ECO-DRIVING ASSISTANCE SYSTEM FOR LOW FUEL CONSUMPTION OF A HEAVY VEHICLE: ADVISOR SYSTEM

L. NOUVELIERE (University of Evry, France)
H.T. LUU (INRETS/LIVIC, France)
F.R. DUVAL (CETE NC, France)
B. JACOB (LCPC/LIVIC, France)
S. MAMMAR (University of Evry, France)
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Introduction

ADEME : French Agency for Environment and Energy Control

- France (2005) : 553 M tons of GHG
- French crude : -2% from 1990 to 2005
- Transportation emissions : +22%
  - Transport : 1/3 of the total energy consumption
- French government objectives :
  - 20% reduction of the total energy consumption and GHG emissions by 2020
Introduction

• Fuel consumption:
  – Responsible for 35% of the nation-wide emissions of CO₂

• GHG rejections:
  – Strong raise of the displacements
  – Trucks: 26% of these emissions
  Increase of the GHG rejections
Introduction

- Economy:
  - Anti-polluting normalization more constraining

- Stakes of the GHG reduction effect:
  - More and more vehicle drivers look for a low fuel consumption behaviour
  - Eco-driving
    - A fuel consumption reduction of up to 15% is hopped
    - Limitation of the GHG effect on the climatic condition
    - Decrease of the risk of accidents from 10 to 15%

- Fuel prices increasing with the decrease of oil
Introduction

- Two approaches
  - Eco-driving training
    - How to better use our vehicle, to anticipate
  - EDAS (Eco Driver Assistant System)
    - Precise advices in speed, gear ratio, …
Fuel consumption modelling

• Major principles of consumption/emissions modelling:
  – Done for a given traffic on a given road network
  – Associate an emission factor database with a running motor fleet of vehicles
• Emissions factor: only in g/km, while the consumption/polluting emissions depend on the vehicle type for a given speed or driving cycle
Fuel consumption modelling

– Need traffic data set characterizing a specific situation (covered distance, current speed, slope, load rate, …)

– Two fleet types: Static/in-motion
  
  • Static: all the vehicles owned by households, companies, institutions of the country
  
  • In-motion: for a given year, distribution of kilometers covered by the vehicles of the static fleet according to the vehicles type.
  
  • Current french in-motion fleet: assessed by INRETS from 1990 to 2025
Fuel consumption modelling

- Existing fuel consumption modelling:
  - COPCETE: consumption/emissions modelling tool, related to road transports
    - Based on the European COPERT methodology for different road vehicles
    - Combines an emission factor database of different vehicles (COPERT) and the french in-motion fleet (INRETS)
Fuel consumption modelling

– 2007 : ARTEMIS (by a EU consortium)
  • Takes more into account the traffic conditions (not the speed average)
  • Provides the data pre-calculated from some predefined driving cycles
  • But does not compute the instantaneous consumption/emissions
Fuel consumption modelling

- Modelling the fuel consumption/emissions requires the knowledge of the emission vehicles factors, the precise knowledge of the in-motion fleet → current limitation
- In-motion fleet of heavy commercial vehicles and tonnage transported on the French network not accurately known → Not sufficient for a driving assistance system
Vehicle modelling

- **Heavy vehicle type**: city bus (19 to 27 tons)

- **Hypothesis**:
  - Heavy vehicle structure is stiff,
  - A non-slip assumption is done: \( v = r w_r \),
  - Power of the heavy vehicle accessories (air conditioning, ...) is supposed to be constant: \( T_{acc} w_m = P_{acc} = constant \)
Vehicle modelling

- State equations:
  - Gearbox inertia and effectiveness of its slowing down system are considered

\[
X = \begin{bmatrix} x & \omega_r & T_f & \omega_m & T_m \end{bmatrix}
\]

\[
\dot{x} &= v = r \omega_r \\
J_{eq}\dot{\omega}_r &= T_{diff} - T_{res} \\
\dot{T}_f &= \frac{1}{3\tau_f}(T_{f_{map}}(\beta) - T_f) \\
\dot{T}_m &= \frac{1}{3\tau_m}(-T_m + T_{map}(\alpha, \omega_m))
\]

with _bypass: \( \omega_m = \omega_{conv} \)

without _bypass: \( \omega_m = \frac{T_m - T_{acc} - \lambda(G_{conv})\omega_m^2}{J_m + J_{ConvIn}} \)

\[
J_{eq} = \begin{cases} 
\frac{J_\text{by} R_g^2 + J_m + J_{\text{ConvIn}} + J_{\text{ConvOut}}}{R_g^2} + mr^2 + N_r J_r, \\
\frac{J_\text{by} R_g^2 + J_{\text{ConvOut}}}{R_g^2} + mr^2 + N_r J_r,
\end{cases}
\]

\[
T_{res} = r \left(C_a v^2 + C_r mg \cos(\theta) + mg \sin(\theta) \right)
\]

\[
T_{diff} = \frac{T_{\text{conv}}}{R_g} + \frac{T_{\text{rulent}}(\omega_m)}{R_{diff}}
\]

\[
\omega_{conv} = \frac{\omega_r}{R_g}
\]

\[
T_{\text{conv}} = \begin{cases} 
\text{with _bypass: } T_m - T_{acc}, \\
\text{without _bypass: } \omega_m^2 \mu(G_{conv}) \lambda(G_{conv})
\end{cases}
\]

\[
G_{\text{conv}} = \frac{\omega_{conv}}{\omega_m}
\]
Vehicle modelling

- Engine: use of a vehicle engine speed/throttle angle cartography
Consumption modelling

