R_{tire}$$

$$F_{res} = F_{roll} + F_{aero} + F_{grade}$$

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

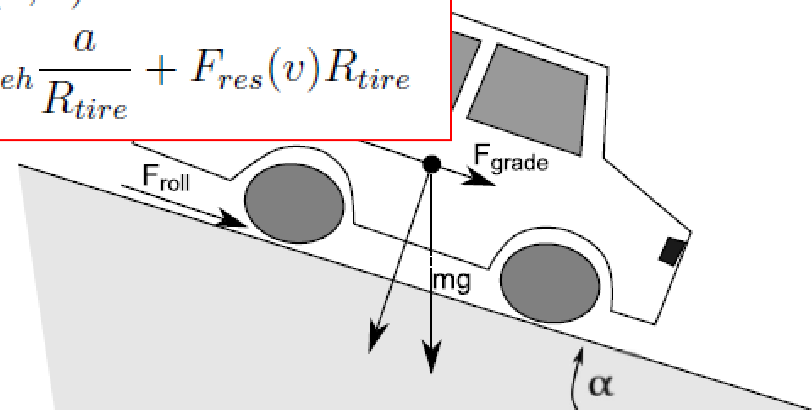
$$F_{aero} = \frac{1}{2} \rho C_x S_x v^2$$

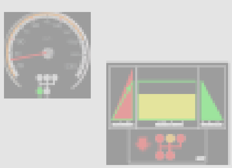
$$F_{grade} = M_{veh} g sin(\alpha)$$



Inversion

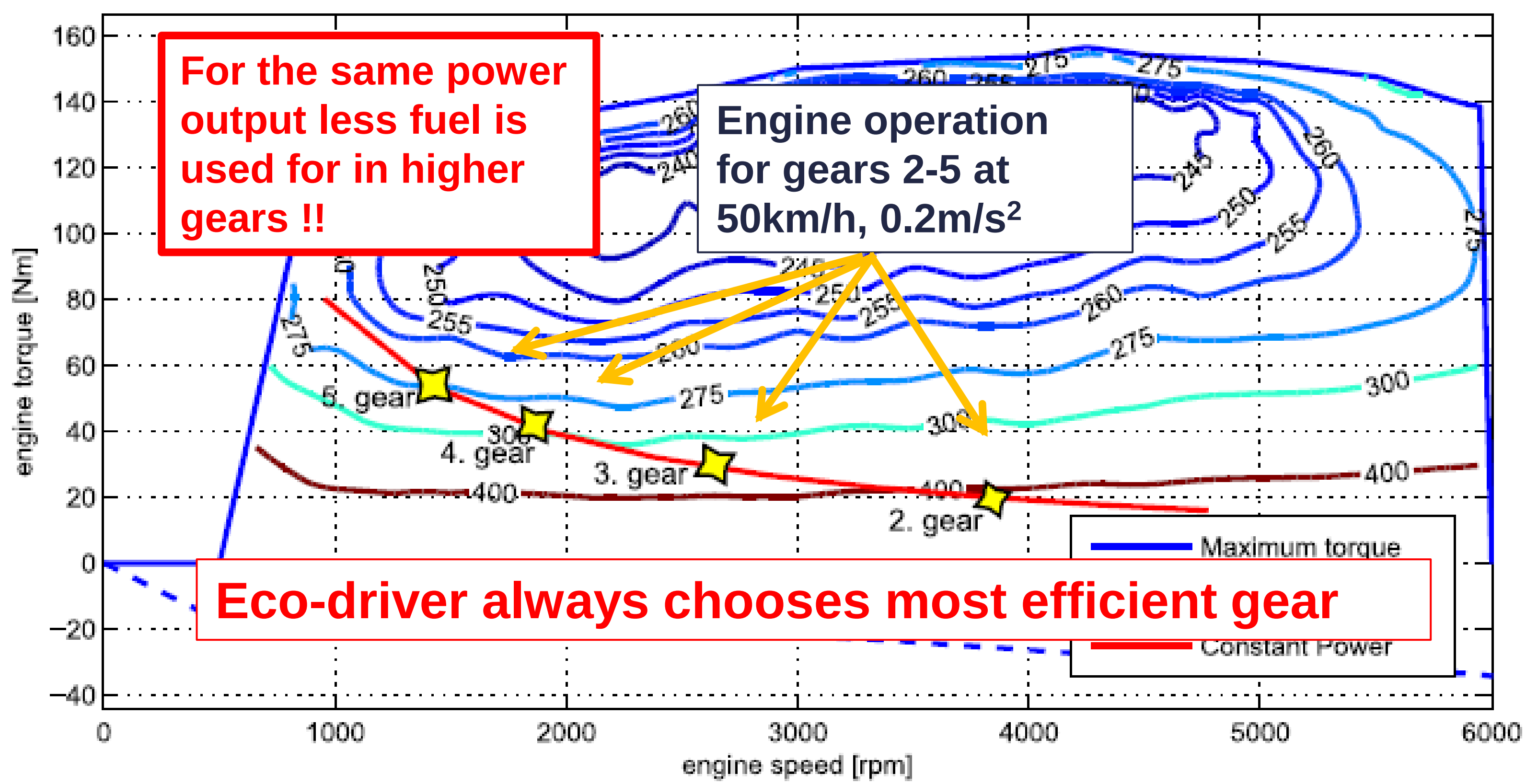
$$\begin{aligned} T_{drive} &= f(v, a) \\ &= J_{veh} \frac{a}{R_{tire}} + F_{res}(v) R_{tire} \end{aligned}$$





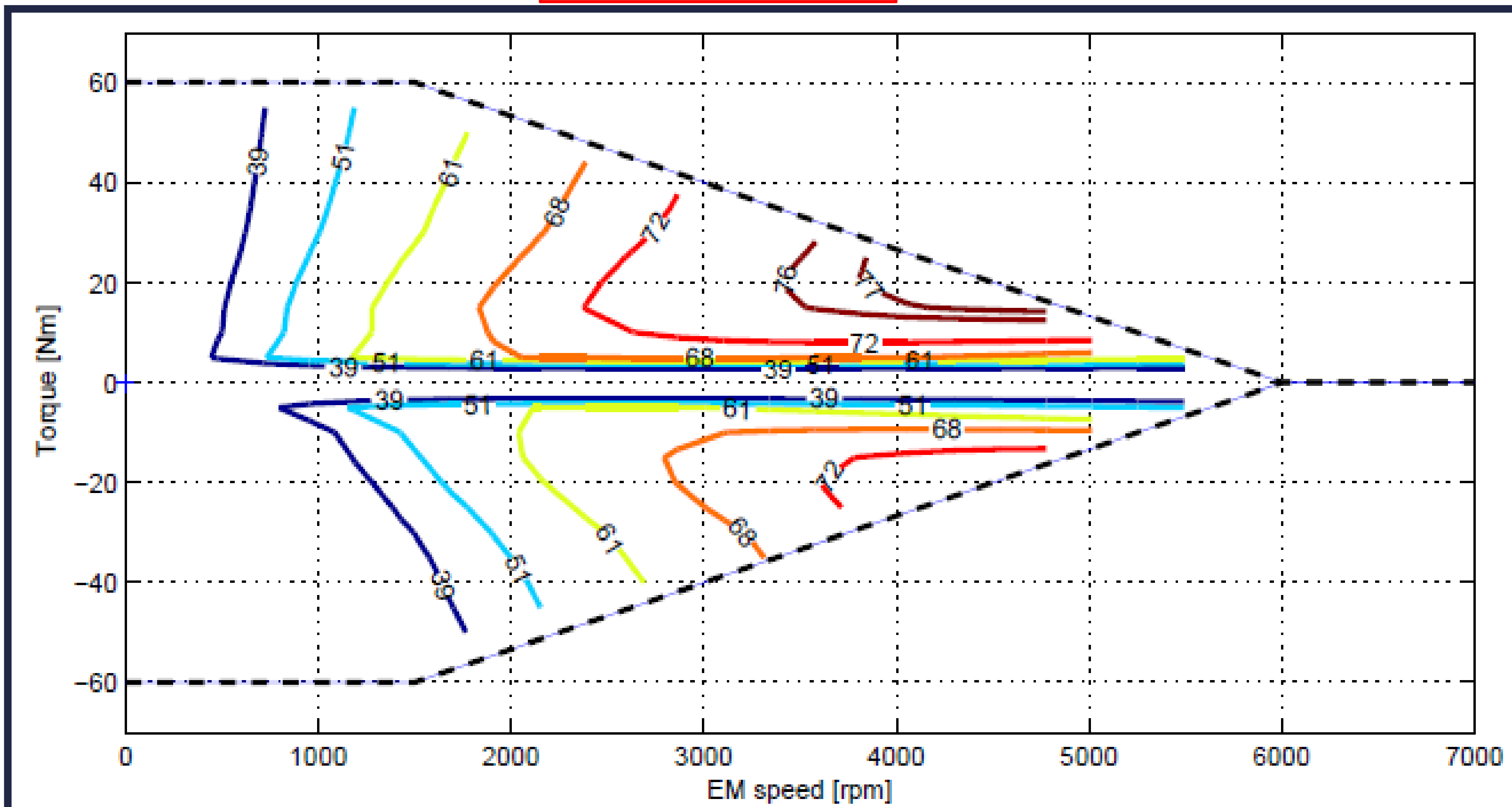
The vehicle drive train

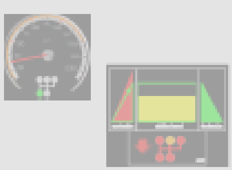
$$\dot{m}_{fuel} = f(v, a)$$



The vehicle drive train

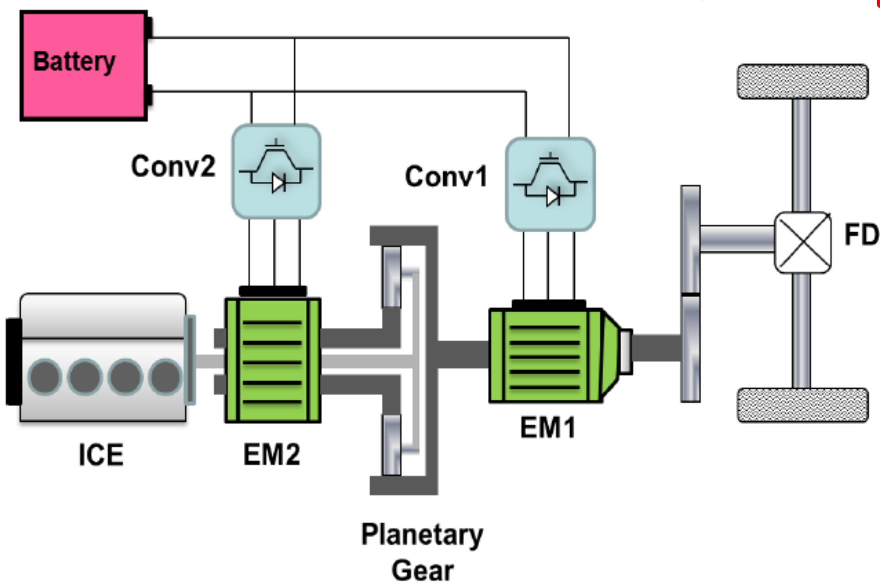
$$P_{batt} = f(v, a)$$

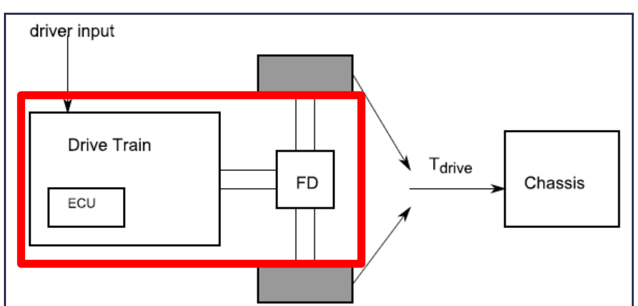




The vehicle drive train

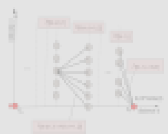
$$\dot{m}_{fuel} = f(v, a, SOC)$$





- Multiple power sources
- Modeling of energy management[27]

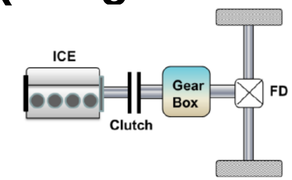
[27] E. Vinot, J. Scordia, R. Trigui, B. Jeanneret, F. Badin. Model simulation, validation and case study of the 2004 THS of Toyota Prius. International Journal of Vehicle Systems Modelling and Testing, 3(3): 139-167, 2008



System Modeling - Conclusion

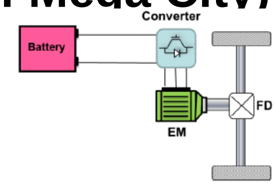
Summary:

- **Inverse vehicle model**
  - **Conventional vehicle (Peugeot 308)**



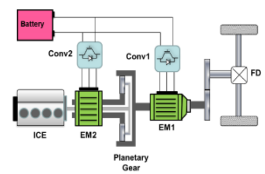
$$\dot{m}_{fuel} = f(v, a)$$

  - **Electric vehicle (Aixam Mega City)**



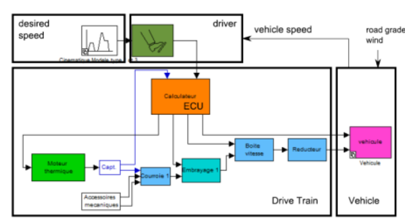
$$P_{batt} = f(v, a)$$

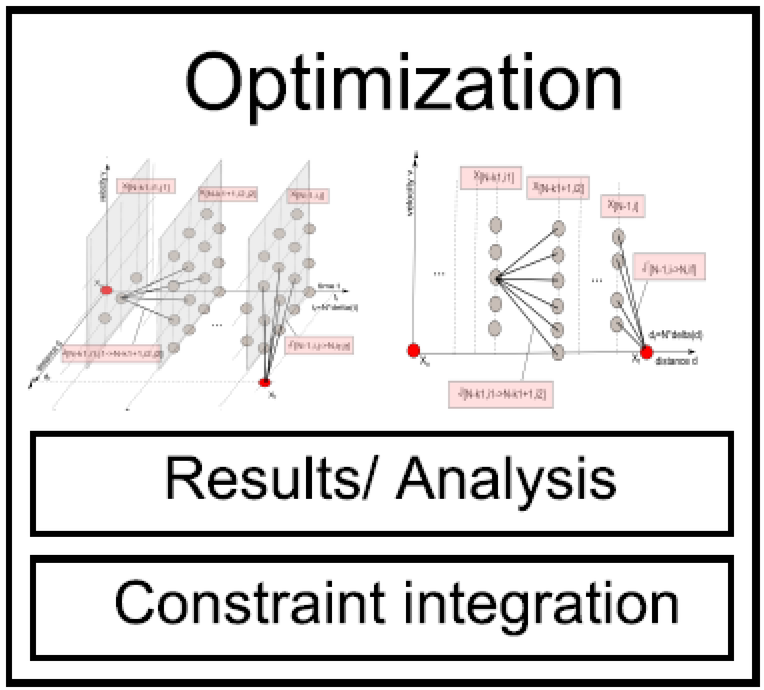
  - **Hybrid vehicle (Toyota Prius)**



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

- **Direct dynamic vehicle simulation (VEHLIB)**

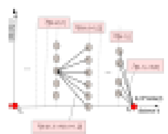



Optimization
Results/ Analysis
Constraint integration

Introduction

System modeling

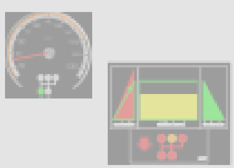
Optimization



Results/ Analysis

Constraint integration

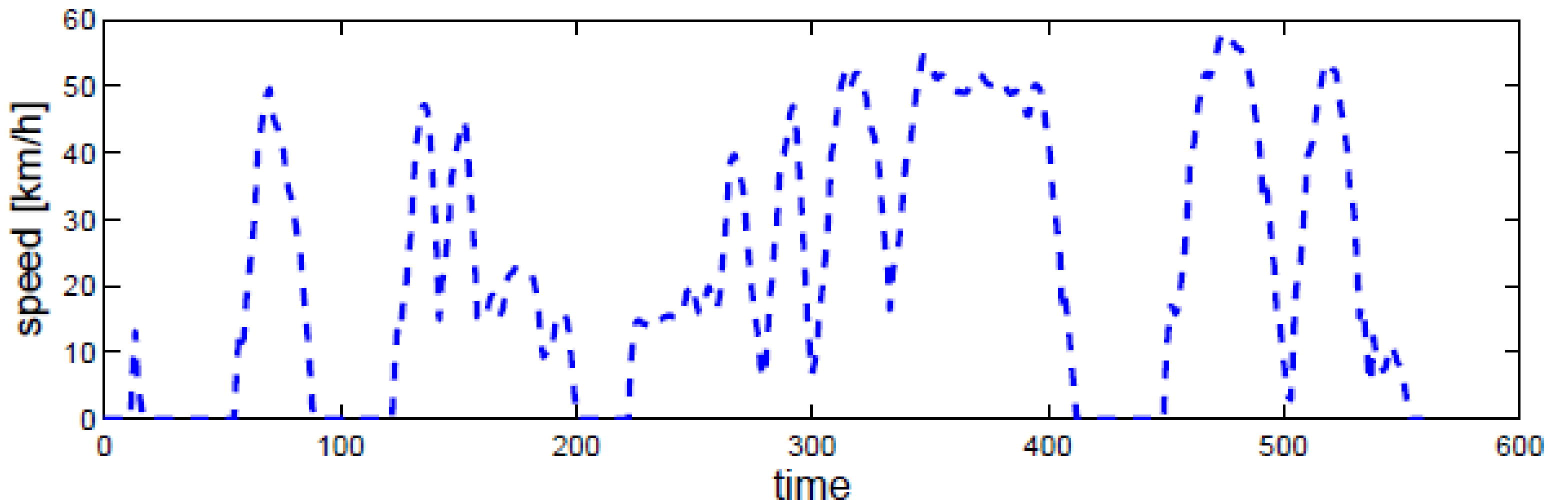
ADAS



Conclusion

Problem definition

Vehicle mission



➔ 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

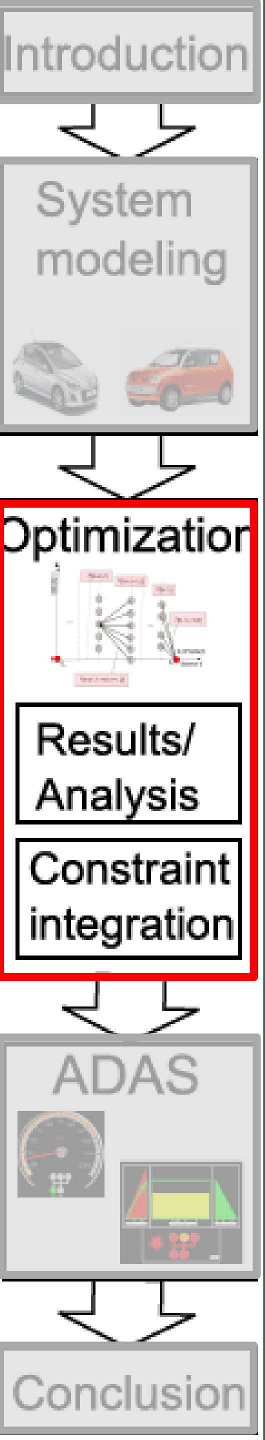
$$\Gamma_1 = \int_t \gamma_{veh}(t)dt \approx \sum_{i=1}^{n} \gamma_{veh_i}(t_i \rightarrow t_{i+1})$$

f(v,a)

$$\gamma_{veh}^{conv}(t) = \dot{m}_{fuel_i}(t_i -> t_{i+1})\Delta t_i$$

$$\gamma_{veh}^{elec}(t) = P_{batt_i}(t_i -> t_{i+1})\Delta t_i$$

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



Problem definition

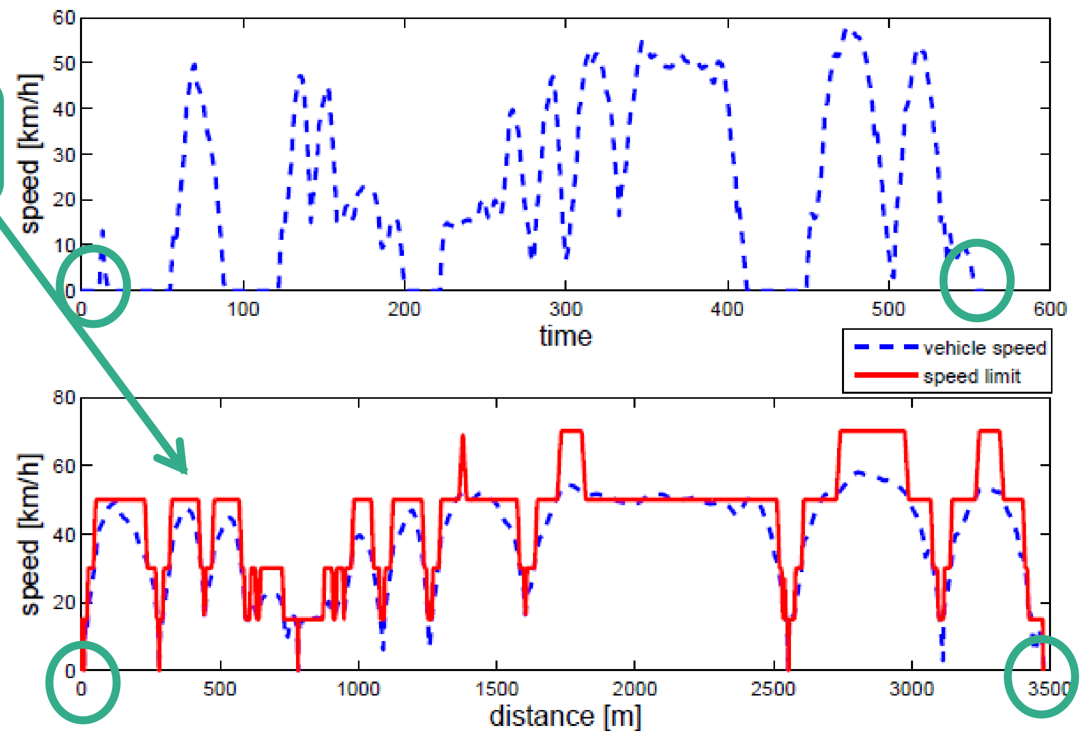
- **Trip constraints**

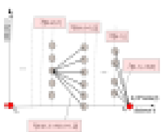
$$d(0) = d_0 \qquad d(t_f) = d_f$$
$$v(0) = v_0 \qquad v(t_f) = v_f$$
$$t_f = T$$

- **Road constraints**

$$v(d_i) < v_{max}(d_i)$$

- **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

Literature review

- **Pontryagin's maximum principle**[30]
  - Al
  - Constraint integration is not trivial

Used for problems with simple constraints

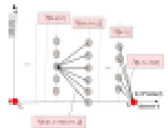
- **Bellman principle (ex: Dynamic Programming (DP))**[31],[32]
  - Computational effort grows with dimensions
  - C

Used when discreet problem with complex constraints

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

14(5):455-470, 2004.
[30] E. Hellstroem, J. Aslund, L. Nielsen. Horizon l... lents for fuel-optimal look-ahead control. Proceedings 6th IFAC Symposium on Advances ..., 2010
[31] J.N. Hooker. Optimal driving for single-vehicle fuel economy. Transportation Research A, 183-201, 1988.

