Trip Prediction and Route-Based Vehicle Energy Management

2014 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

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Argonne National Laboratory

Sponsored by David Anderson

Project ID # VSS125

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Project Overview

Timeline	Barriers
• Start: September 2012 • End: September 2014 • Status: 70% complete	• Cost of testing advanced technologies through multiple vehicle builds • Risk aversion of OEM to commit to unproven technologies • Constant advances in technologies

Budget	Partners
• FY2013 - $ 300k • FY2014 - $ 300k	• 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

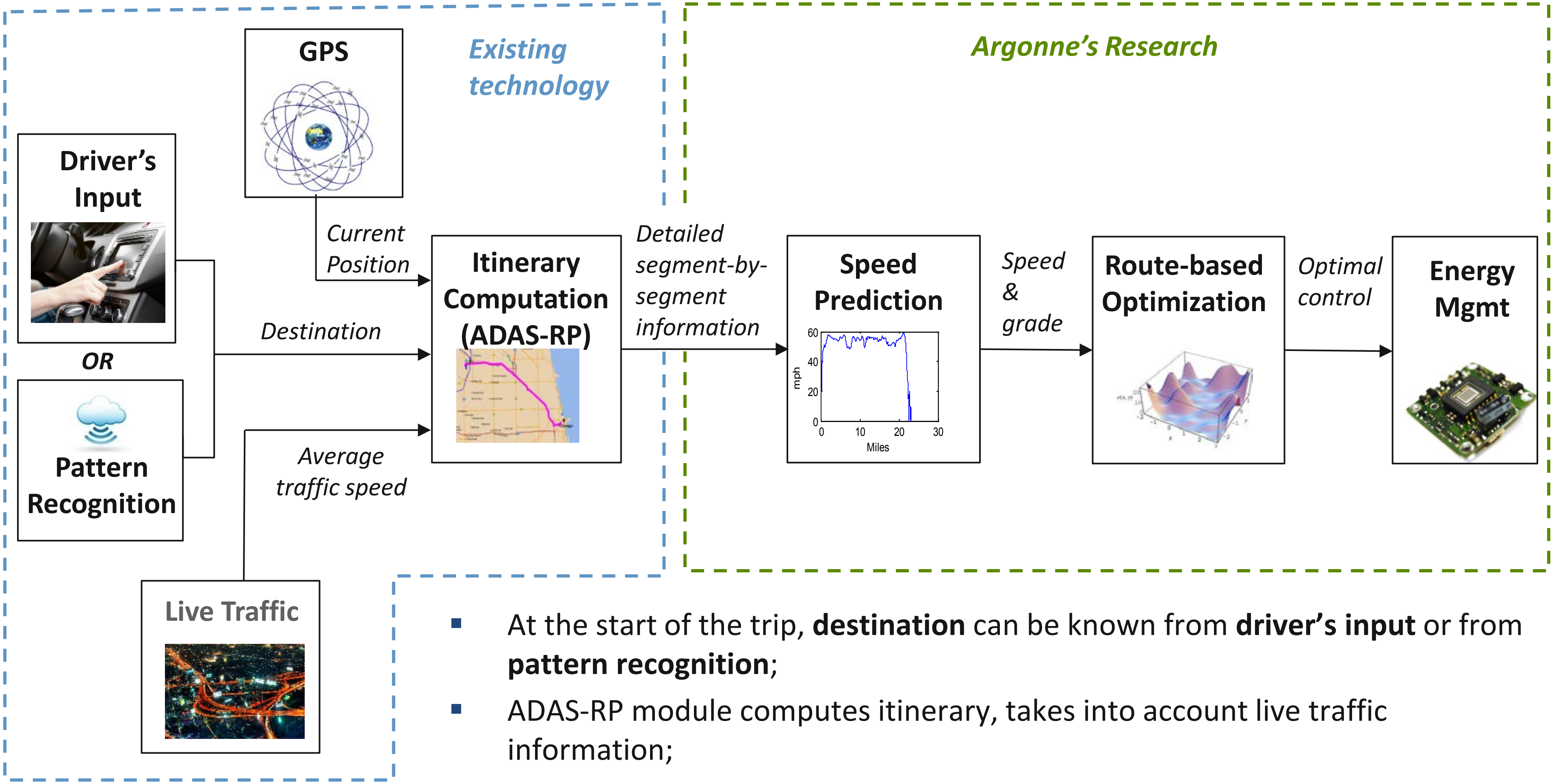
100%	Develop a process to generate stochastic speed prediction under constraints
100%	Process CMAP real-world trip records database into transition probability matrices
100%	Link stochastic speed prediction to Geographical Information Survey (ADAS-RP)
30%	Improve performance and reusability of trip prediction 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

