Trip Prediction and Route-Based Vehicle Energy Management

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Dominik Karbowski (PI), Aymeric Rousseau (Presenter), Sylvain Pagerit, Namwook Kim, Daeheung Lee
Argonne National Laboratory

Sponsored by David Anderson

Project ID # VSS125
## Project Overview

### Timeline
- Start: September 2012
- End: September 2014
- Status: 70% complete

### Barriers
- Cost of testing advanced technologies through multiple vehicle builds
- Risk aversion of OEM to commit to unproven technologies
- Constant advances in technologies

### Budget
- FY2013 - $300k
- FY2014 - $300k

### Partners
- HERE* (Map data)
- Argonne’s Transportation Research and Analysis Computing Center (TRACC) (traffic modeling expertise)

*A Nokia Company; formerly NAVTEQ
Relevance

**Project Objective: Increase vehicle efficiency by leveraging road and traffic data**

- **Objective 1**: Develop a method to predict speed profile
  - Use data that can be made available to real vehicles TODAY
  - Model the stochastic nature of driving
  - With a resolution high enough to be used for fuel consumption prediction

- **Objective 2**: Develop a vehicle energy management that can use speed prediction

- **Objective 3**: Evaluate route-based energy management within a stochastic environment (i.e. actual speed is different from predicted speed)

*Relevant to the VT Program goals: enable highly efficient cars and reduce both energy use and greenhouse gas emissions*
Milestones

100% Develop a process to generate stochastic speed prediction under constraints

100% Process CMAP real-world trip records database into transition probability matrices

100% Link stochastic speed prediction to Geographical Information Survey (ADAS-RP)

30% Improve performance and reusability of trip prediction tool

80% Develop energy management strategy for Prius PHEV (reference and route-based)

100% Evaluate potential benefits of route-based energy management with stochastic trips (small scale)

0% Evaluate benefits of route-based energy management on a large number of stochastic trips
Approach
Tackle All the Aspects of “Route-Based” Energy Management

- At the start of the trip, destination can be known from driver’s input or from pattern recognition;
- ADAS-RP module computes itinerary, takes into account live traffic information;
- Vehicle speed profiles are generated and optimal control is computed;
- The vehicle energy management executes the optimal control.
Approach
Simulation Framework Developed for Trip Prediction and Route-Based Energy Management

- Our approach:
  - Work on both optimal control and prediction;
  - Propose implementable solutions;
  - Provide achievable benefits estimation.
Technical Accomplishments

Speed Profile Generated from Constrained Markov Chain

- Driving is modeled as a Markov chain, vehicle speed and acceleration as the random variables;
- A Markov chain is defined by a transition probability matrix (TPM) \( P \); \( P_{i,j} \) is the probability of transitioning from state at time \( t \) to state at time \( t+1 \).

Our Speed Profile Generation Algorithm

**Segment attributes**

GIS provides itinerary, divided in segments, with:
- attributes for each segment
- position of stops and traffic lights

**Segment-by-segment Markov chain**

For each segment, the algorithm generates stochastic speed profiles iteratively until a solution that matches the segment constraints (average speed, distance, etc.) is found.

**Entire Trip**

The entire trip is then the concatenation of stop periods and speed profiles from all segments.
Technical Accomplishments
Examples of Synthetic Vehicle Speed Profiles

Multiple stochastic speed profiles for the same target micro-trip

One synthetic speed profile for one entire itinerary

- $V_{\text{max}}$
- $V_{\text{avg}}$
- $V_{\text{tgt}}$
- $V_{\text{act}}$
- $t_{\text{stop}}$

Speed Limit 50 km/h

Target Speed 32 km/h

Speed (km/h) vs. Distance (m)

Speed (km/h) vs. Time (s)
Technical Accomplishments
Markov Chains Defined Using Real-World Data

- Real-world trips:
  - Chicago metro area
  - >6M points

Database Processing, QC and filtering
- Original database correction
- Division into micro-trips (μTp)
- QC to remove abnormal μTps (≈30% points removed):
  - μTps w/ missing points
  - Bad GPS signal
  - Impossible speeds and accelerations
  - Exactly zero acceleration
- Moderate filtering of remaining μTps

TPM Building
- Each μTp is quantized
- Each transition of state counts toward the transition matrix
- After normalization, we get the transition probability matrix

\[
P = \begin{bmatrix}
    p_{1,1} & \cdots & p_{1,n} \\
    \vdots & \ddots & \vdots \\
    p_{n,1} & \cdots & p_{n,n}
\end{bmatrix}
\]

Transition Probability Matrix
Technical Accomplishments

Optimal Prius PHEV Energy Management Developed Using PMP

**THEORY**
- Optimal control strategy is based on the Pontryagin Minimization Principle (PMP)
- At each time step, we find the optimal battery power demand that minimizes instantaneous power cost

\[ P_b^* = \arg\min_{P_b} \left( P_f(P_b) + r(t)\theta(P_b)P_b \right) \]

- Fuel Power
- Function of through optimal operation maps
- Equivalence Factor (depends on trip!)
- Battery Power Command

- PMP is implemented in a control strategy for Autonomie
- Uses I/Os and information flow typically found in actual vehicles

**IMPLEMENTATION**

PMP w/ ICE

- Speed/Torque Targets (HEV)
- Cost HEV
- ICE ON/OFF Logic
- ICE ON/OFF
- Cost EV
- Speed/Torque Targets (EV)
Technical Accomplishments
Benefits of Optimal Energy Management Evaluated