Dynamic Programming Optimization Method



Application of DP to our problem

Equations of motion

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

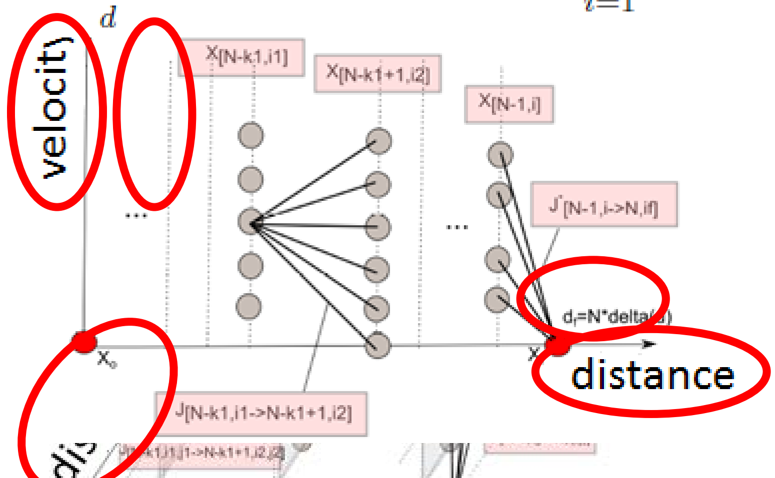
2 state variables

Constraints

$$d(0) = d_0 \qquad d(t_f) = d_f$$
$$v(0) = v_0 \qquad v(t_f) = v_f$$
$$v(d_i) < v_{max}(d_i)$$
$$t_f = T$$

Objective

$$\Gamma_2 = \int_d \gamma_{veh}(d)dt + \beta \Delta t(d) \approx \sum_{i=1}^{n} \gamma_{veh_i}(t_i -> t_{i+1})\Delta t_i + \beta \Delta t_i$$



three
d,v,t)

Constraints in two dimensions (d,v)

DP in 3 dimensions

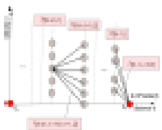
DP in 2 dimensions with weighting factor

[36] V. V. Monastyrsky, I.M. Golownykh. Rapid computation of optimal control for vehicles. Transportation Research Part B: Methodological, 27(3):219-227, 1993.
[34] J.N. Hooker. Optimal driving for single-vehicle fuel economy. Transportation Research A, 183-201, 1988.
[37] F. Mensing, E. Bideaux, R. Trigui, B. Jeanneret, Trajectory optimisation for eco-driving - an experimentally verified optimisation method, Int. J. Vehicle Systems Modelling and Testing, accepted for publication
[35] F. Mensing, R. Trigui, E. Bideaux. Vehicle trajectory optimization for application in Eco-driving. IEEE Vehicle Power and Propulsion Conference, September 2011

Introduction

System modeling

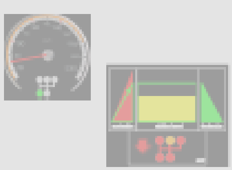
Optimization



Results/ Analysis

Constraint integration

ADAS



Conclusion

Application of DP to our problem

Mission

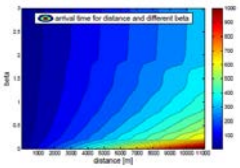
$d(0) = d_0 \qquad d(t_f) = d_f$

$v(0) = v_0 \qquad v(t_f) = v_f$

~~$v(d_i)$ … $v_{max}(d_i)$~~

! ~~t_f … T~~ !

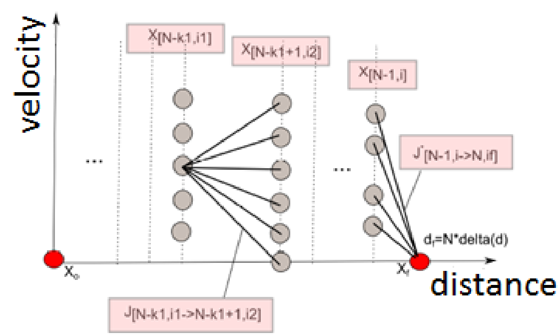
~~gr … (d_i)~~



Weighting factor

β

DP 2D Optimization



$$\Gamma_2 \approx \sum_{i=1}^{n} \gamma_{veh_i}(t_i -> t_{i+1})\Delta t_i + \beta \Delta t_i$$

Optimal trajectory with some final time T_f

$$T_f = f(mission, \beta)$$

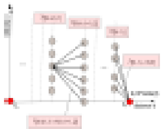
How to identify β?

1. **Chosen by driver**

   Time constraint!!

2. **Look-up table**

   $\beta = f(T_f, d_{trav})$



Application of DP to our problem

Mission

$d(0) = d_0 \qquad d(t_f) = d_f$

$v(0) = v_0 \qquad v(t_f) = v_f$

! $v(d_i) < v_{max}(d_i)$!

! $t_f = T$!

! $grade\ (d_i)$!

Weighting factor

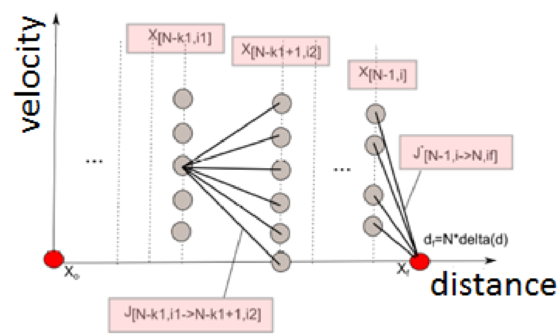
β

β – update Root-finding methods[38]

$f_{error} = T_f - t_f^{des}$

NO

DP 2D Optimization



$$\Gamma_2 \approx \sum_{i=1}^{n} \gamma_{veh_i}(t_i -> t_{i+1})\Delta t_i + \beta \Delta t_i$$

$T_f \approx t_f^{des}$

YES

Solution: Optimal trajectory

$T_f = f(mission, \beta)$

How to identify β?

1. **Chosen by driver**

   Time constraint!!

2. **Look-up table**

   $\beta = f(T_f, d_{trav})$

3. **Nested Solution with root-finding methods**

[38] R.P. Brent. An algorithm with guaranteed convergence for finding a zero of a function. The Computer Journal, 14(4):422-425.1971.

Optimization - Conclusion

Vehicle mission

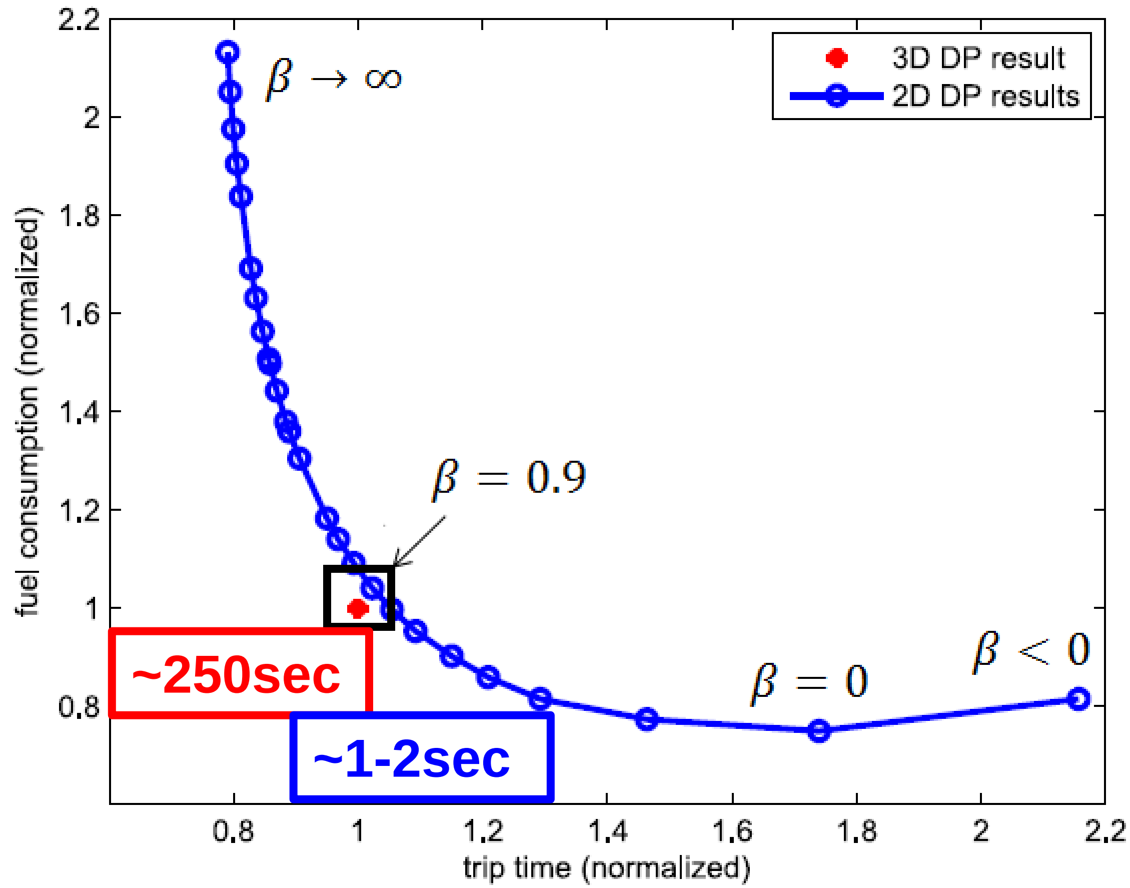
Constraints

Optimization

Optimal vehicle operation

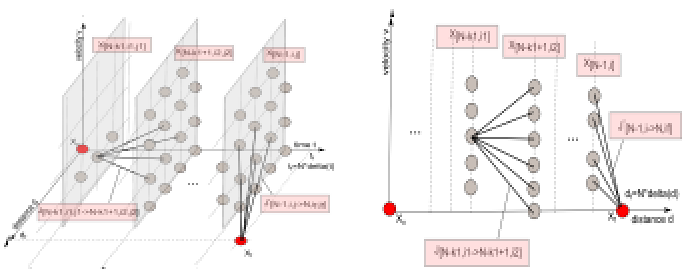
Dynamic Programming Optimization

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



Results/ Analysis

Optimization



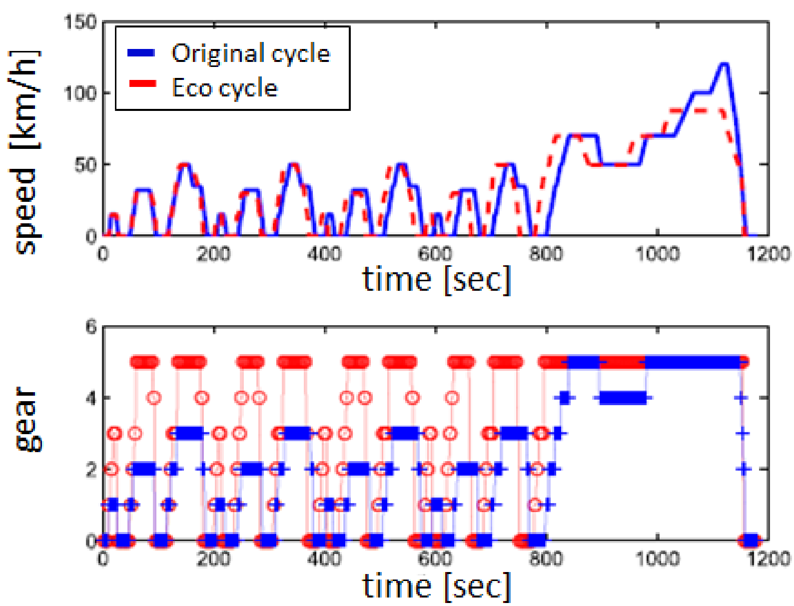
Results/ Analysis

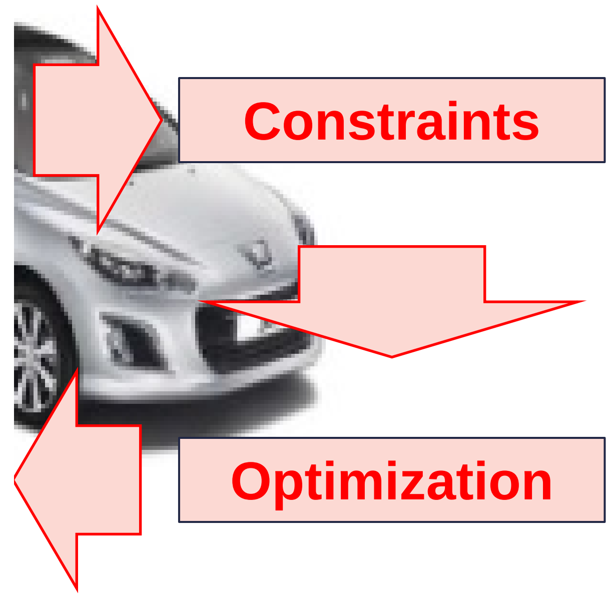
Constraint integration

Potential gains of eco-driving

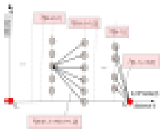
Cycle	max speed	stop frequency	distance	time
NEDC	120km/h	1.1 per km	11km	887sec
Urban	58km/h	1.1 per km	3.5km	560sec
Extra-urban	103[illegible]	[illegible]	11.2km	754sec
Freeway [38]	138km/h	0.1 per km	46.2km	1741sec

Conventional vehicle



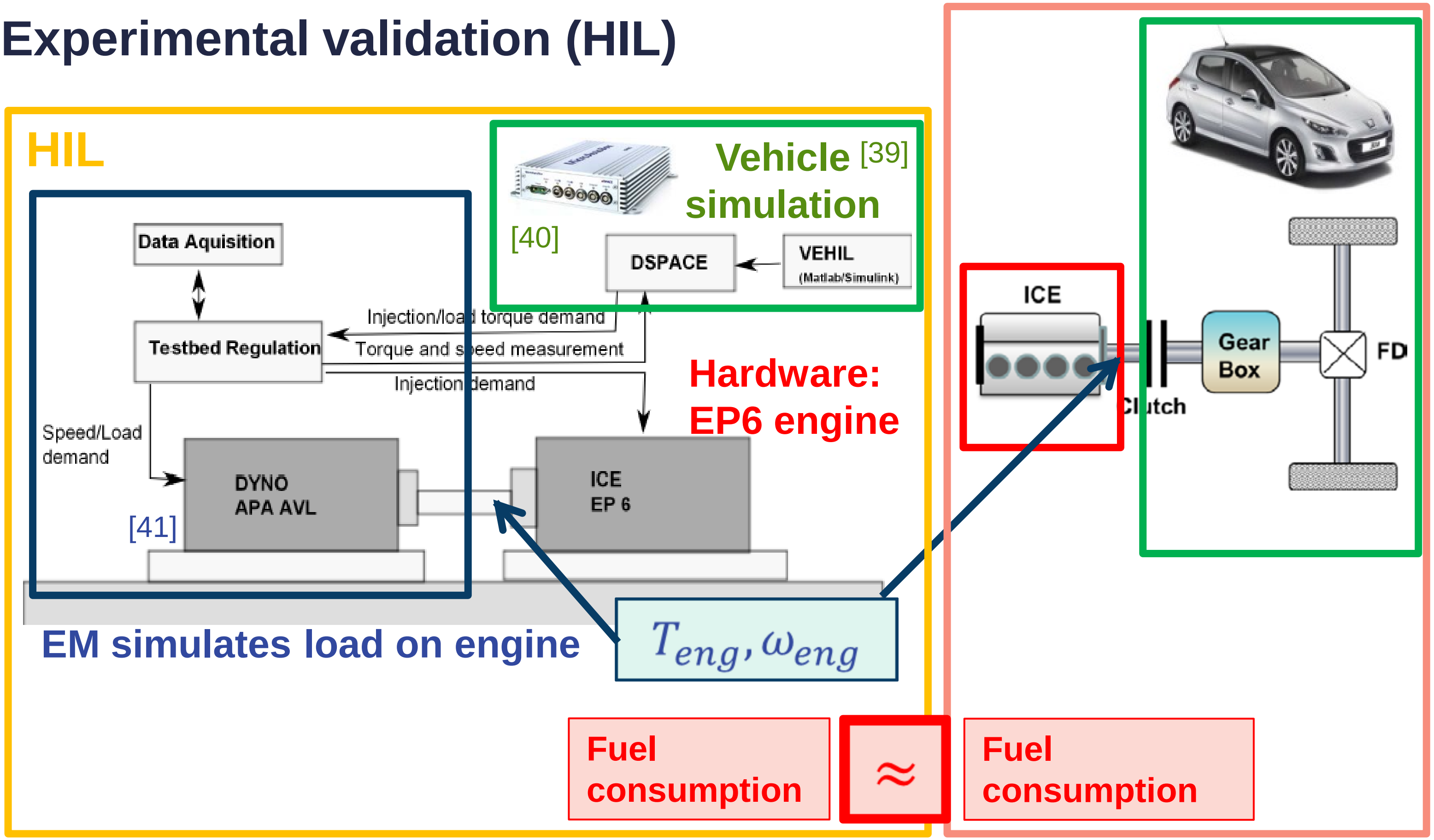


[38] Michel Andre. Artemis european driving cycles for measuring car pollutant emissions. Science of the Total Environment, 73-84. 2004.



Potential gains of eco-driving

Experimental validation (HIL)

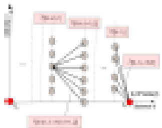


[39] R. Trigui, B. Jeanneret, B. Malaquin, C. Plasse. Performance comparison fo three storage systems for mild-HEVs using PHIL simulation. IEEE Transactions on Vehicular Technology, 3959-3969, 2009.
[40] Dspace MicroAutoBox http://www.dspace.com/de/gmb/home/products/hw/micautob.cfm
[41] AVL. https://www.avl.com

Introduction

System modeling

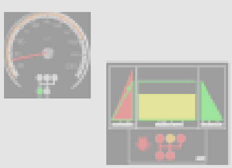
Optimization



Results/ Analysis

Constraint integration

ADAS



Conclusion

Potential gains of eco-driving

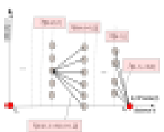
drive cycle	original [L/100km]	eco [L/100km]	reduction [%]
NEDC	6.7	5.5	17.9
HYZURB	9.76	7.11	27.2
HYZROUT	7.22	5.41	25.1
HYZAUTO	6.92	6.37	7.9

urban and extra-urban area

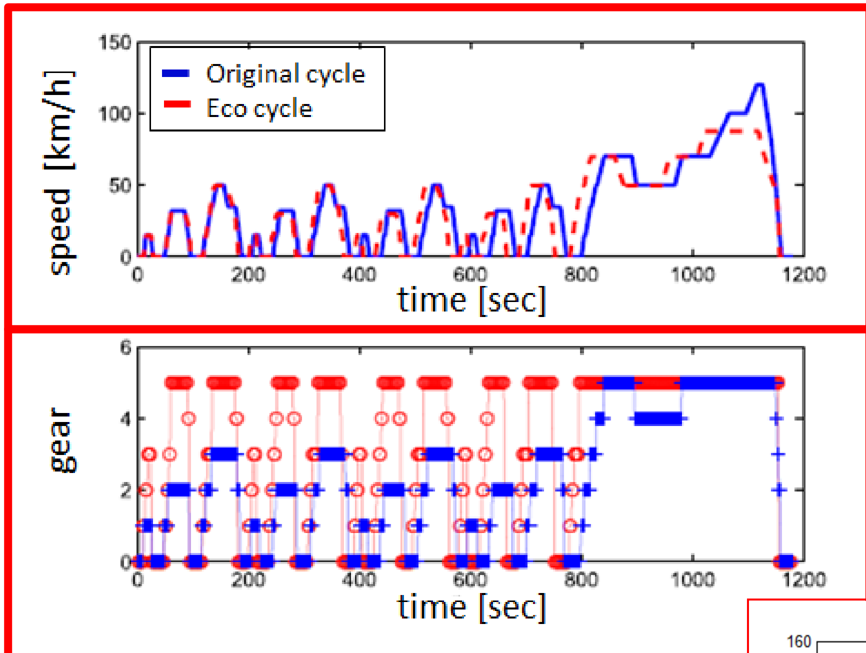
Highway/ freeway driving

Significant reductions in fuel consumption

HOW???