• Model versus engine speed, engine torque

\[ f_c = \beta_1 + \beta_2 \omega_m + \beta_3 \omega_m T_m + b_4 T_m \quad \text{if } T_m < 0 \]
\[ = \alpha + \gamma \omega_m + \theta \omega_m^2 \quad \text{if } T_m \geq 0 \]

• Parameters \( \beta_1, \beta_2, \beta_3 \) and \( \beta_4 \) or \( \alpha, \gamma \) and \( \theta \) are estimated from experimental data with a least square method

• Fuel consumption along the trip :

\[ FC = \sum_{k=0}^{K-1} f_{ck}(\omega_m, T_m) \]
Consumption modelling

• Estimation error between experimental data and modelling

The estimation error does not exceed 6% (at the map extremity) and 2% elsewhere.
Criterion formulation

• Criterion $J$ to be minimized under constraints: $J = Q_1 \cdot FC + Q_2 \cdot T + Q_3 \cdot SMOOTH$

$SMOOTH = \sum_{k=0}^{K-1} (A(\max(0, v_{k+1} - v_k)) + (1 - A)abs(\min(0, v_{k+1} - v_k)))$

• SMOOTH term: used to face to the penalty induced by a speed changing to obtain a smoother driving:
  – Driver/passengers comfort if a bus
  – Mainly for transported loads comfort if a truck
Optimal problem formulation

• Classical discrete form

\[
\min_U \sum_{k=0}^{K} J_k(X_k, U_k) \\
X_{k+1} = f(X_k, U_k, \theta_k) \\
X_k \in [X_{lb_k}, X_{ub_k}] \\
X(0) = X_0 \\
X(N) = X_N
\]

with the control variable: \( U_k = \begin{bmatrix} T_{m_k} \\ G_k \end{bmatrix} \)
Optimization problem formulation

• Constraints:
  – Intervals: \([X_{lb_k}, X_{ub_k}]\) and \([U_{lb_k}, U_{ub_k}]\)

• The longitudinal motion of the vehicle is a function of:
  – Various heavy vehicle parameters (gear ratio, performance of transmission,...)
  – Road (slope)
  – Weather (aerodynamic resistance,...)
Optimization problem formulation

• The initial states are known and the final states may be known or unknown

• Dynamic Programming technique:
  – Recurrent Hamilton-Bellman-Jacobi equation:

\[
  J_N = \xi_N(X_N)
\]

\[
  \text{for} \quad k = N - 1, \ldots, 0
\]

\[
  J_k(X_N) = \min_{U_k} (\xi_k(X_k, U_k) + J_k(f(X_k, U_k)))
\]

where \( \xi_k \) is the cost to move from one state to another
Optimization problem formulation

• Numerical solution: obtained by the inverse dynamic programming technique
  – Two inverse steps
    1) computes the optimal control versus the states
    2) rebuilds the optimal control from the initial states, using the stored mapping at each inverse iteration
Simulation results

• Vehicle model without torque converter is used to generate the optimal speed profile from the DP method

• Vehicle model with torque converter is used to simulate a driving assistance system:
  – Information of the optimal speed profile to the driver
  – Information of the optimal gear ratio to the driver
Simulation results

- Conditions of the simulation:
  - 1000m covered distance
  - 10m sampling interval
  - City bus parameters \((m=22t, C_a=0.6)\)
  - Consumption modelling: estimated with experimental data from a modern city bus
  - Engine map known for this city bus
Simulation results

• Constraints:
  – Heavy vehicle speed: \( v_{lb} = 0 \text{ m/s}, \ v_{ub} = 30 \text{ m/s} \)
  – Heavy vehicle acceleration:
    \( a_{lb} = -3 \text{ m/s}^2, \ a_{ub} = 3 \text{ m/s}^2 \)
  – Heavy vehicle engine torque: constrained by the maximum and minimum allowed engine torques of the heavy vehicle given by the engine map
Simulation results

\[ J = Q_1 \cdot FC + Q_2 \cdot T + Q_3 \cdot SMOOTH \]

- Influence of the road slope:

\[
\begin{align*}
Q_1 &= 1, \quad Q_2 = 4, \quad Q_3 = 1, \quad A = 0.4 \quad (42.098 \text{ l/100 km}) \\
Q_1 &= 1, \quad Q_2 = 4, \quad Q_3 = 1, \quad A = 0.4 \quad (19.2298 \text{ l/100 km})
\end{align*}
\]
Simulation results

\[ J = Q_1 \cdot FC + Q_2 \cdot T + Q_3 \cdot SMOOTH \]

- **Influence of \( Q_1 \):**

  \[ Q_1 = 1, \ Q_2 = 4, \ Q_3 = 1, \ A = 0.4 \]
  
  (42.098 l/100 km)

  \[ Q_1 = 4, \ Q_2 = 4, \ Q_3 = 1, \ A = 0.4 \]
  
  (30.4605 l/100 km)
Simulation results

\[ J = Q_1 \cdot FC + Q_2 \cdot T + Q_3 \cdot SMOOTH \]

- **Influence of Q₂:**

  \[ Q_1=3, \ Q_2=1, \ Q_3=3, \ A=0.4 \text{ (} 30.0754 \text{ l/100 km, 70 s}) \]

  \[ Q_1=1, \ Q_2=4, \ Q_3=1, \ A=0.4 \text{ (} 30.0901 \text{ l/100 km, 58 s}) \]
Driving assistance system

- Objectives:
  - Advisor system
  - Help for the driver to eco-drive
Conclusion / Future works

• This EDAS was implemented on a bus in the french city of Rouen (ANGO PREDIT/ANR project)
  – Several bus drivers are testing this system during several months
  – The fuel consumption gain will be known in next few weeks!

• Adding the safety issue: be safe while less consuming (legal speed, spacing)
• Adding a control module: active EDAS
Thank you for your attention!

nouveliere@ibisc.univ-evry.fr