- Simulation environment: **Autonomie**, forward-looking
- ≈ **Prius** 2012 PHEV:
  - Battery: 4 kWh, 200 V, Li-ion
  - Rated all-electric range: 26 km
  - Top EV speed = 100 km/h
- Trip: 36 km, mix of urban and highway, defined in ADAS-RP
- **One itinerary, 10 stochastic predictions**
- On average ≈5% savings

Example of operations
Technical Accomplishments
Quantifying Fuel Savings for a Stochastic Trip

- “Equivalence Factor” (EQF) links the energy management to the route
- Prediction will never match actual speed because of the stochastic nature of driving => EQF will not necessarily be optimal
- What if we use the EQF from one prediction on another

**Average benefit for a given EQF over “best” 8 trips**

**Average benefit for a given EQF over all 10 trips**

- **Design of experiments:**
  - For one itinerary, generate 10 speed predictions
  - For each speed prediction, run a range of EQFs
  - Evaluate fuel saving compared to baseline “EV+CS”
- **Plot:** 1 given shape/color = one speed prediction
- **Results:**
  - There is one EQF that would on average bring benefits for all trips
  - Too high EQF leads to not fully discharged battery and higher fuel consumption
- **Future studies:**
  - same but at much larger;
  - deduct EQF-itinerary relationships.
Collaboration and Coordination with Other Institutions

- **HERE (NOKIA)***
  - Provided a free demo license of ADAS-RP, including detailed road information and traffic patterns.
  - Provided support to process their data.

- **Argonne’s Transportation Research and Analysis Computing Center (TRACC)**
  - Provided expertise in understanding traffic dynamics
  - Participated in stochastic tool development.

- **OEMs**: discussions with R&D engineers

*Formerly NAVTEQ*
Proposed Future Work

- **Improve performance and reusability of speed prediction tool:**
  - Evaluate techniques to make speed generation faster: different random variable definition, clustering, space-domain, etc.
  - Make the code more reusable
  - Generate hundreds of itineraries and for each of them tens of speed predictions for use in large-scale studies.

- **Evaluate the sensitivity of route-based energy management** to trip prediction on a larger scale.

- **More on trip prediction:**
  - Implement functionality to automatically generate trips matching user-defined distributions; could be used for other DOE studies.
  - Integrate real-world trips from other real-world trip databases (Atlanta, Austin, etc.).
  - Evaluate speed prediction in real-world situations.

- **More on route-based optimal energy management:**
  - Evaluate optimal control on Argonne’s engine-in-the-loop (thermal effects, emissions, etc.).
  - Integrate thermal aspects into optimization.
  - Evaluate benefits for other applications (trucks, buses, etc.) and configurations (parallel, etc.).
Summary

Argonne’s research covers all the aspects of route-based control

- **Stochastic speed prediction** for a given itinerary, using data from a GIS (HERE’s ADAS-RP).
- **Optimal PHEV energy management** strategy that depends on the route (the equivalence factor) implemented in Autonomie.
- We use information that can be obtained in a modern car TODAY.

Preliminary results show **fuel savings are to be expected**; larger study to provide better estimation.

Argonne’s research will have impacts beyond Prius-like PHEV:

- Can be applied to **other platforms**: commercial vehicles, HEVs, etc.
- Stochastic trip generation can be used to generate **“custom” drive cycles**; can be used for VTO studies or by OEMs for powertrain sizing and design

Potential future applications:

- **Route optimization** and fleet planning
- **EV range prediction**
- Energy optimization of **automated vehicles**
Back-up Slides
Combining Markov Chains and Geographical Information

Itinerary in GIS (ADAS-RP)

Raw Data Formatting + Segmentation

Vehicle Speed

Distance

Synthesized Trip

Iterative Stochastic Generation for each Segment

for segment = 1 to n
Algorithm to Generate Speed Profiles

**Main Algorithm**

1. **Initialization (i=0)**
   - Compute segment i
   - Has a solution been found?
     - No
       - Add solution to cycle
     - Yes
       - ++i
       - i=nb of segments?
         - No
           - Speed Profile
         - Yes
           - Has a solution been found?
             - No
               - Add solution to cycle
             - Yes
               - Speed Profile

**Segment Generation Algorithm (with Markov Chain)**

1. Initialization (a=0, v=v_init)
2. TPM
3. Random number generation
4. Compute next state
5. d>d_target?
   - No
     - v=v_end?
       - No
         - Metadata matches target?
           - No
             - Speed Profile
           - Yes
             - Speed Profile
       - Yes
         - Metadata matches target?
           - No
             - Speed Profile
           - Yes
             - Speed Profile
   - Yes
     - Compute next state
     - d>d_target?
       - No
         - v=v_end?
           - No
             - Metadata matches target?
               - No
                 - Speed Profile
               - Yes
                 - Speed Profile
           - Yes
             - Speed Profile
Route-Based Control with PMP: How the Equivalence Factor Depends on the Trip

\( r_0 \) (EQF) too high:
- Electricity is too “expensive”
- There is battery energy left at the end of the trip
- Worst fuel consumption than baseline

\( r_0 \) optimal

\( r_0 \) too low:
- Electricity is too “cheap”
- Battery is discharged too early
- Missed opportunity to displace more fuel