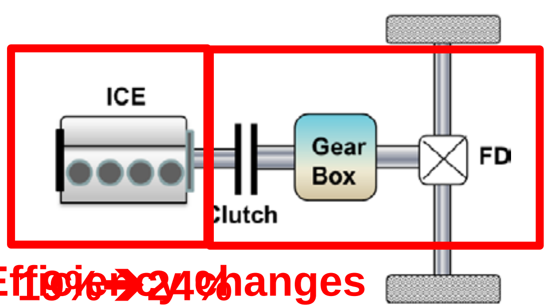
Optimal vehicle operation



NEDC
Potential gain:

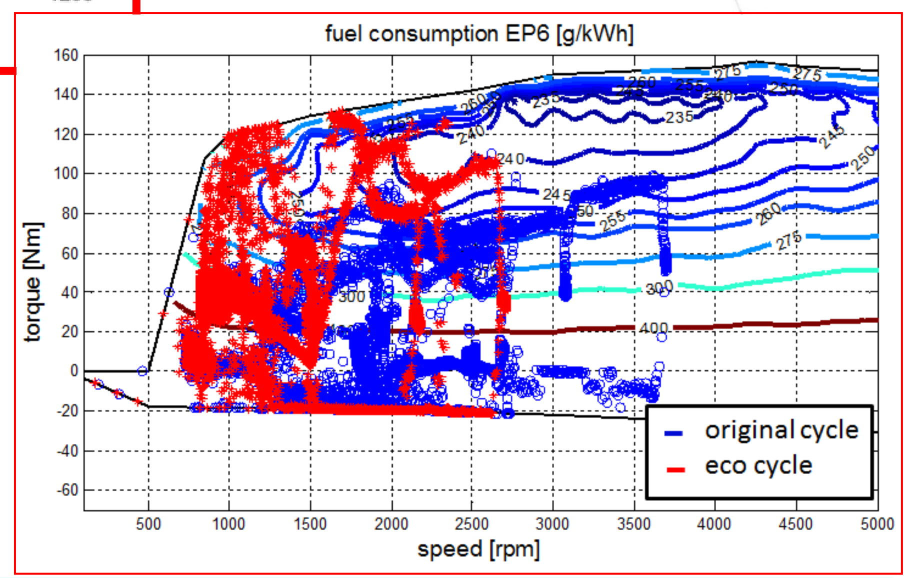
18%

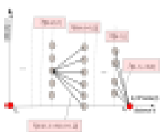
1. Component operation



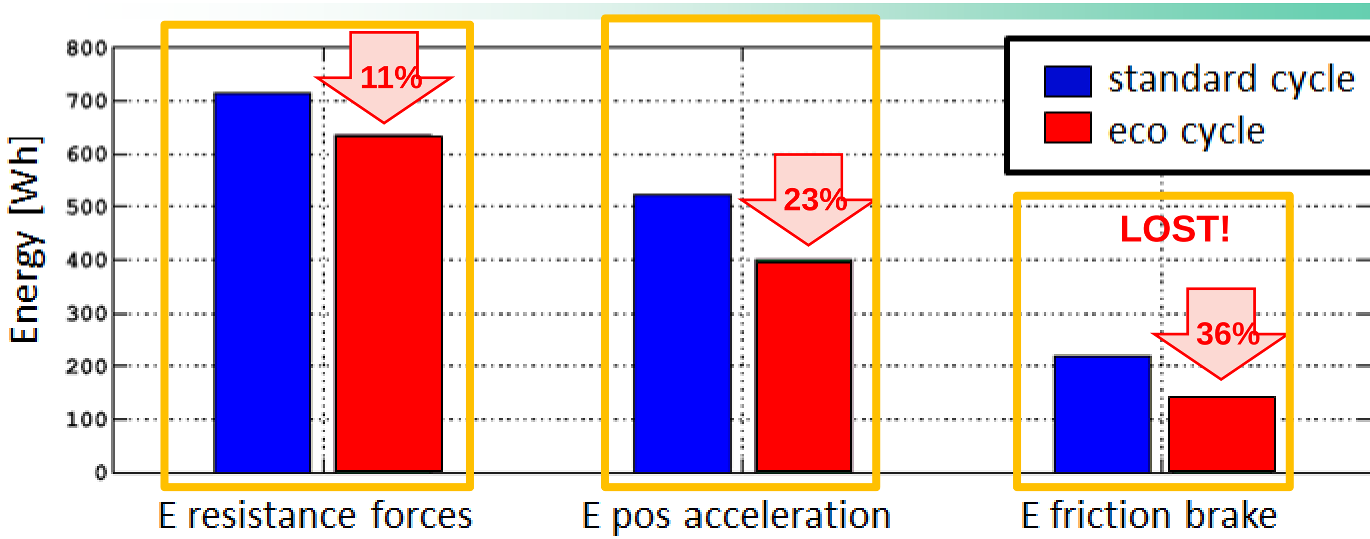
Efficiency changes minimal

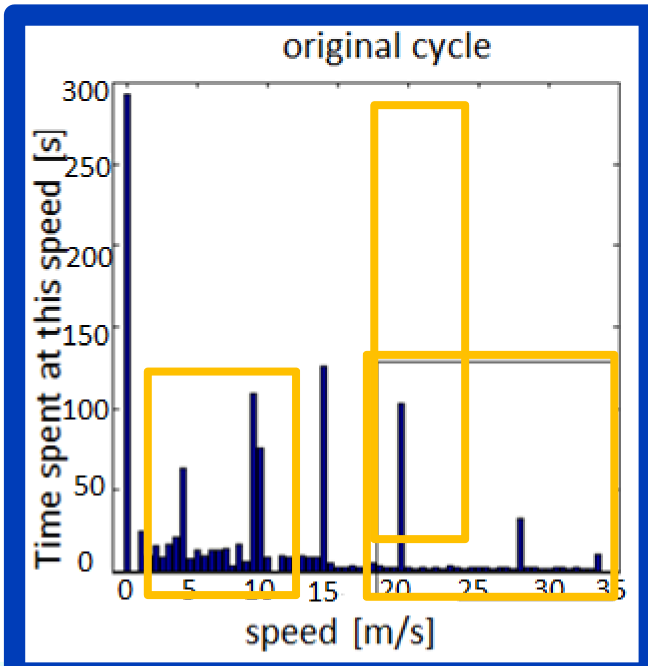
15%→24%

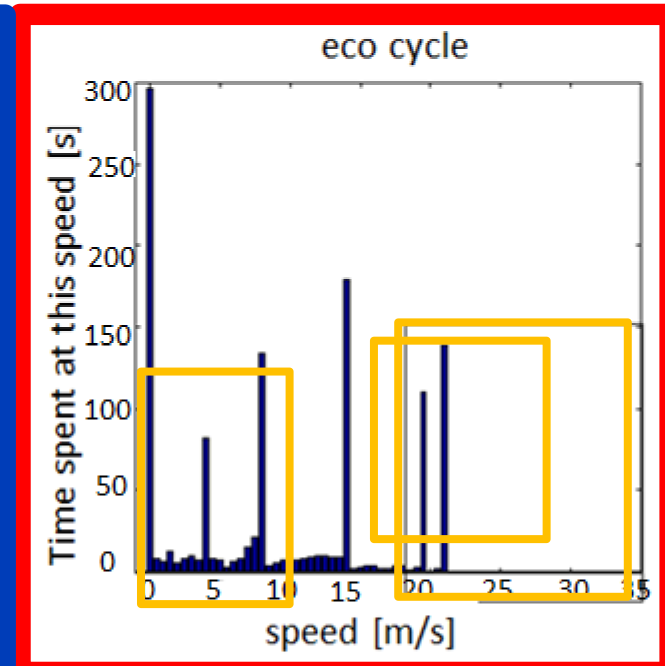


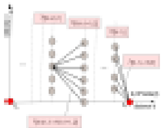


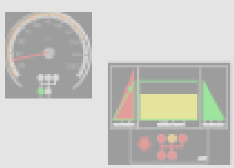
Optimal vehicle operation











Optimal vehicle operation

Conventional vehicle:

1. Transmission:
   H...
   ➔ increase engine efficiency

Next section:emissions

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:

...influence

Low constant speed

=

High, short acceleration
➔ save time, rapidly approach cruising speed
(time constraint!!)

=

(friction break)

Hybrid vehicle:

No influence

Low constant speed

High, short acceleration
➔ save time, rapidly approach cruising speed
(time constraint!!)

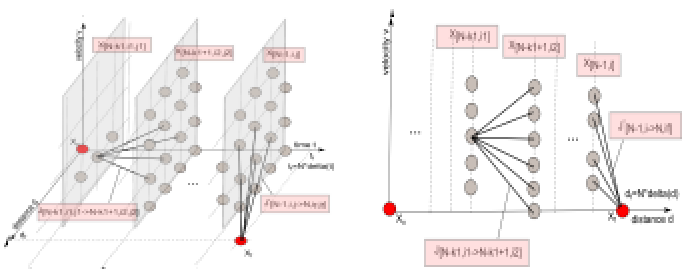
break)

Factors dependent on
***Chassis**
***Performance of components**

Factors dependent on
***Drive train➔ optimal energy regeneration**

Constraint Integration

Optimization



Results/ Analysis

Constraint integration

- Traffic
- **Emissions**

Is eco-driving environmentally friendly?

Eco-driving

Economic advantages
(energy, fuel ($\approx CO_2$))

$$\Gamma_{veh_1} = \int \gamma_{fuel}(t)dt$$

Ecologic advantages [41]
(energy+pollutant emissions)

$$\Gamma_{veh_2} = \int (\gamma_{fuel}(t) + \lambda\gamma_{emission})dt$$

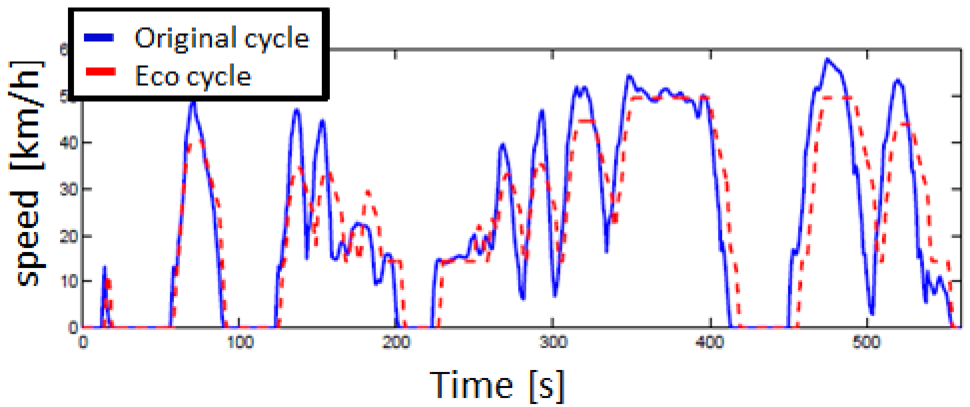
ting factor?
target?

Emission cost

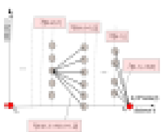
Constraints

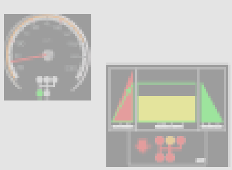
Optimization

$$\Gamma_{veh_1} = \int \gamma_{fuel}(t)dt$$

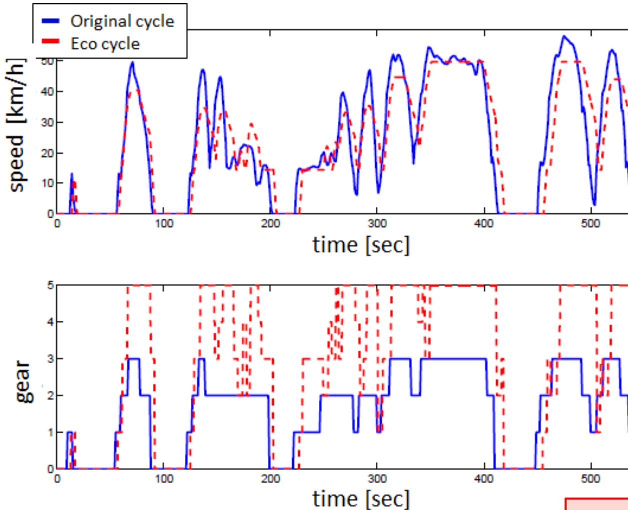


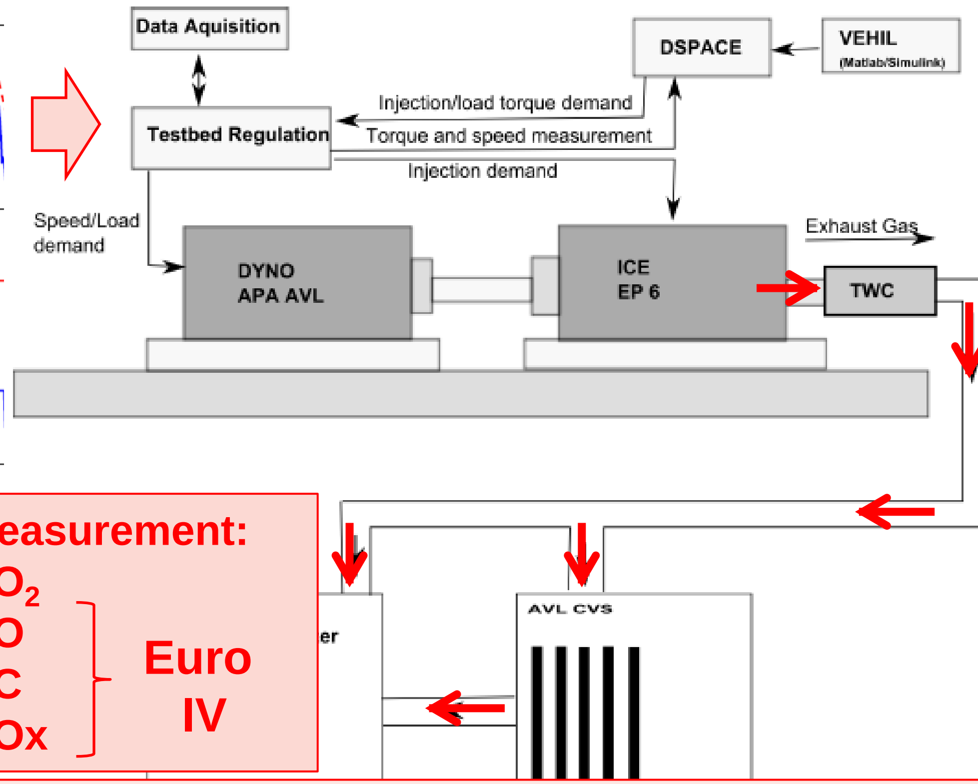
[42] H. Johansson, P. Gustafsson, M. Henke, M. Rosengren. Impact of eco driving on emissions. Proceedings of 12th Symposium Transportation and Air Pollution, June 2013





Experimentation





Measurement:
CO_2
CO
HC
NOx
} **Euro IV**

Perfect combustion:
Fuel + oxygen ➔ energy + water vapor + carbon dioxide (CO_2)

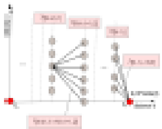
Real combustion:
Fuel + air ➔ energy + water vapor + carbon dioxide (CO_2)
+ hydrocarbon (HC) + carbon monoxide (CO) + nitrogen oxides (NO_x) …

[43] HORIBA http://www.horiba.com/
[44] U.S. Environmental Protection Agency. Automobile emissions: An overview. EPA 400-f-92-007, 1994

Introduction

System modeling

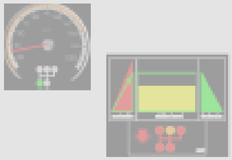
Optimization



Results/ Analysis

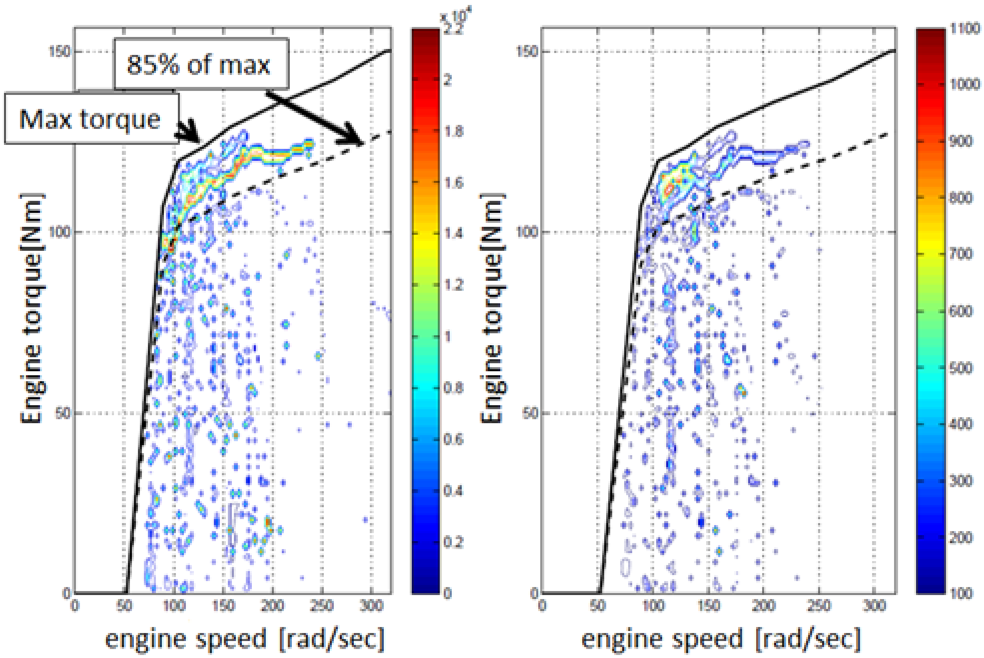
Constraint integration

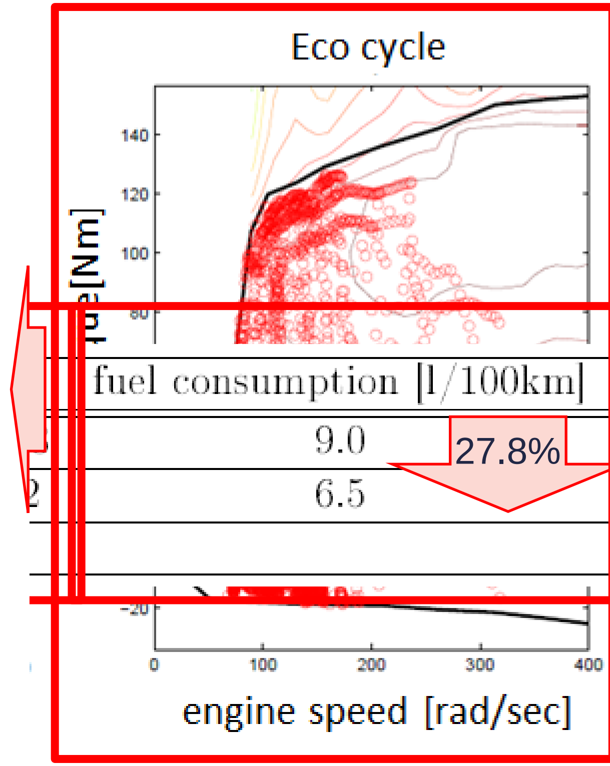
ADAS



Conclusion

Economic vehicle operation

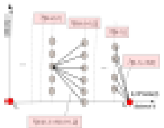




Introduction

System modeling

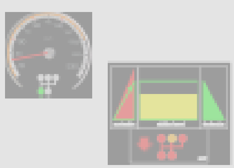
Optimization



Results/ Analysis

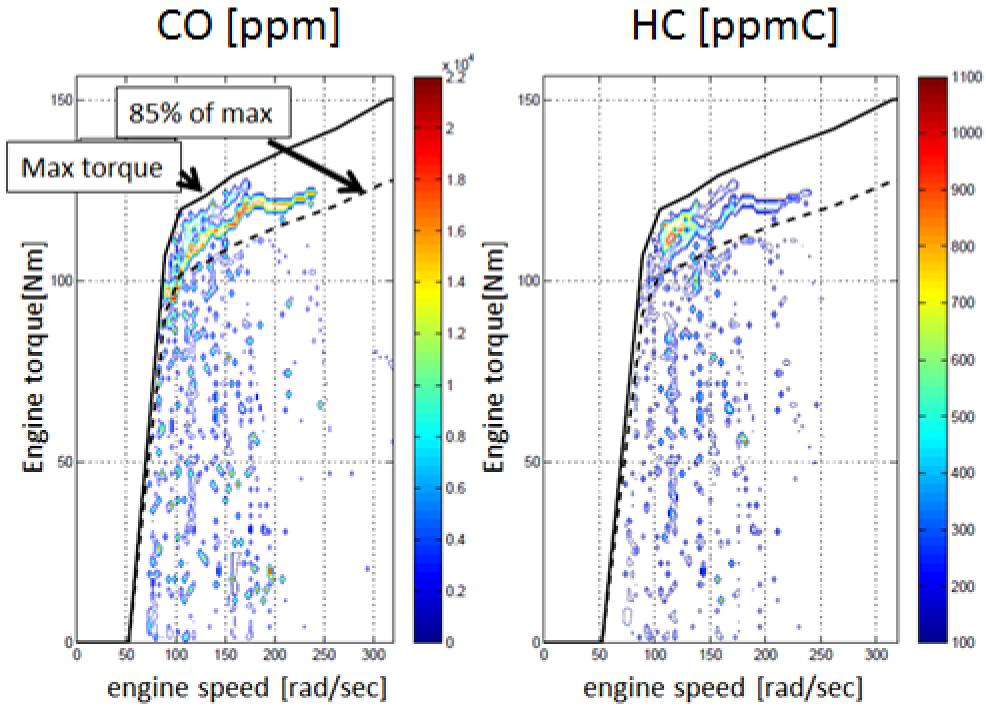
Constraint integration

ADAS



Conclusion

Ecologic (eco2) vehicle operation



χ =.85

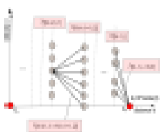
Emissions as soft constraint:
λ_0 large

$$\Gamma_{veh_2} = \sum_i (\gamma_{fuel}(t_i) + \lambda_i) \qquad \lambda_i = \begin{cases} \lambda_0 & if\ T_{eng} > \chi T_{engmax}(\omega_{eng}) \\ 0 & if\ T_{eng} <= \chi T_{engmax}(\omega_{eng}) \end{cases}$$

Introduction

System modeling

Optimization



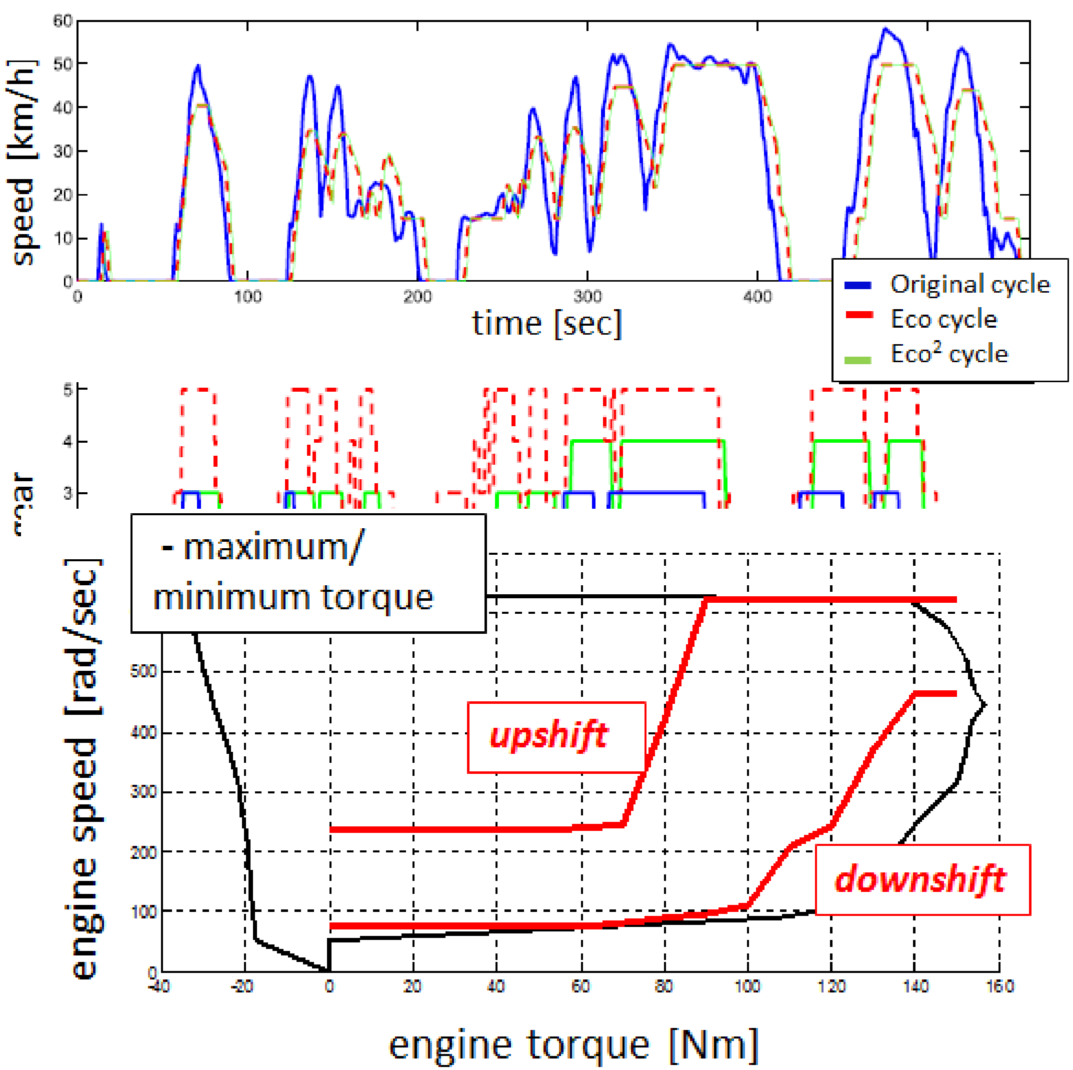
Results/ Analysis

Constraint integration

ADAS

Conclusion

Ecologic (eco2) vehicle operation



Constraints

Optimization

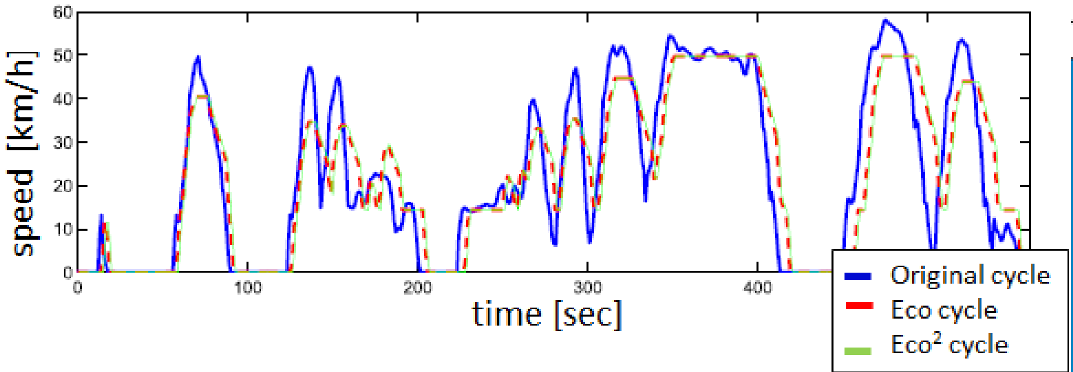
$$\Gamma_{veh_2} = \sum_i (\gamma_{fuel}(t_i) + \lambda_i)$$

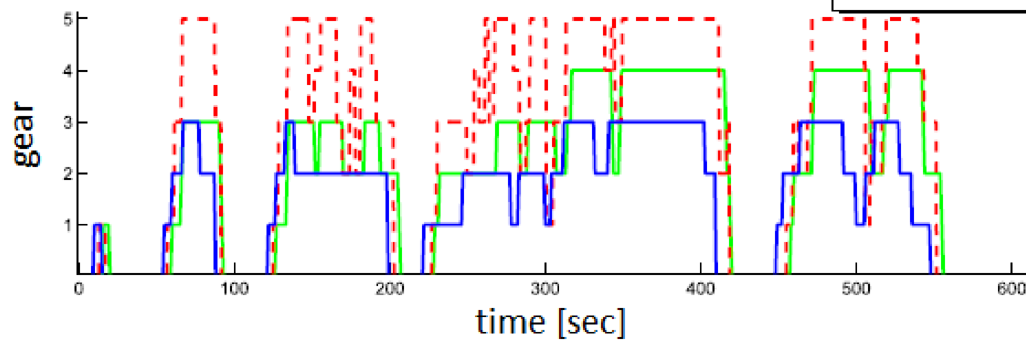
$$\lambda_i = \begin{cases} \lambda_0 & if\ T_{eng} > \chi T_{engmax}(\omega_{eng}) \\ 0 & if\ T_{eng} <= \chi T_{engmax}(\omega_{eng}) \end{cases}$$

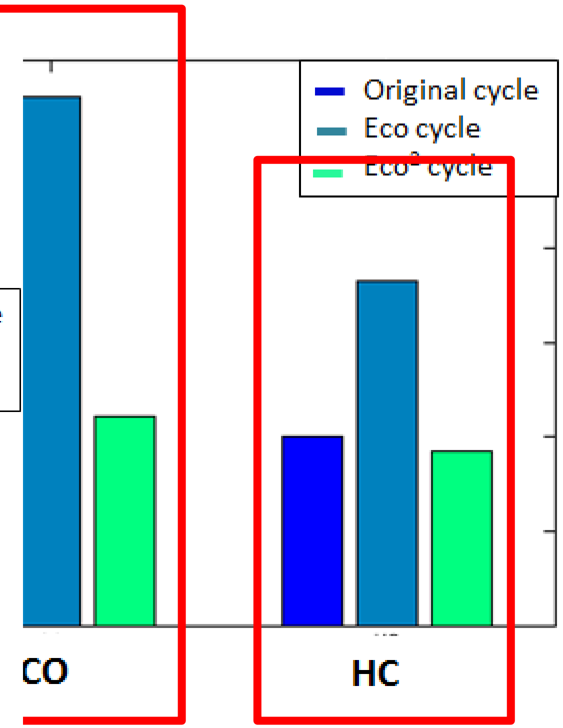
Dynamic optimal gear identification using vehicle model

simulation

Ecologic (eco2) vehicle operation

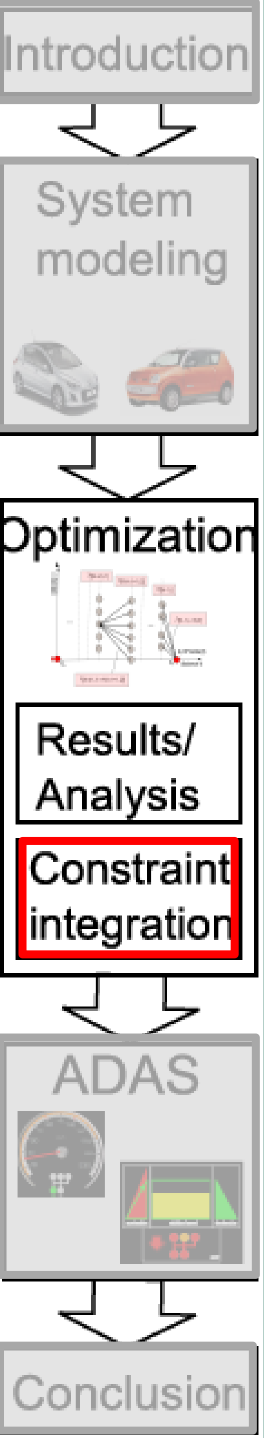






Emission in g/km	CO2	CO	NOx	HC	fuel consumption [l/100km]
Original Cycle	206.96	2.06	0.0055	0.068	9.0
Eco Cycle	140.96	5.78	0.0046	0.12	6.5
Eco^2 Cycle	151.51	2.18	0.0025	0.063	6.7

Is eco-driving environmentally friendly?

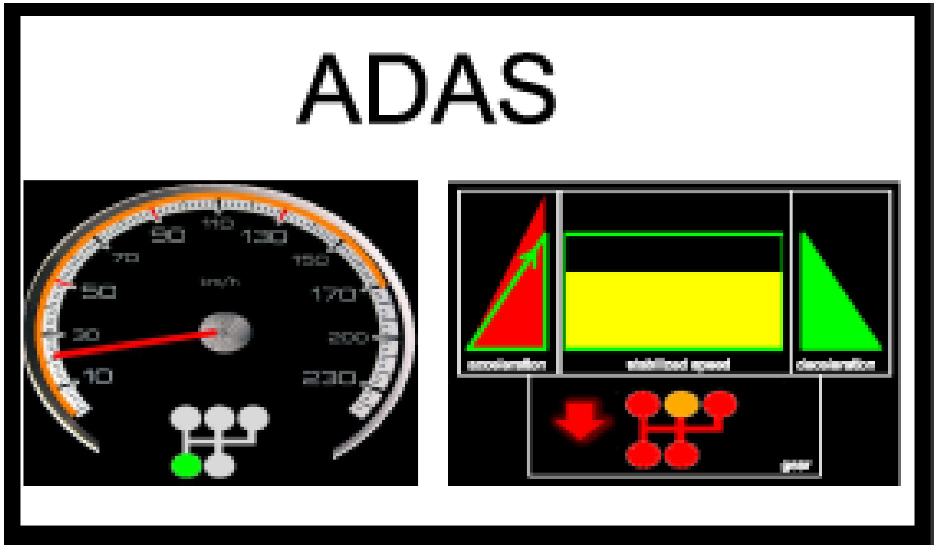


- **Eco-driving can be economic and ecologic:**

  ➔Emissions need to be taken into account

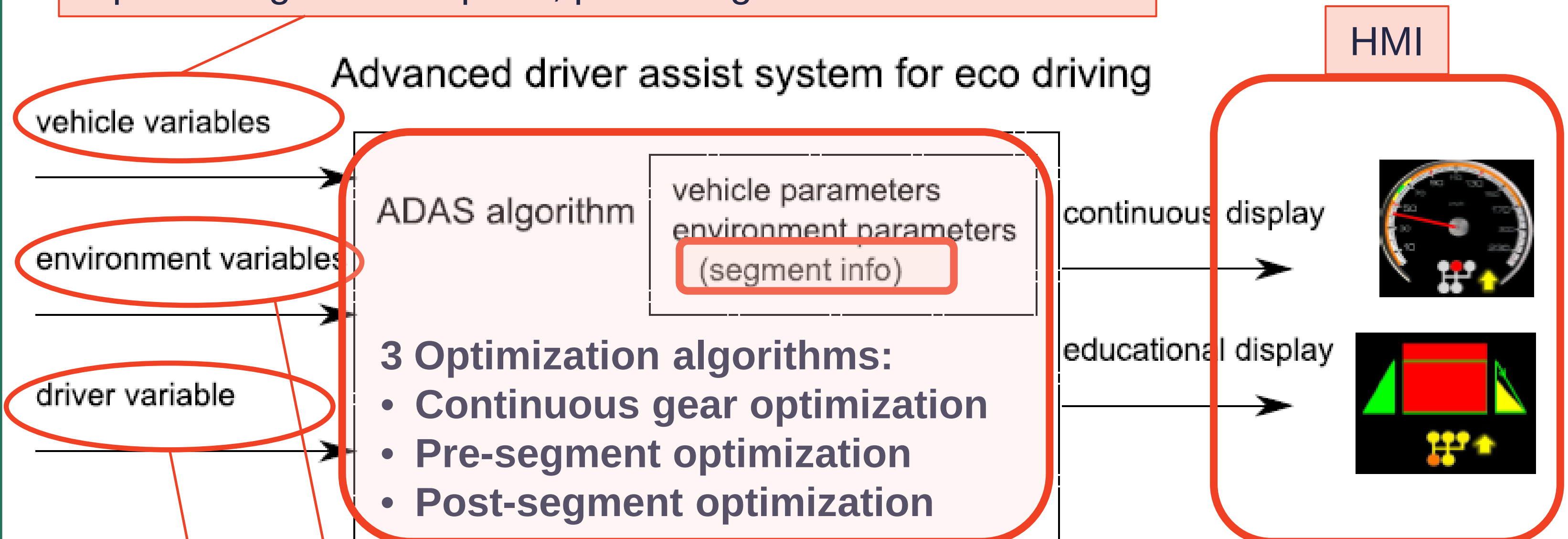
- **Vehicle operation ➔ optimal energy consumption**
- **Component operation/ transmission ➔ reduce emissions**

Advanced Driver Assist System (ADAS)



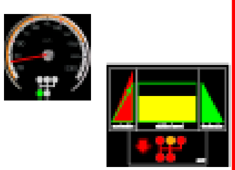
Development of ADAS system

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

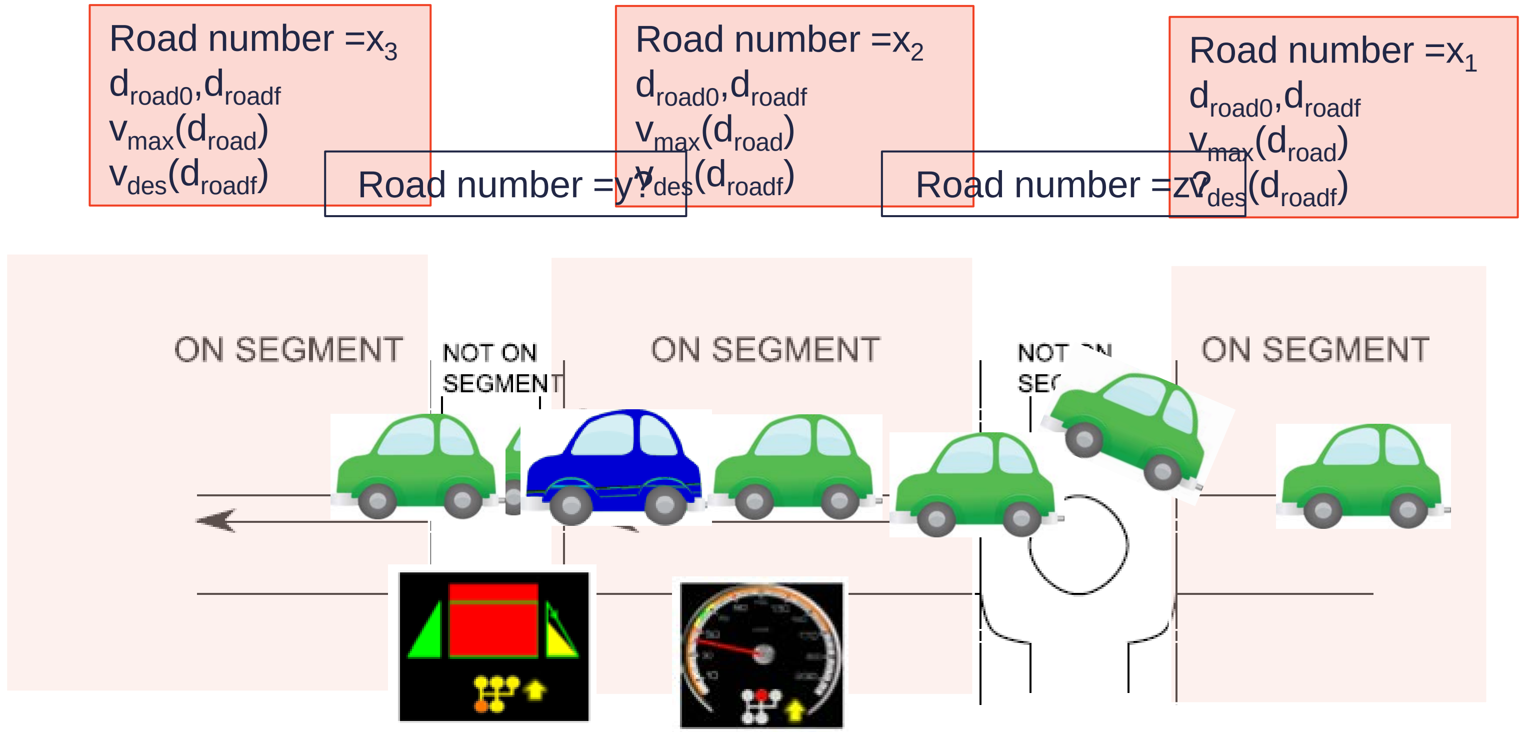


GPS or road mapping:
Segment information (road number, distance on road) ➔ vehicle position

Driver's trade-off time vs energy



Development of ADAS system - Algorithm

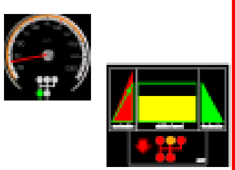


Gear optimization

Pre-segment optimization

Pre-segment optimization

Post-segment optimization



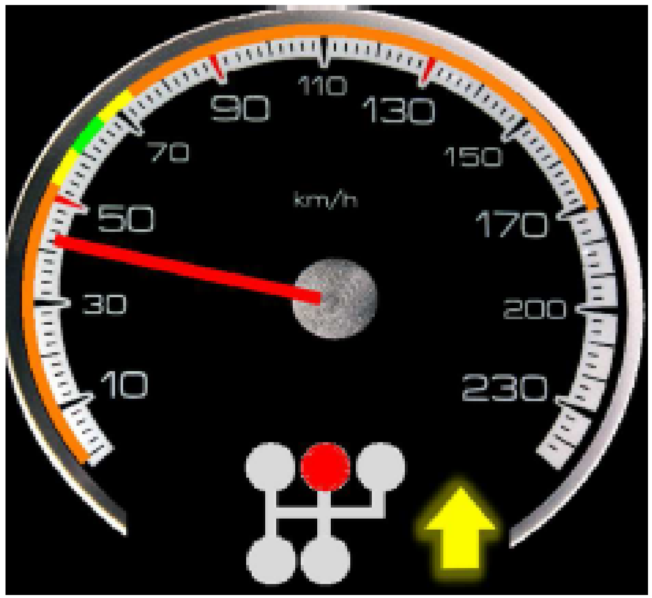
Development of ADAS system - HMI

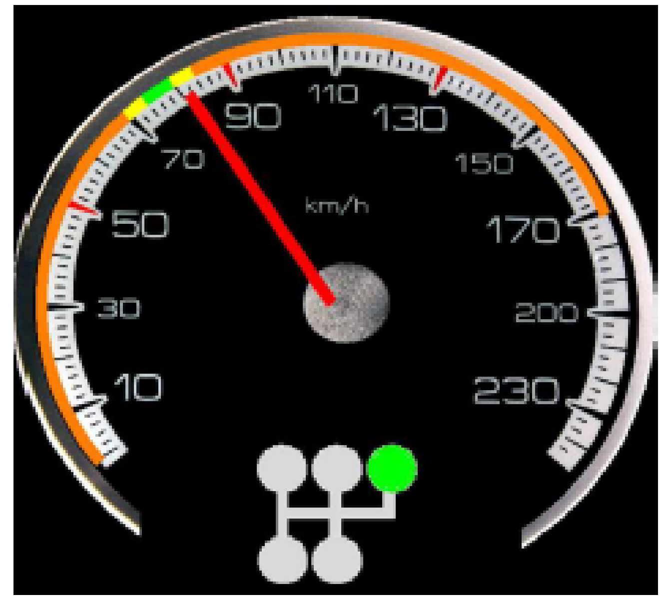
educational display

continuous display

Development of ADAS system - HMI

Continuous display





With advice / Without advice

Results

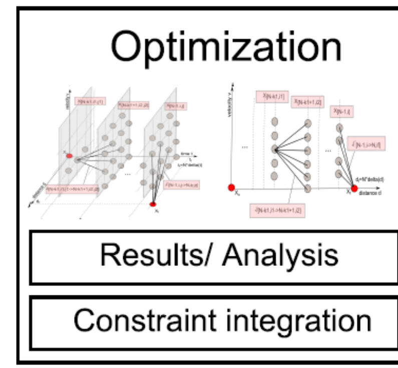
Average Gain: **11%**

Gain: **8.74%** **15.25%**

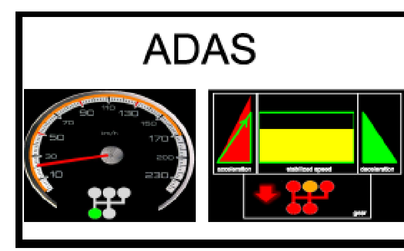
Conclusion

- **Inverse model of three vehicles**
  (conventional, electric and hybrid)

- **Dynamic programming optimization ➔ energy optimal vehicle operation for given mission**
  (3D ➔ 2D + weighting factor)
- **Analysis/ Comparison of optimal vehicle operation**
- **Eco-driving with constraints**
  Traffic and emissions



- **Integration of algorithms in ADAS**



Communications

Conference papers

- *F. Mensing, R. Trigui, E. Bideaux. Vehicle trajectory optimization for application in ECO-driving. 2011 IEEE Vehicle Power and Propulsion Conference (VPPC)*

- *F. Mensing, R. Trigui, E. Bideaux. Vehicle trajecotry optimization for hybrid vehicles taking into account battery state-of-charge. 2012 IEEE Vehicle Power and Propulsion Conference (VPPC)*

- *F. Mensing, R. Trigui, E. Bideaux. Vehicle trajeoctyr optimization of electric vehicles for eco driving applications. 2012 European Electric Vehicle Conference (EEVC)*

Journal papers

- *F. Mensing, E. Bideaux, R. Trigui, H. Tattegrain. Trajectory optimization for eco-driving taking into account traffic constraints. Transportation Research Part D: Transport and Environemnt, 18(1):55-61, 2013*

- *F. Mensing, E. Bideuax, R. Trigui, B. Jeanneret. Trajectory optimisation for eco-driving – an experimentally verified optimisation method. International Journal of Vehicle Systems, Modelling and Testing, accepted to be published 2013*

Journal papers in progress

- *F. Mensing, E. Bideaux, R. Trigui, J. Ribet, B. Jeanneret. Eco-driving: An economic or ecologic driving style? Transportation Research Part C: Emerging Technologies.. Submitted for review 2013*
- *F. Mensing, E. Bideaux, R. Trigui, H. Tattgetrain. Development of an effective and safe ADAS for eco-driving. In progress*

Other stuff

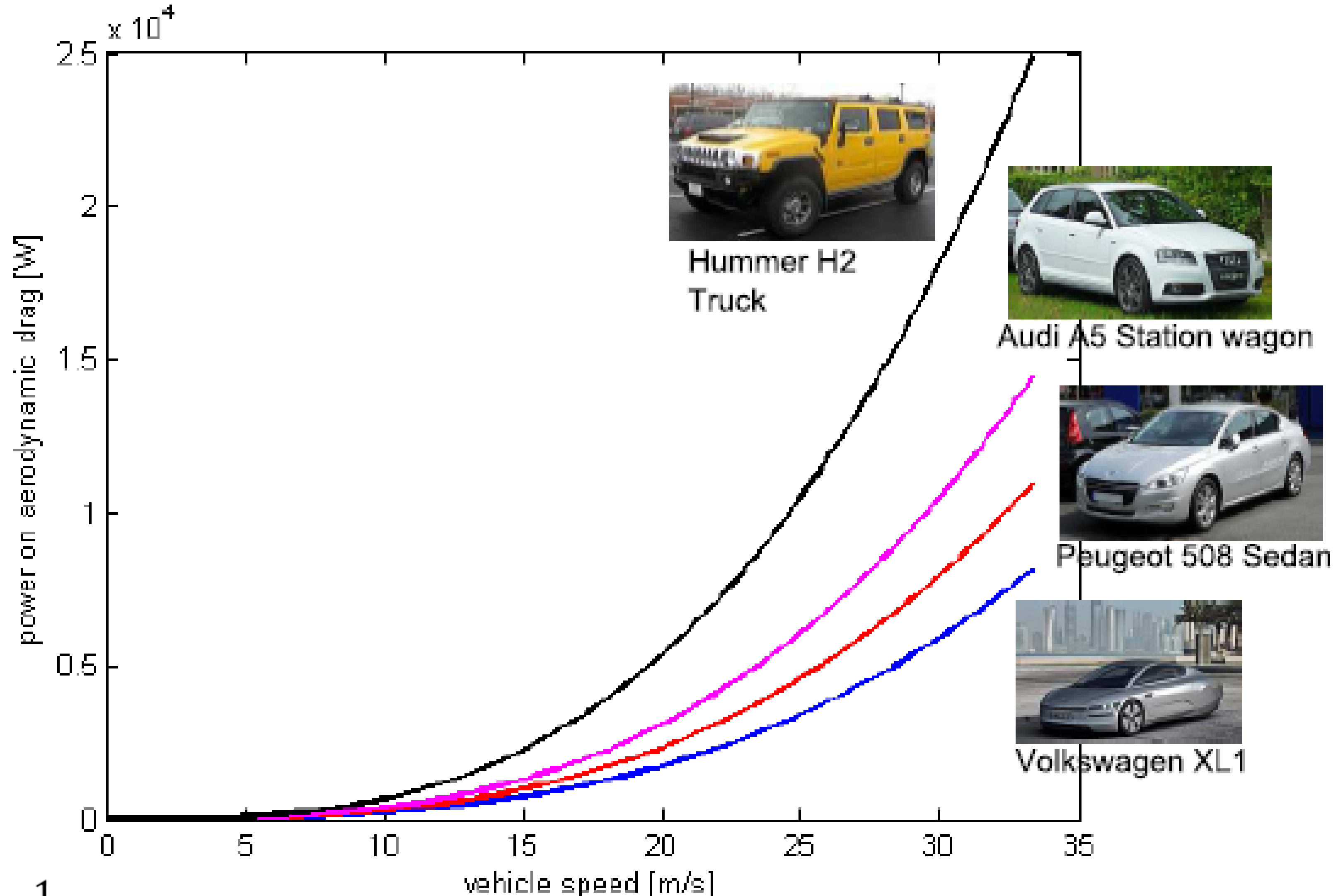
- Vehicle model of electric and hybrid vehicle

- Optimization (Multi-Obj)

- Results Electric
- Results (Optimization) Hybrid

- Traffic constraint study

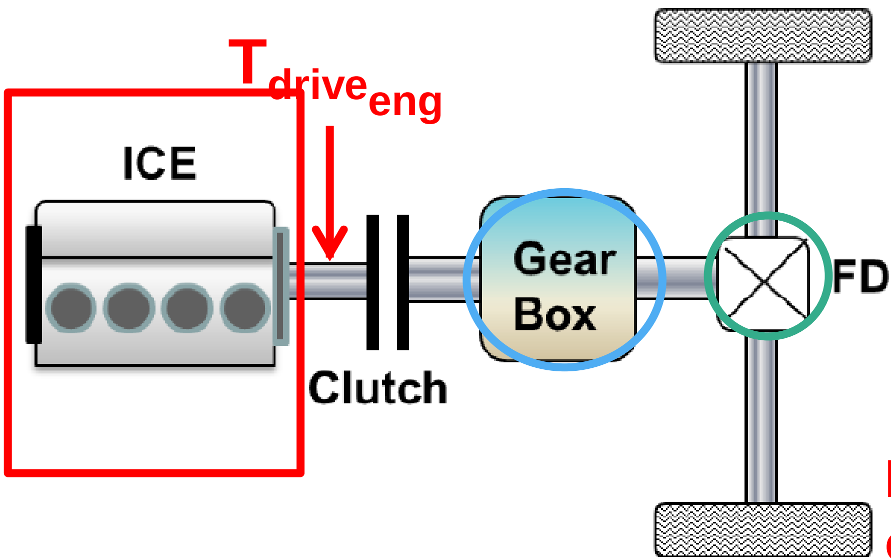
System Modeling – Chassis/Aero



$$F_{aero} = \frac{1}{2}\rho C_x S_x v^2$$

System Modeling- Conventional Vehicle

The conventional vehicle (inverse)



$$\omega_{eng} = max(\omega_{eng-idle}, \omega_{wheel} * R_{FD} * R_G(i_{gear}))$$

Dynamics of drive shaft not considered

Inversion

$$T_{eng} = T_{drive}\frac{\eta_{FD}^{\psi}\eta_G^{\psi}(i_{gear})}{R_{FD}R_G(i_{gear})} + \frac{P_{aux}}{\omega_{eng}} + J_{eng}\dot{\omega}_{eng}$$

Engine dynamics

$$J_{eng}\dot{\omega}_{eng} = T_{eng} - T_{drive_{eng}} - T_{aux}$$

Engine operation

Hypotheses:

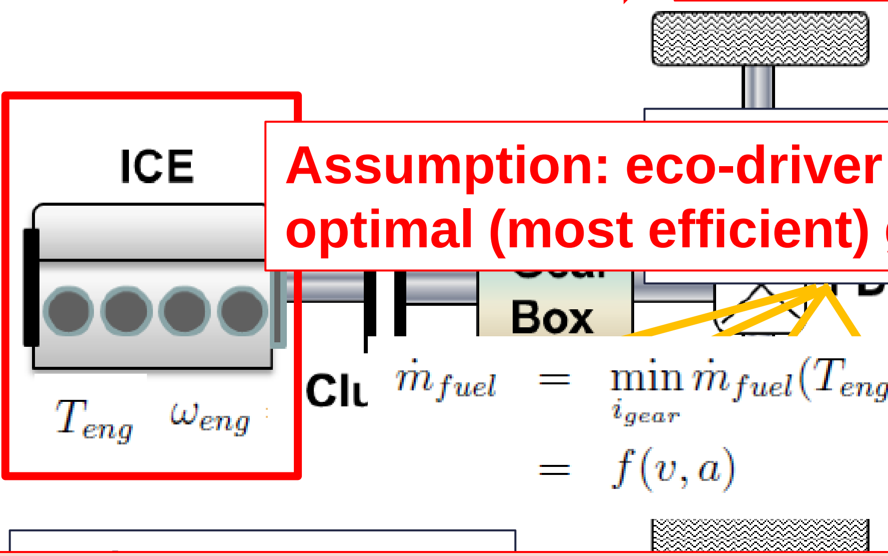
- Instantaneous gear engagement
- No losses in clutch unless shaft speed below idle
- Constant auxiliary power (P_{aux}=300W)

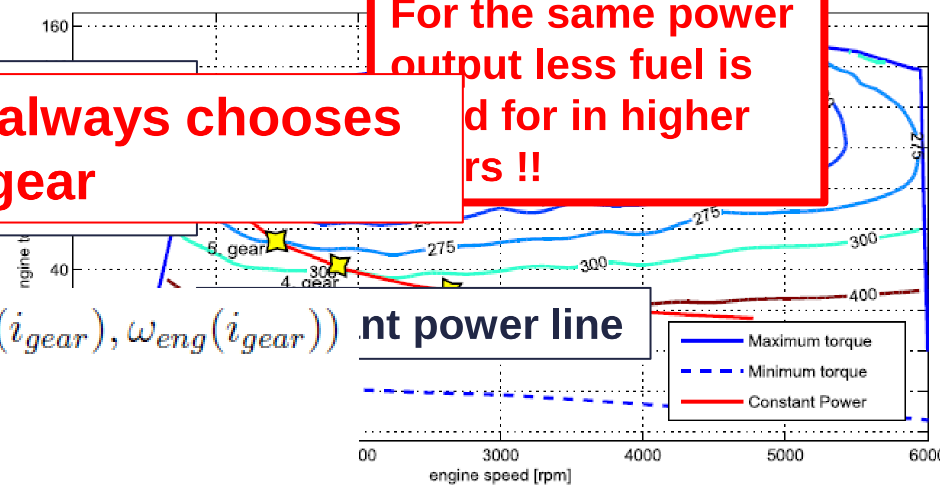
$$T_{aux} = \frac{P_{aux}}{\omega_{eng}}$$

System Modeling- Conventional Vehicle

The conventional vehicle (inverse)

Engine operation → **Fuel consumption (== energy consumption)**





For the same power output less fuel is ...d for in higher ...rs !!

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

$$\dot{m}_{fuel} = \min_{i_{gear}} \dot{m}_{fuel}(T_{eng}(i_{gear}), \omega_{eng}(i_{gear})) = f(v, a)$$

...nt power line

Energy consumption as a function of vehicle speed and acceleration

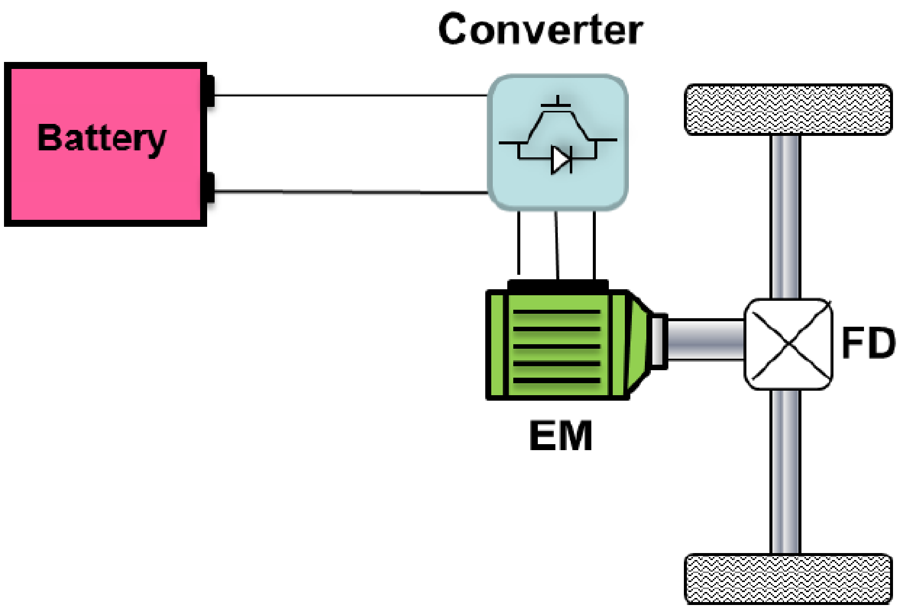
1.6L gasoline engine
T_{max}: 160Nm(4250rpm)
P_{max}: 88kW(6000rpm)

Engine map: Instantaneous fuel consumption in g/kWh

System Modeling – Electric vehicle

Electric vehicle (inverse)

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



$$\omega_{EM} = \omega_{wheel} R_{FD}$$

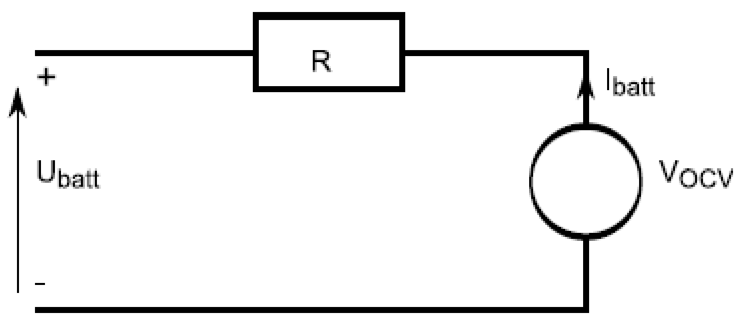
$$T_{drive_{EM}} = T_{wheel} \frac{\eta_{FD}^{\psi}}{R_{FD}} \qquad \psi = \begin{cases} 1 & \text{if } T_{drive} \text{ is positive} \\ -1 & \text{if } T_{drive} \text{ is negative} \end{cases}$$

$$J_{EM}\dot{\omega}_{EM} = T_{wheel} - T_{drive_{EM}} \quad \Rightarrow \quad T_{EM} = T_{wheel}\frac{\eta_{FD}^{\psi}}{R_{FD}} - J_{EM}\dot{\omega_{wheel}} R_{FD}$$

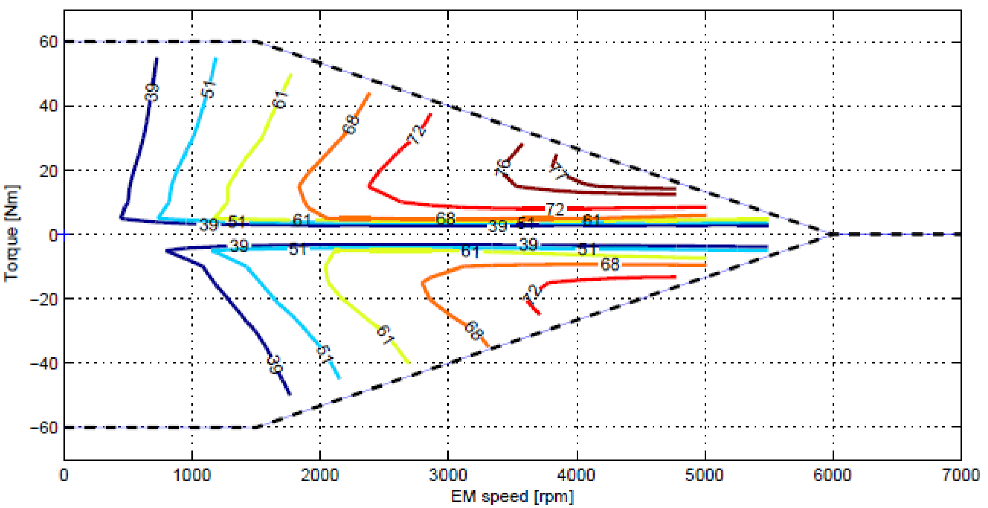
System Modeling- Electric vehicle

Electric vehicle (inverse)

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



$$P_{battout} = V_{OCV} I_{batt} - I_{batt}^2 R$$
$$= U_{batt} I_{batt}$$
$$P_{batt} = V_{OCV} I_{batt}$$



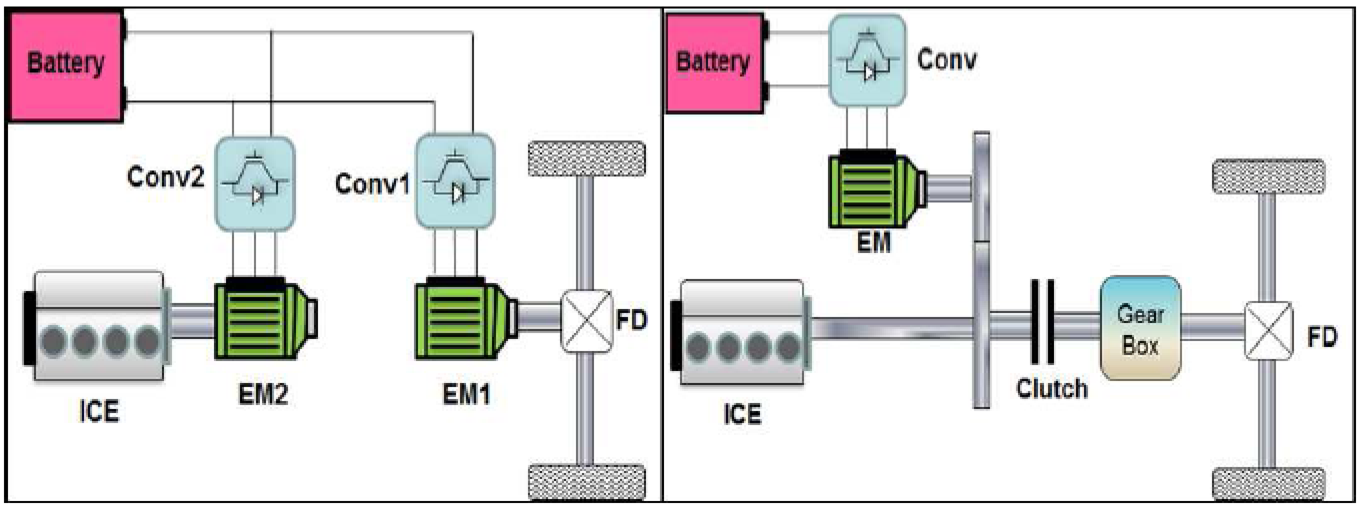
$$P_{batt} = f(v, a)$$

$$\Delta SOC = -\eta_{far} \frac{I_{batt}/3600\Delta t}{C_{ah}/100}$$

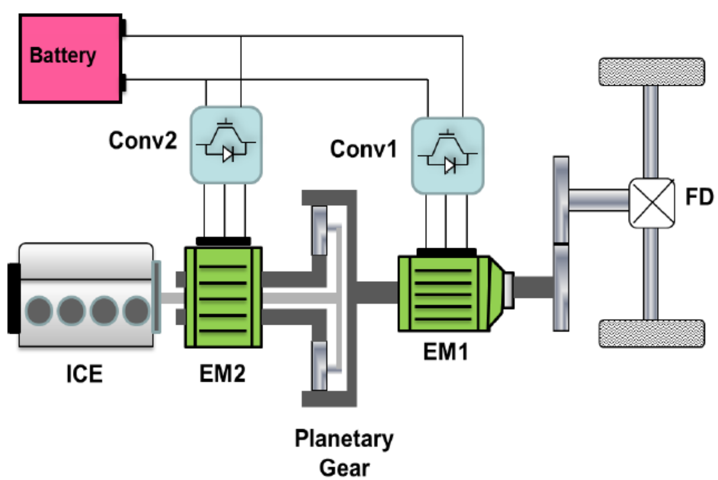
System Modeling- Hybrid Vehicle

Hybrid Vehicle (inverse) - general

Series



Parallel

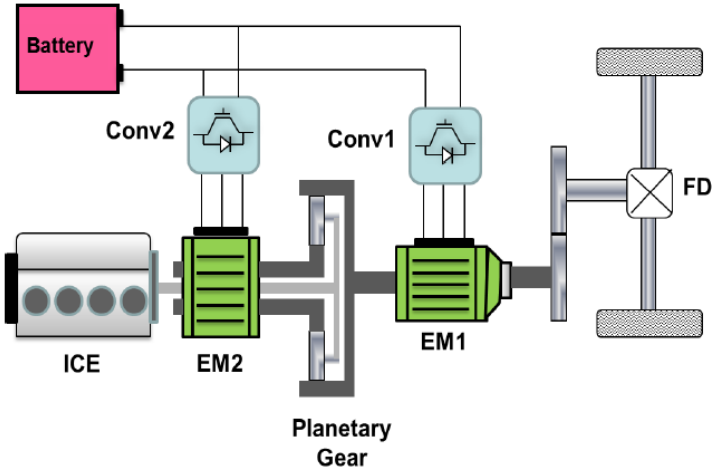


Power split (Toyota Prius)

System Modeling- Hybrid Vehicle

Hybrid Vehicle (inverse) - Prius

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

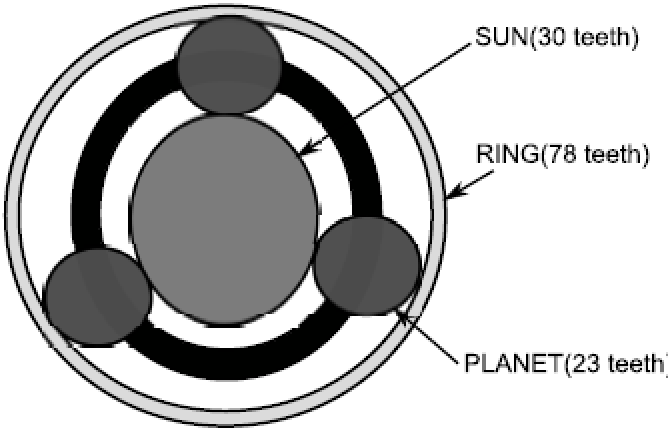


$$\omega_{ring} = \omega_{EM1} = \omega_{wheel} R_{FD}$$

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

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

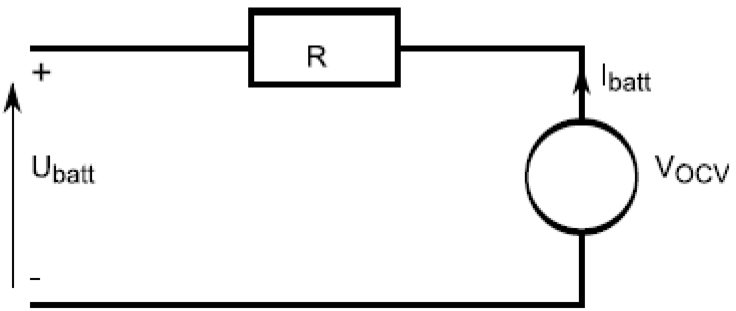
$$T_{sun} = -\frac{1}{1 - R_g} T_{planet} = \frac{1}{R_g} T_{ring}$$

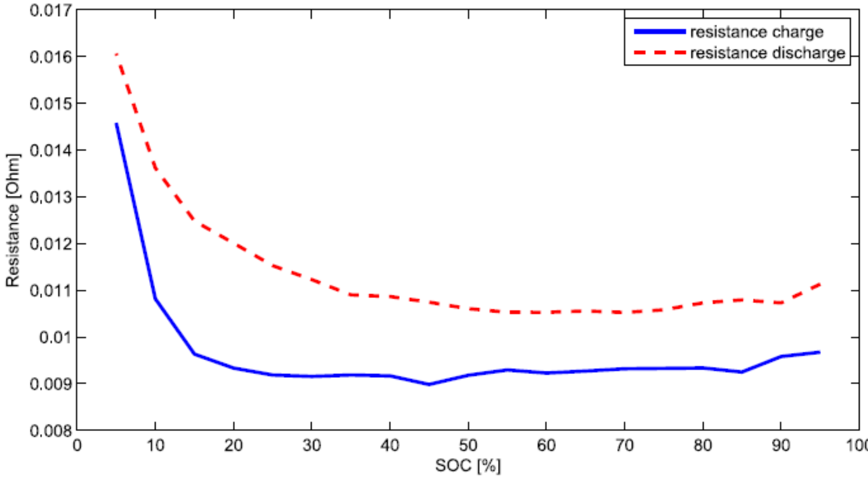


Static modeling of planetary

System Modeling- Hybrid vehicle

Hybrid Vehicle (inverse)





$$P_{battout} = T_{EM1}\omega_{EM1} + PlossEM1 + T_{EM2}\omega_{EM2} + P_{lossEM2} + P_{aux}$$

$$\begin{aligned} P_{battout} &= V_{OCV} I_{batt} - I_{batt}^2 R \\ &= U_{batt} I_{batt} \end{aligned}$$

$$P_{batt} = V_{OCV} I_{batt}$$

System Modeling- Hybrid vehicle

Hybrid Vehicle (inverse) – Control Strategy

Optimization of vehicle operation ≠ Control strategy

Hybrid mode vs Electric mode

SOC < SOC_{minhyb}, $v > v_{vehmaxelec}$

- BMS computes Pdembatt
- Power losses are estimated Ploss
- Total power req from engine is calculated
- Engine speed, torque chosen for max efficiency

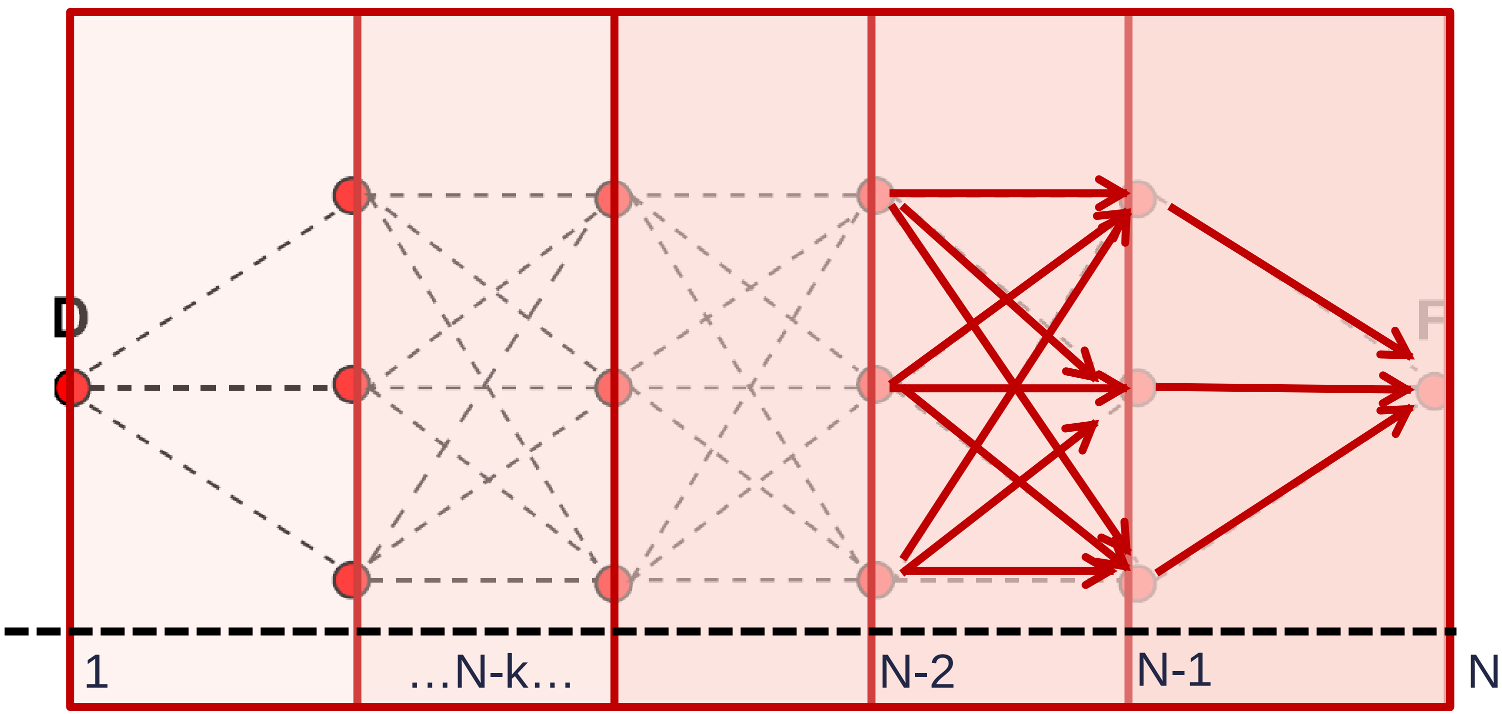
Electric mode:

- EM1 provides output power

$$P_{batt} = f(v, a) \quad + \text{SOC}$$

$$\Delta SOC = -\eta_{far} \frac{I_{batt}/3600 \Delta t}{C_{ah}/100}$$

Dynamic Programming Optimization Method

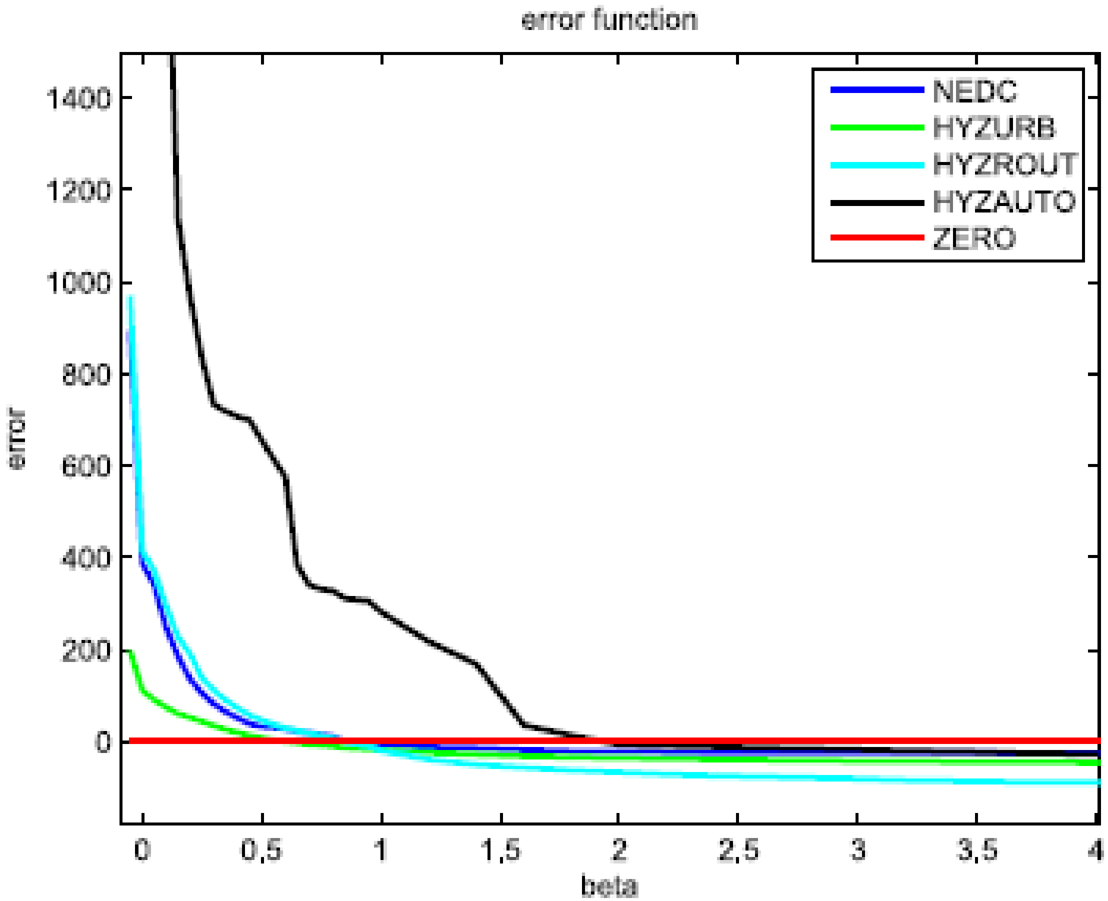


$$J^*_{i1,N-k} = \min_{i2}(J_{i1,N-k\Rightarrow i2,N-k+1} + J^*_{i2,N-k+1})$$

$$J^*_{i1,N-2} = \min_{i2}(J_{i1,N-2\Rightarrow i2,N-1} + J^*_{i2,N-1})$$

$J^*_{i,1}$ … $J^*_{i,N-k}$ … $J^*_{i,N-2}$ $J^*_{i,N-1}$

Root finding methods



Optimization

- **Multi-objective optimization:**

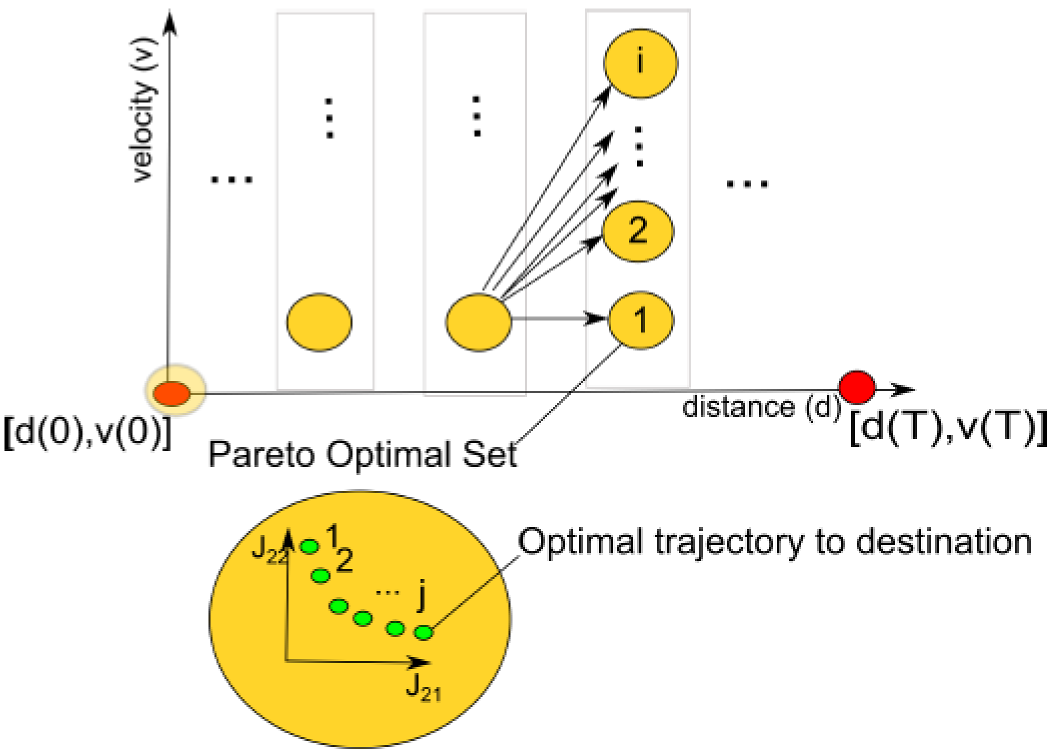
$$\gamma_{21} = \sum_{i=d_0}^{d_f} \gamma_{veh_i}(d_i)$$

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

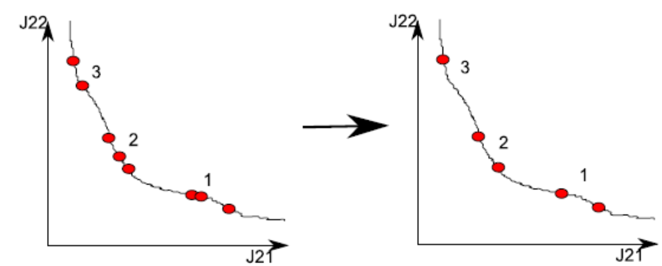
- **Pareto optimal:**
  - **On front if p satisfies** $J_n(p) < J_n(i)$ **for all points i and at least one objective n**
  - **Q not on front if there extist a p s.th.** $J_n(p) < J_n(q)$ **For all n**

Optimization

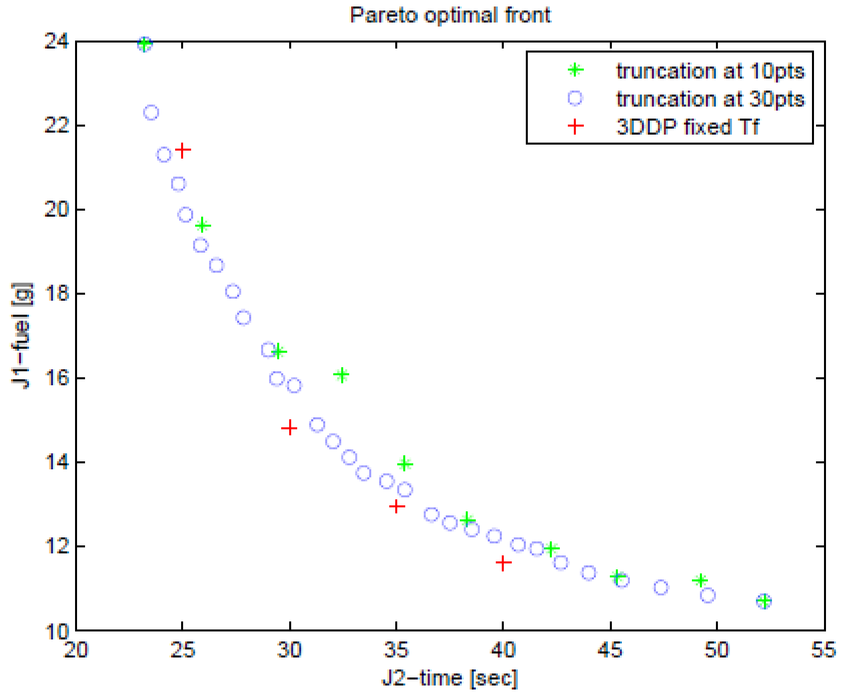
Multi-objective optimization (Dynamic Programming):



truncation

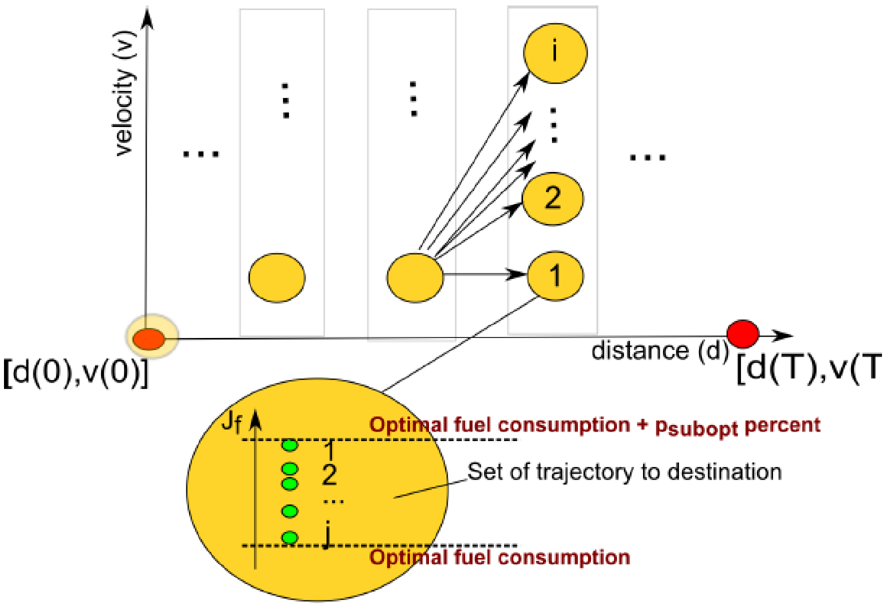


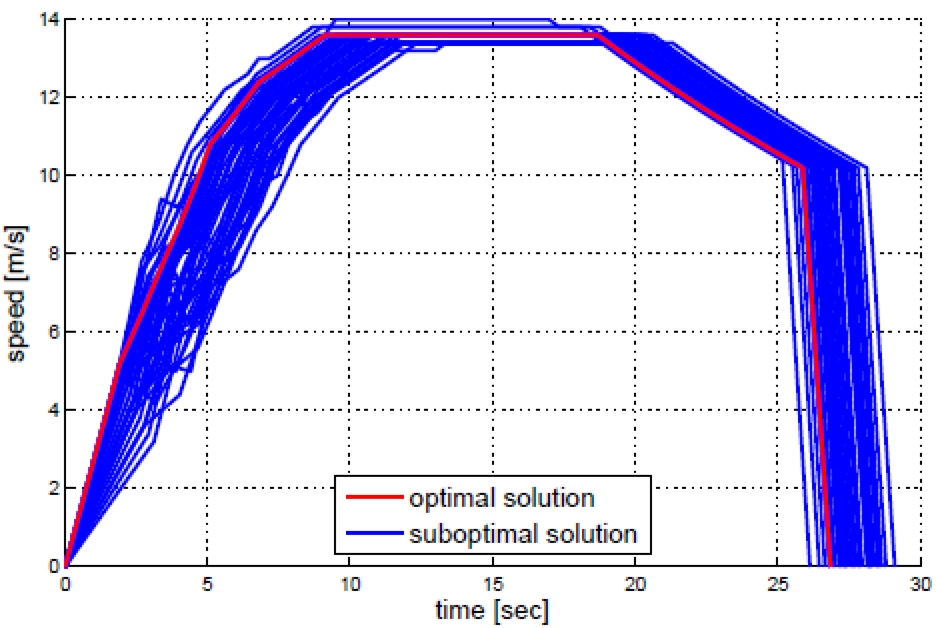
Multi-objective optimization (Dynamic Programming):



Optimization method	Δ t	Δ d	Δ v	trunc pts	computation time [sec]	trajectories calculated
3D Fixed time method	2	1	1	-	240-280	1
2D Flexible time method	-	5	.2	10	155	10
2D Flexible time method	-	5	.2	30	241	30

Divergence from optimal trajectory:

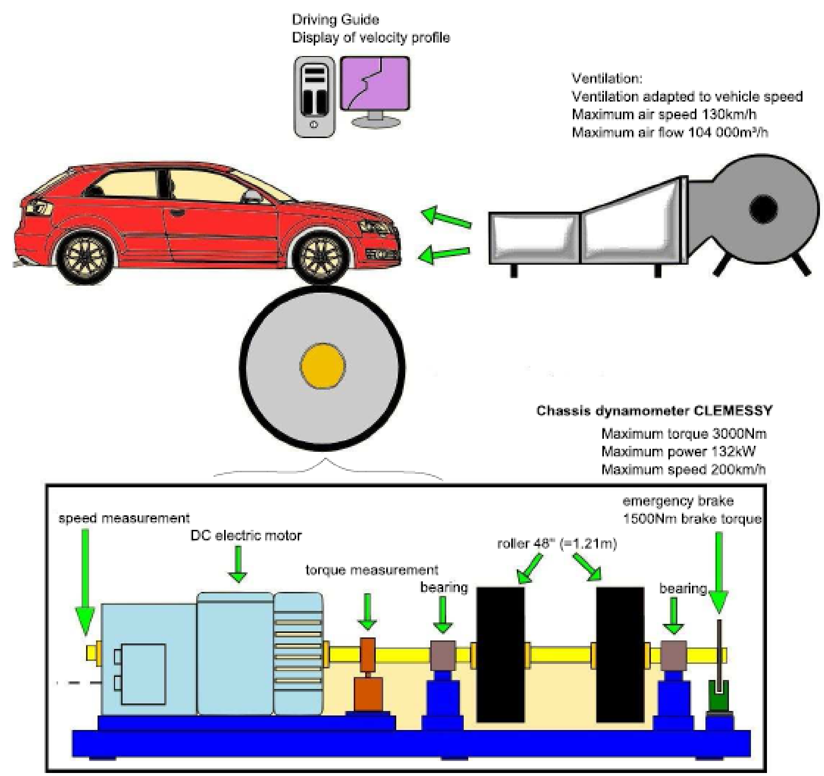




Results Electric

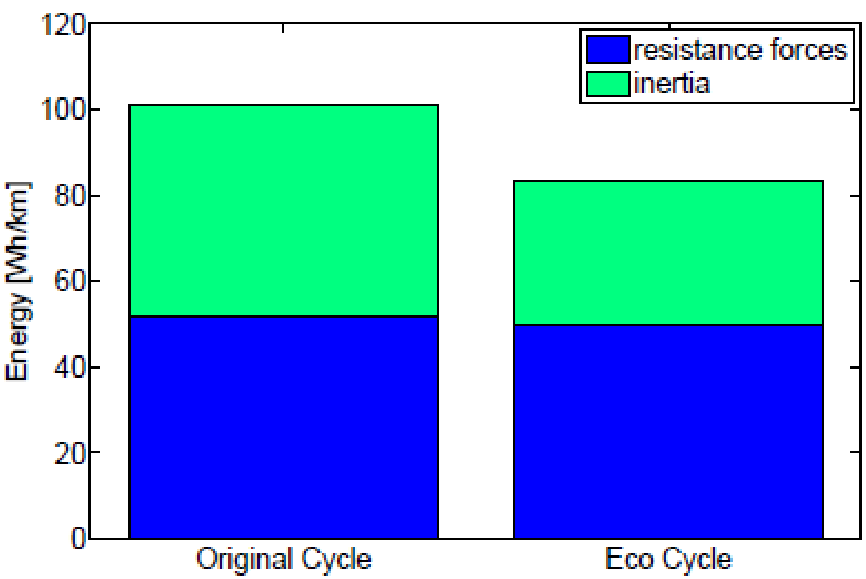
Consumption in Wh

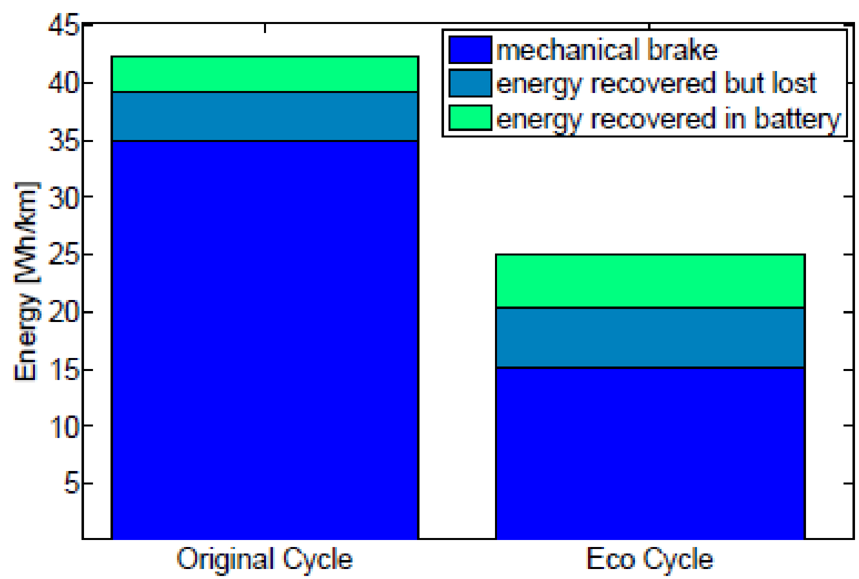
cycle	original cycle	eco cycle	gain
AIXAM1	872.2	705.56	19.3%
AIXAM2	89.4	85.56	4.5%
AIXAM3	283.3	248.89	12.1%
AIXAM4	427.78	386.11	9.4%



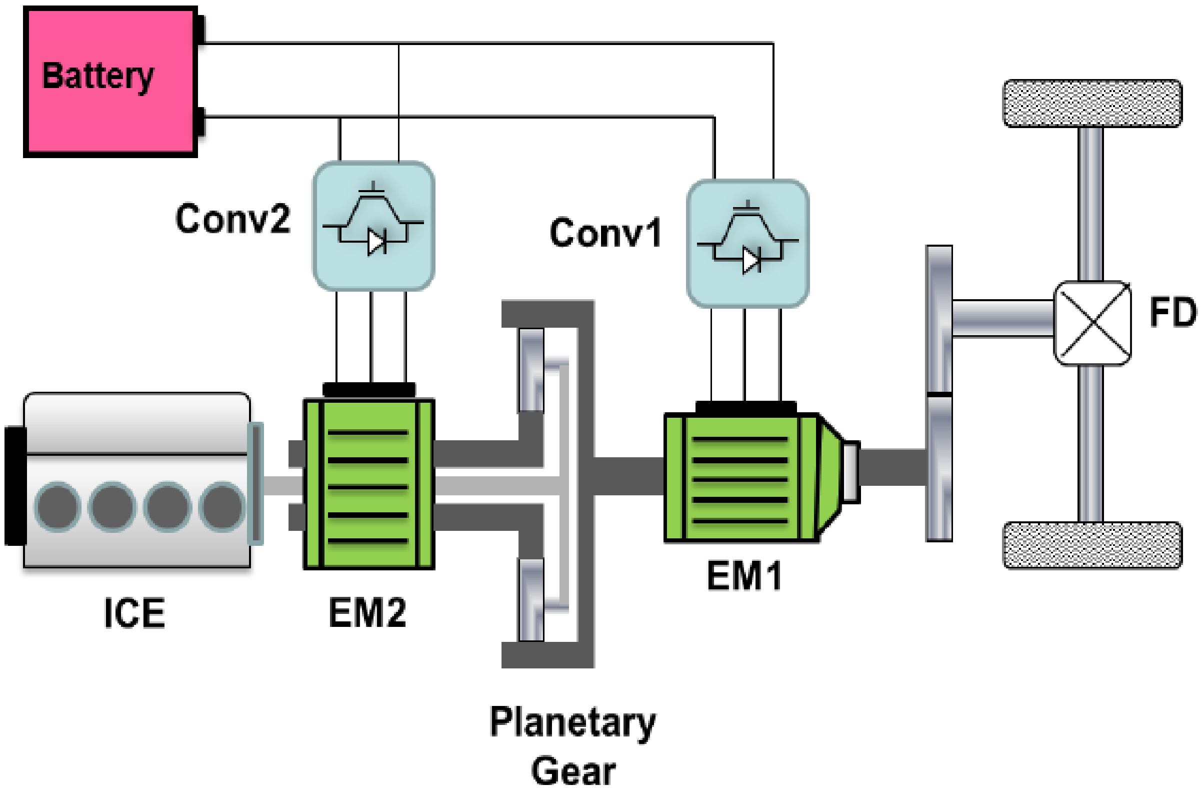
Results Electric

components	original cycle (motor/generator phase)	eco cycle (motor/generator phase)
Final Drive [%]	94	94
Electric Motor [%]	70.82/57.14	69.4/59.5
Battery [%]	92.8/99.31	92.87/99.29





- **Optimization forward:**



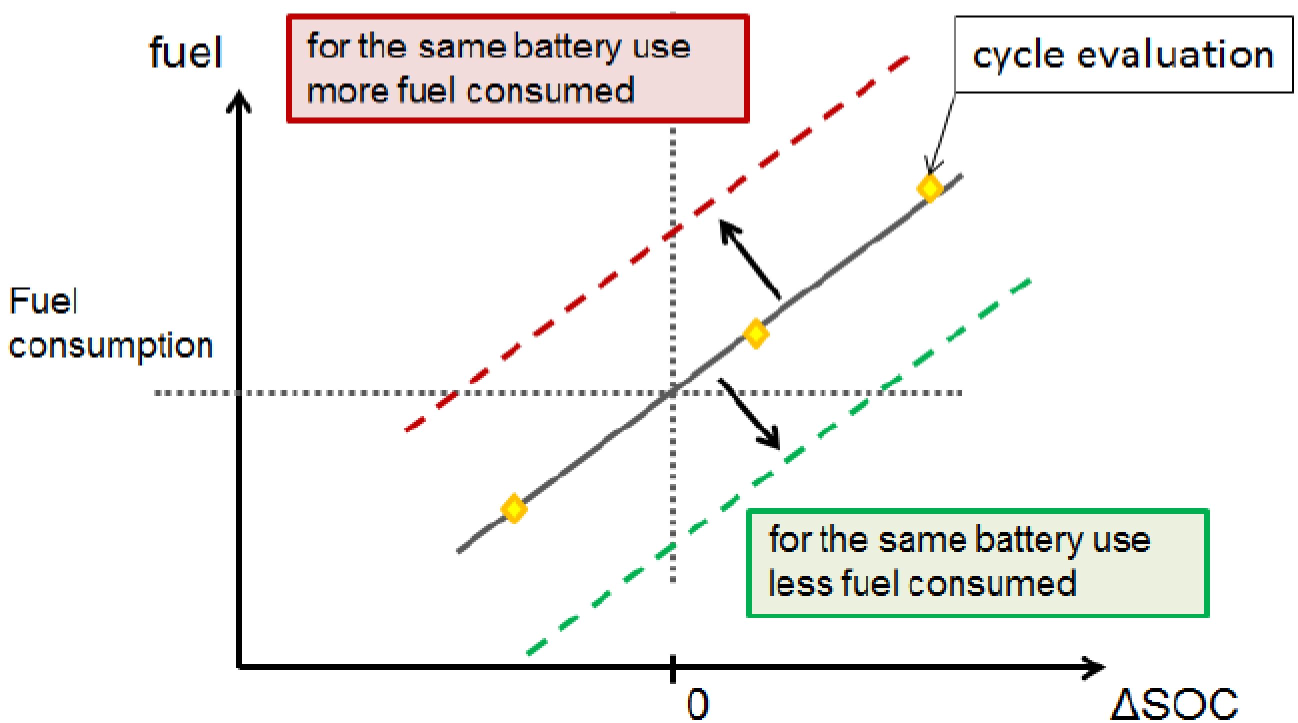
Results Hybrid

Optimization forward:

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

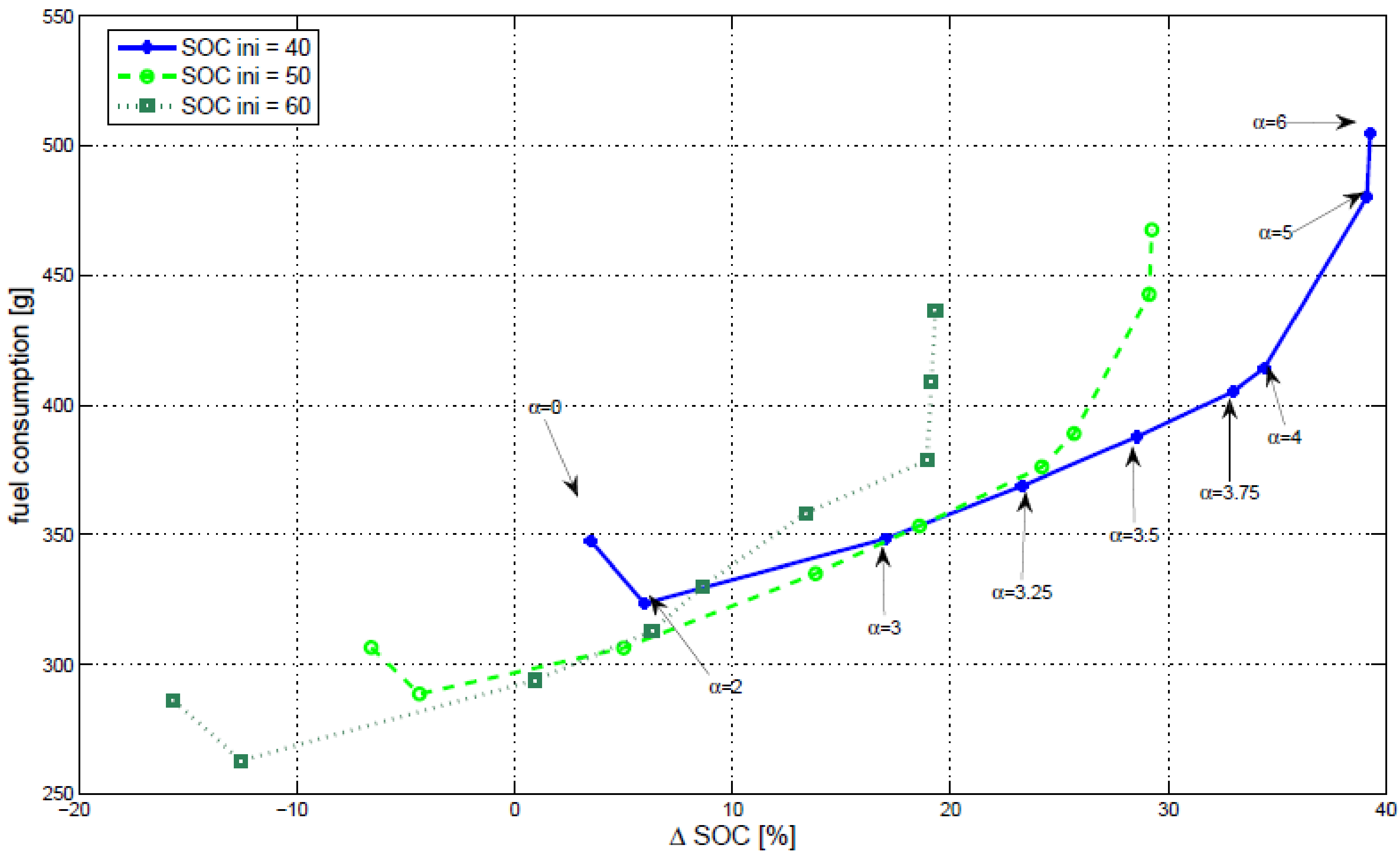
- Initialize optimal costs at $k_1 = 2$: $J^*_{[2,i]} = J_{[1,i_0->2,i]}$
- Increment k_1 and find the optimal cost at each state by comparing $J^*_{[k_1,i_2]} = \min_{i_1}(J_{[k_1-1,i_1->k_1,i_2]} + J^*_{[k_1-1,i_1]})$ while storing the optimal indices
- Compute the optimal trajectory by retracing the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

Hybrid Vehicle Consumption



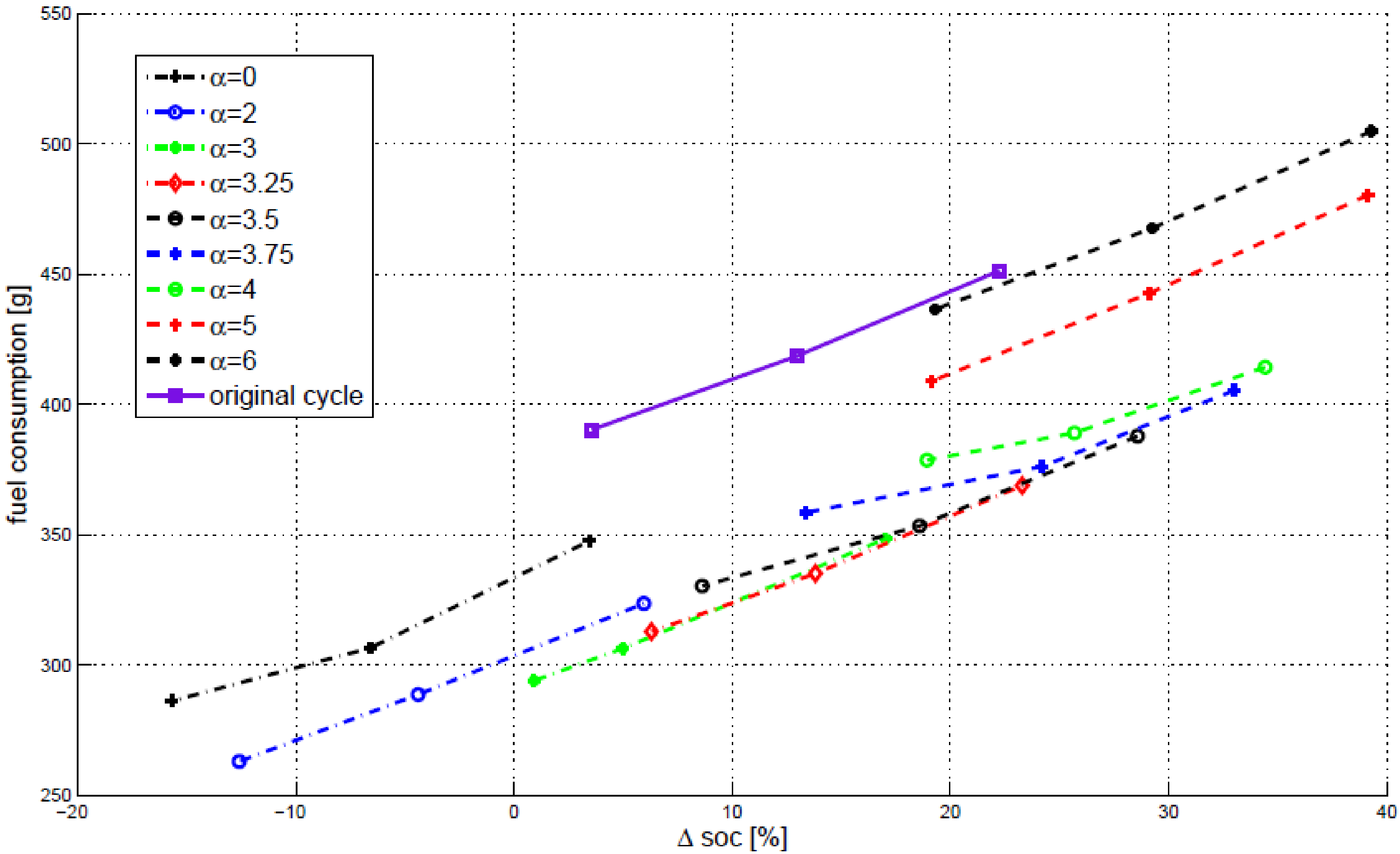
Results Hybrid

Results for different battery weighting



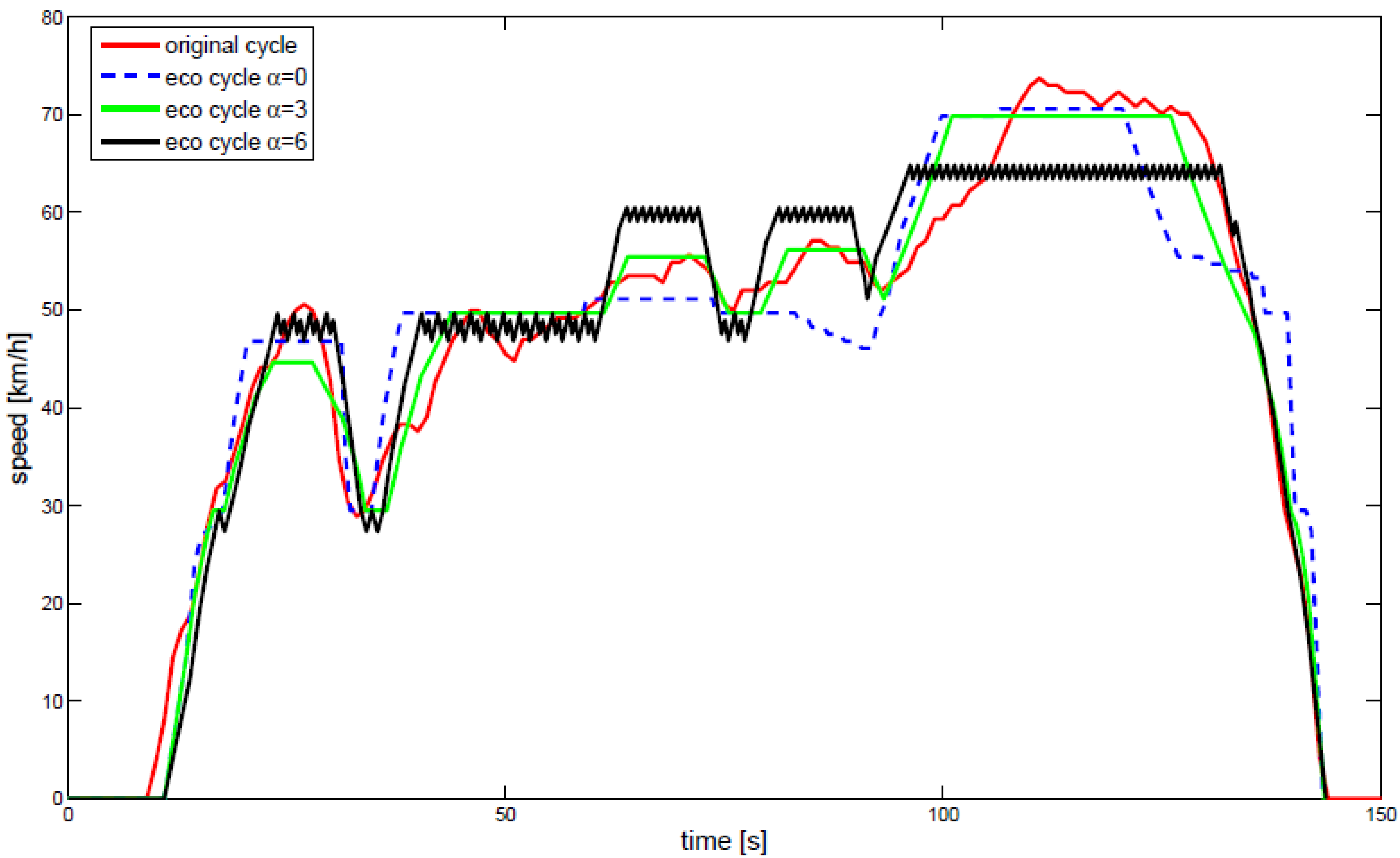
Results Hybrid

- **Results for different battery weighting (gain ~20%)**

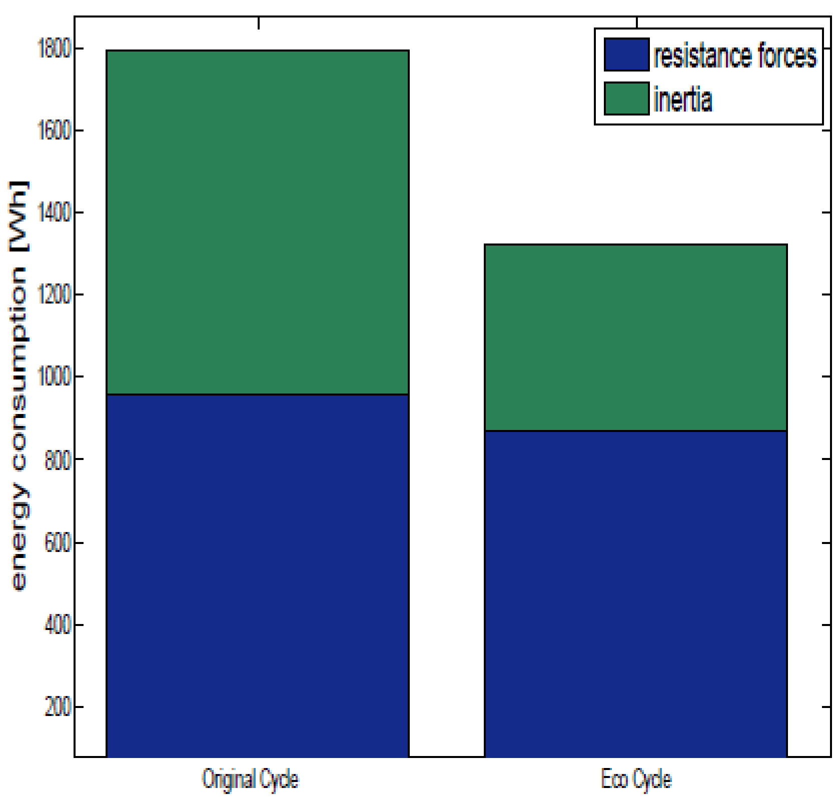


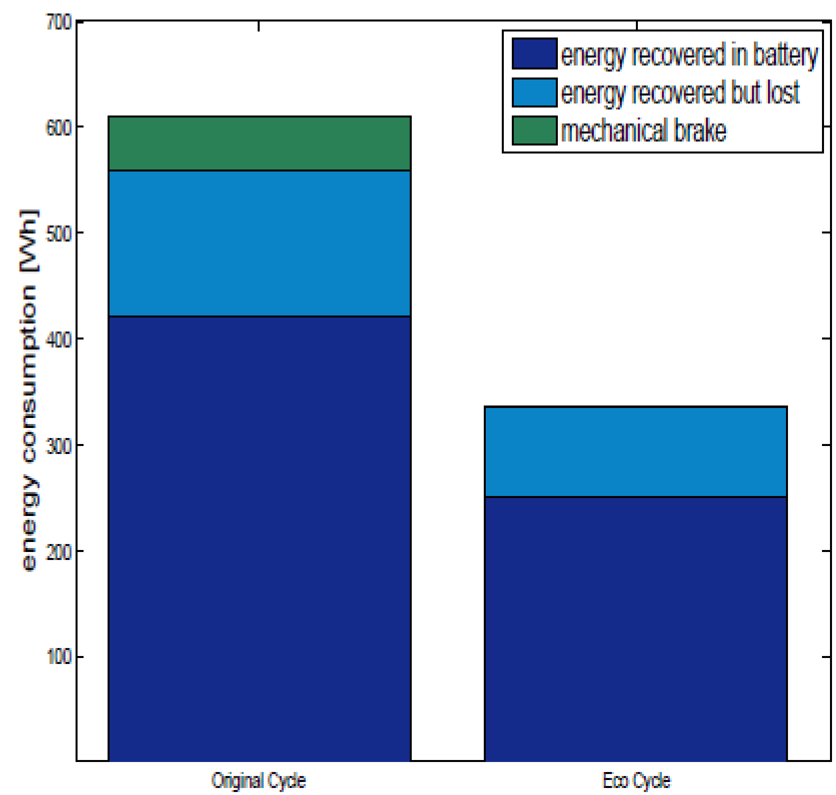
Results Hybrid

Results for different battery weighting

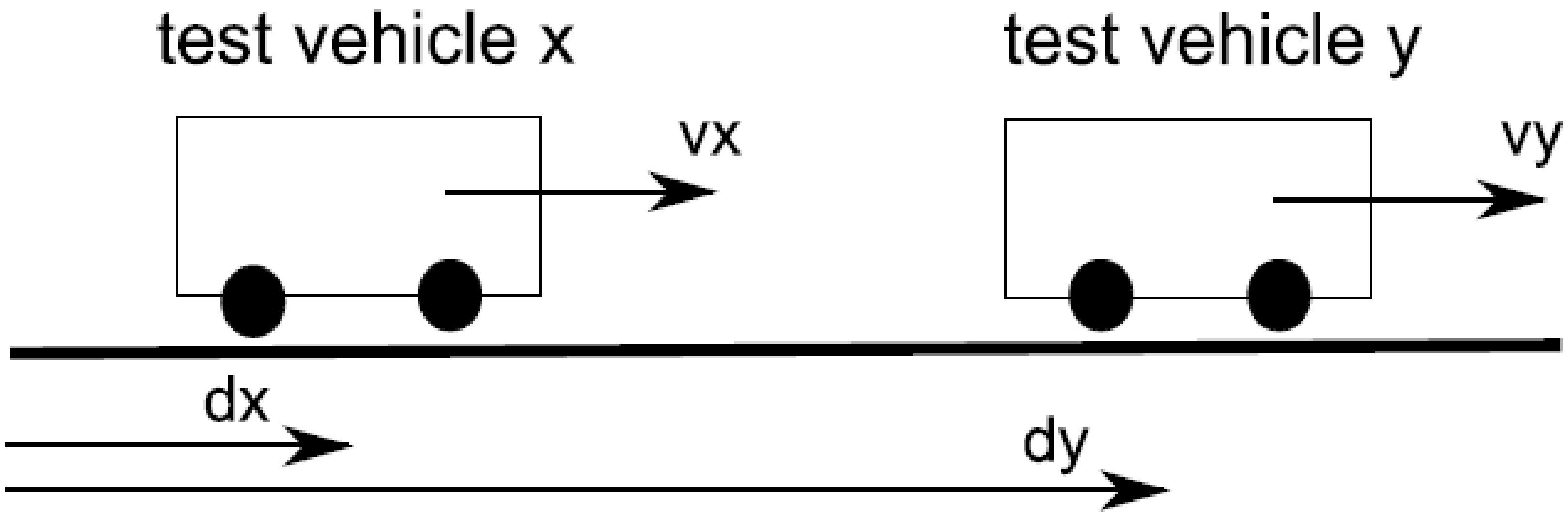


components	original cycle (motor/generator phase)	eco cycle (motor/generator phase)
Final Drive [%]	97	97
EM1 [%]	86.2/87.2	87.2/89.4
EM2 [%]	88.1/88.2	90.8/90.7
Engine [%]	35.1	35.0
Battery [%]	96.3/91.4	96.7/94.7



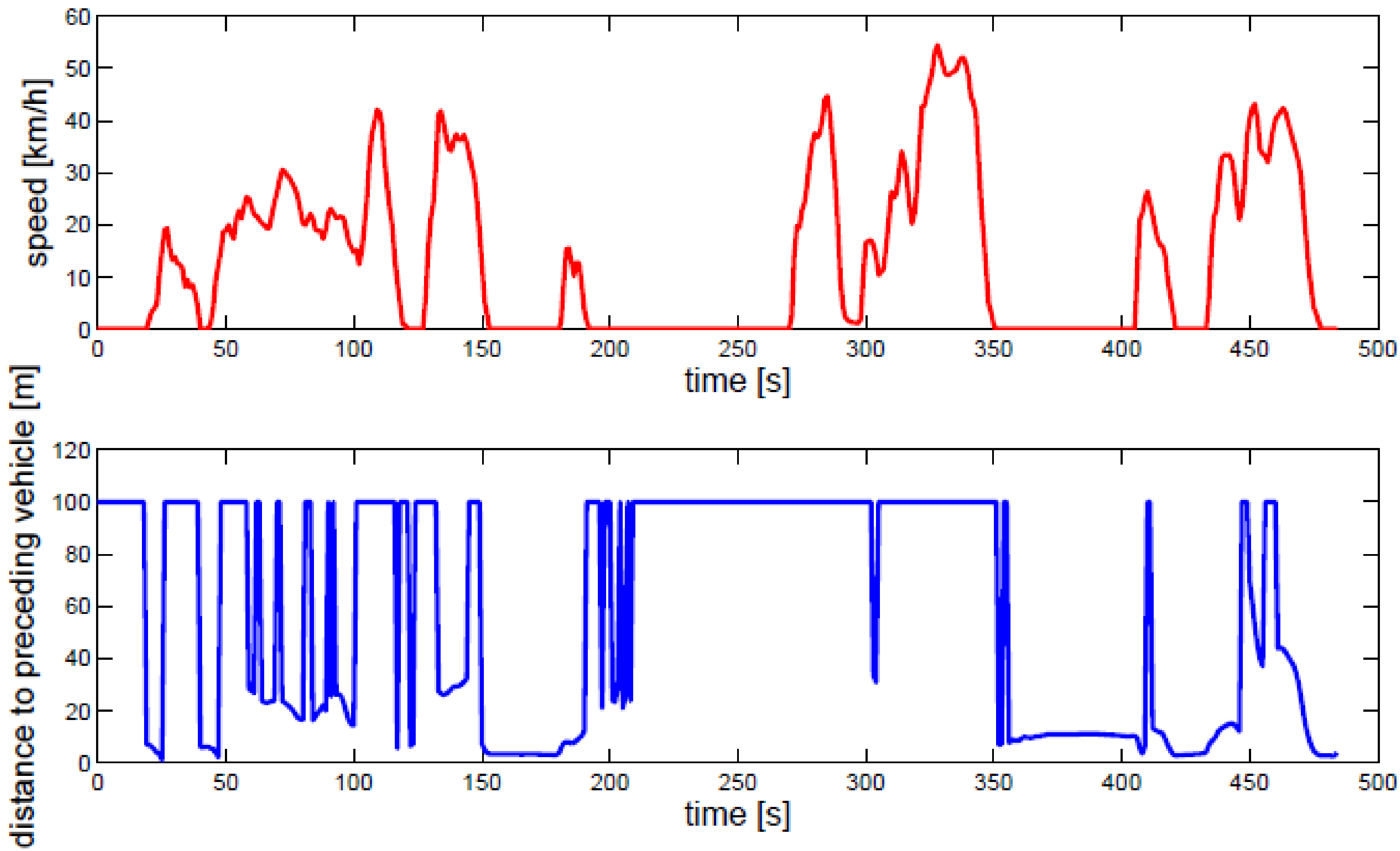


- **Vehicle following situation**



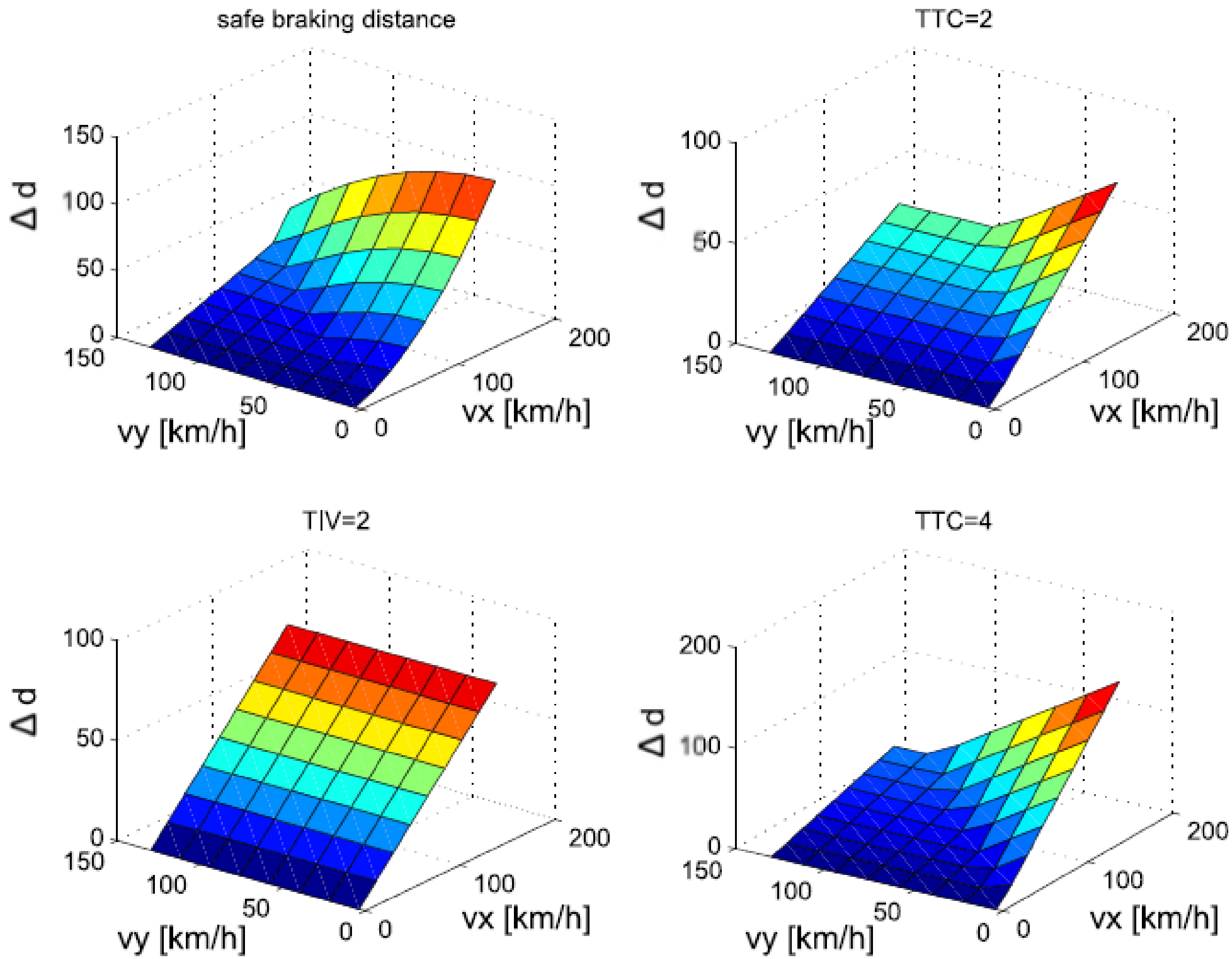
Traffic study

Optimization input



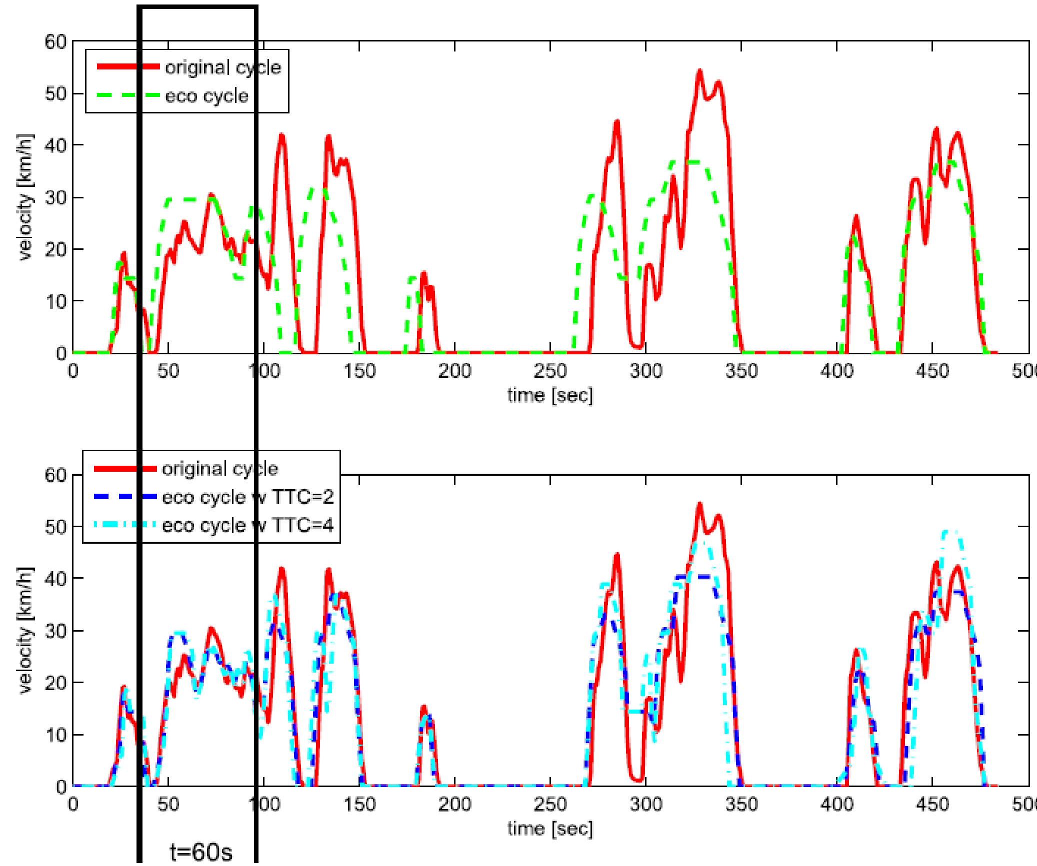
Safety factor:

$$TTC = \frac{(d_y - d_x)}{(v_x - v_y)}$$



Traffic study

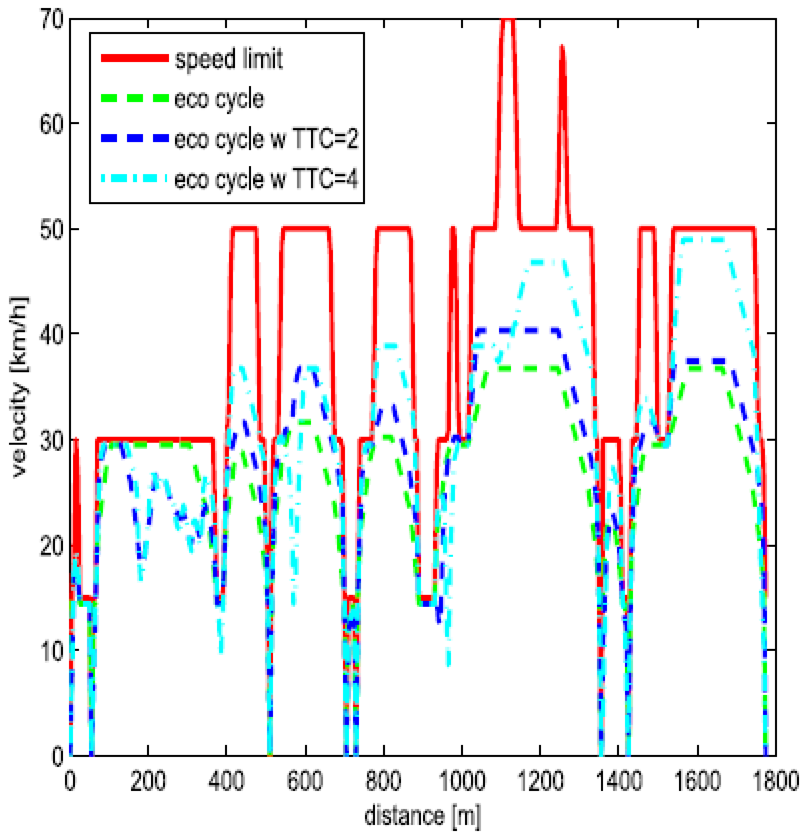
Results-Trajectory

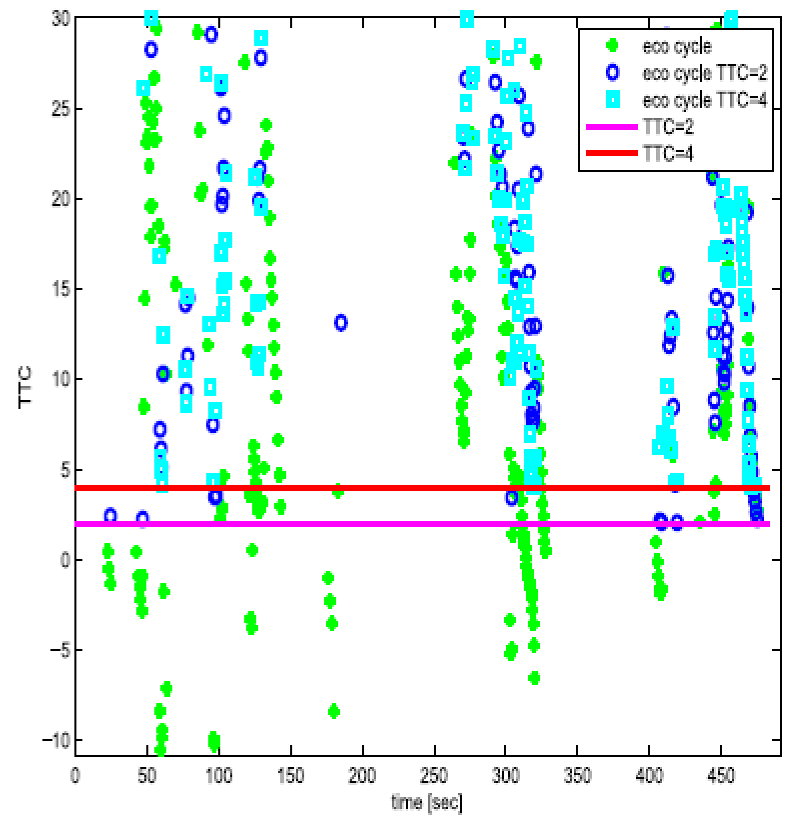


cycle	constraint	fuel consumption [g]	gain [%]
original cycle	driver	97.36	-
eco-drive cycle	-	64.10	34
eco-drive cycle	TTC=2sec	69.62	28
eco-drive cycle	TTC=4sec	82.30	15

Traffic study

Results- Constraints





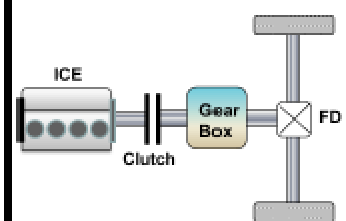
Emission study

Dynamic gear choice

v_{veh}= [0,…,v_{max}]

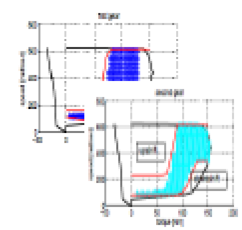
a_{veh}= [a_{min},…,a_{max}]

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



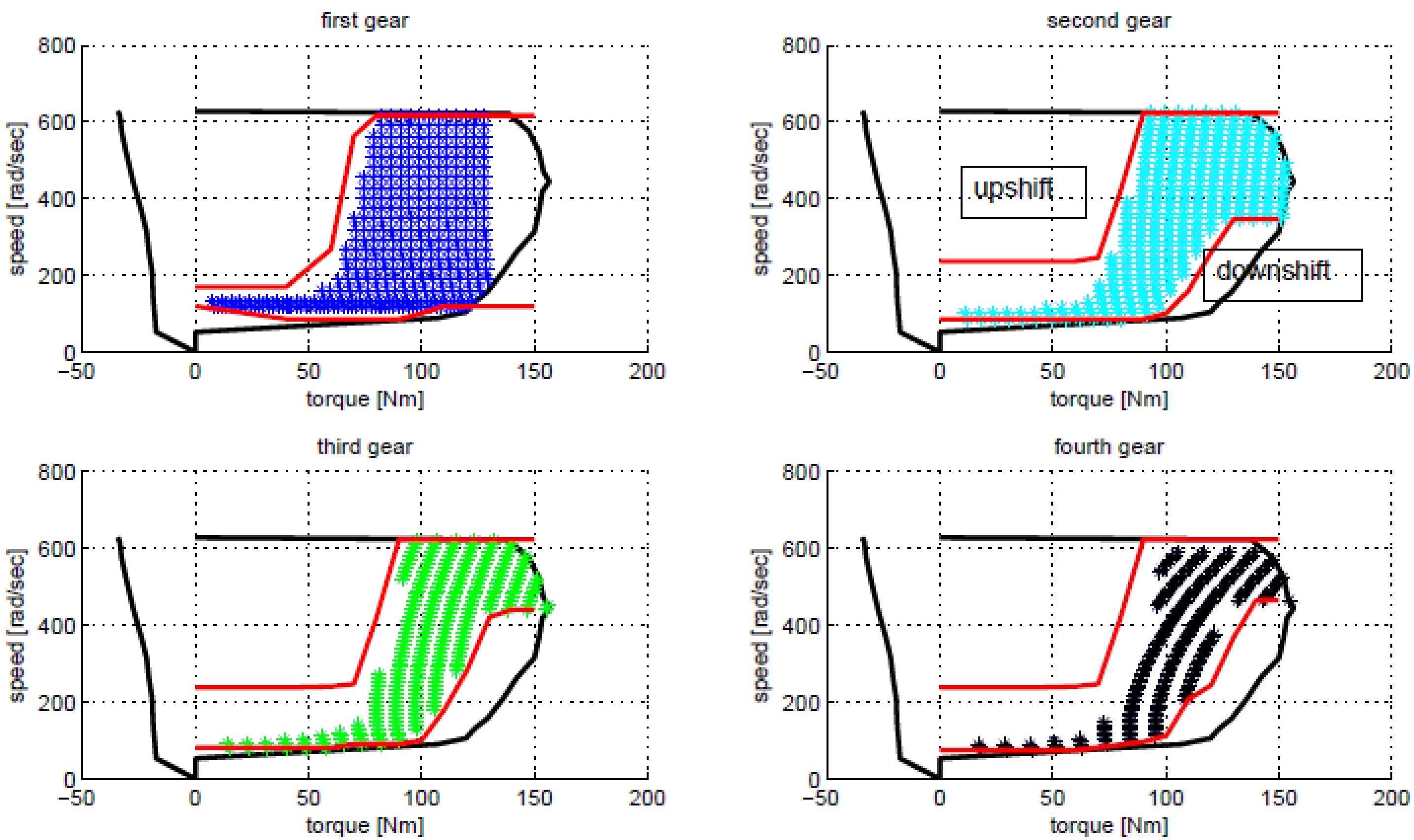
gear(m,n)
ω_{eng}(m,n)
T_{eng}(m,n)

find engine operating points for each gear

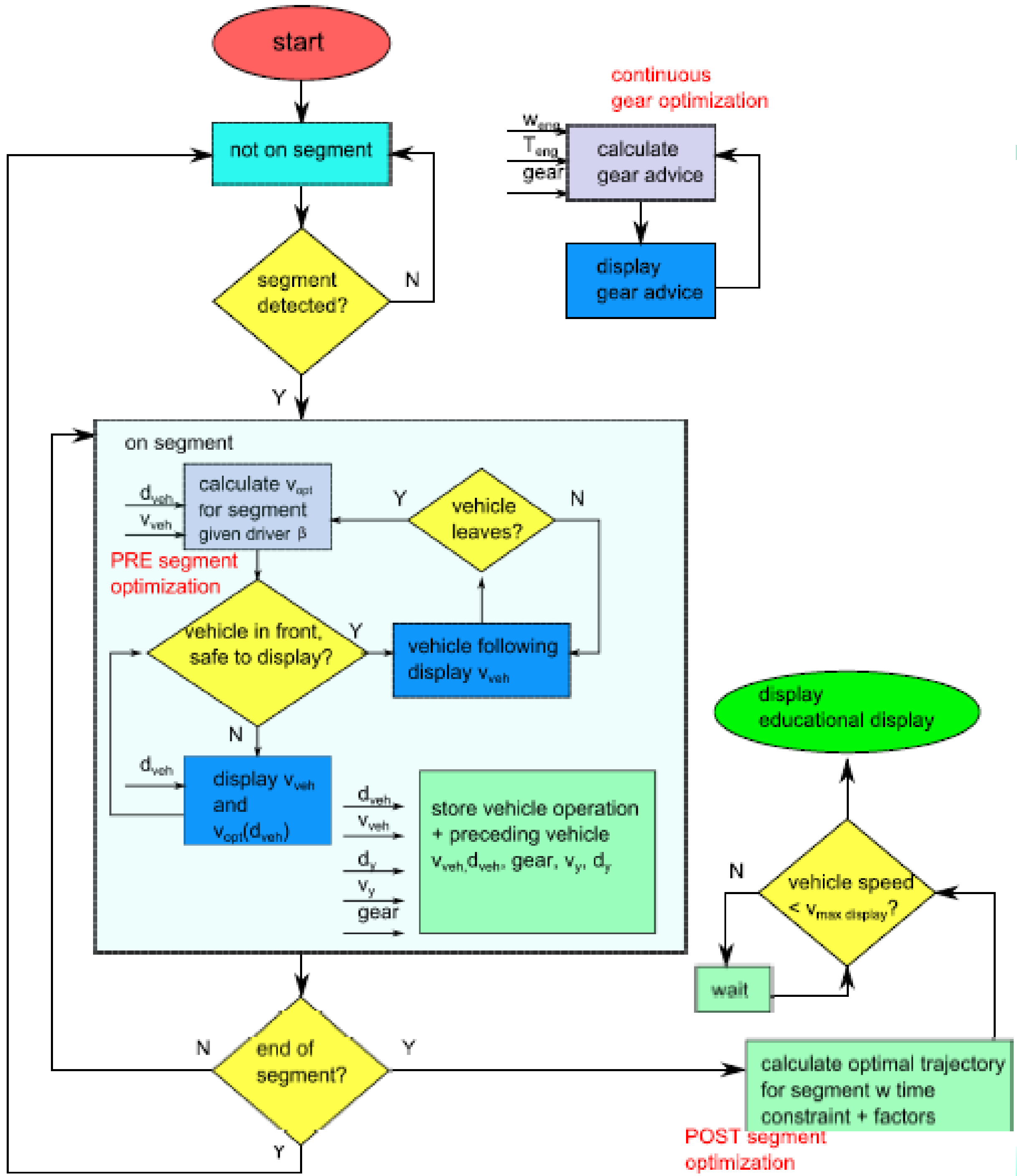


Emission study

Dynamic gear choice



ADAS algorithm



- **Result distribution**