FY 2013 FY 2014

10-12 01-13 04-13 07-13 10-13 01-14 04-14 07-14 10-14 mm-yy

Approach

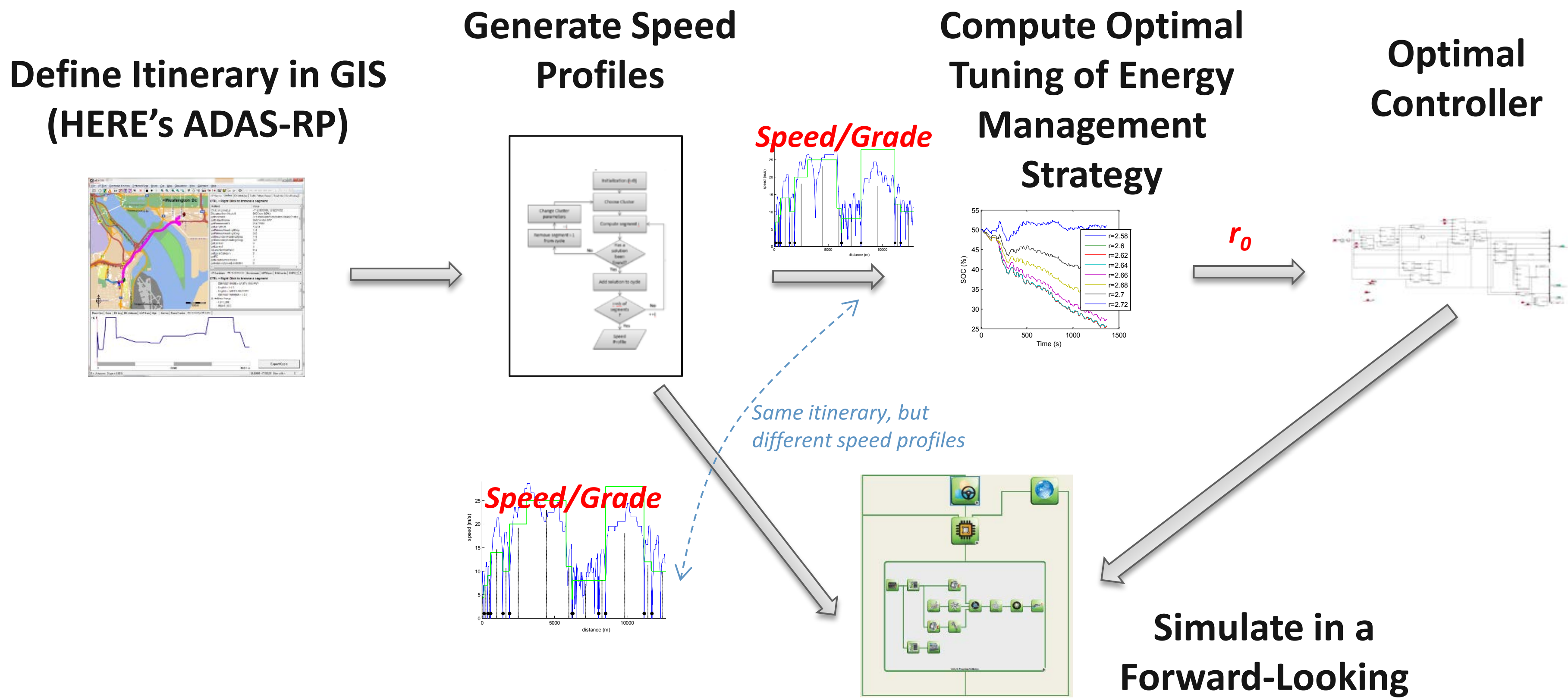
Tackle All the Aspects of "Route-Based" Energy Management



- 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

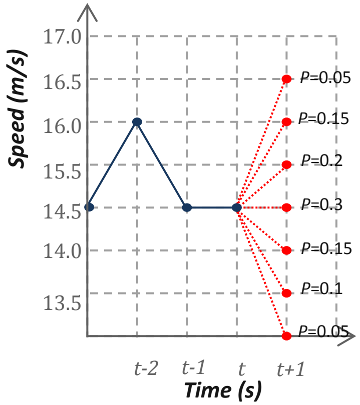
Simulation Framework Developed for Trip Prediction and Route-Based Energy Management



- 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 to state at time .

$$P = \begin{bmatrix} P_{1,1} & \cdots & P_{1,n} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,n} \end{bmatrix}$$

Our Speed Profile Generation Algorithm

Segment attributes

GIS provides **itinerary**, divided in **segments**, with:

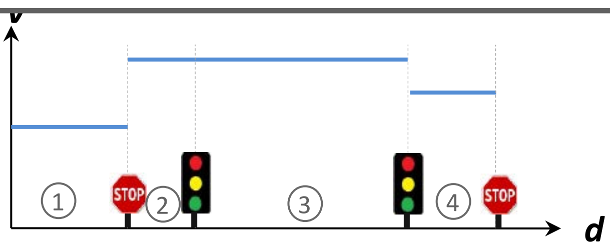
- attributes for each segment
- **position** of **stops** and traffic lights

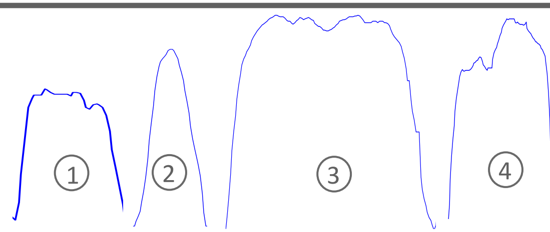
Segment-by-segment Markov chain

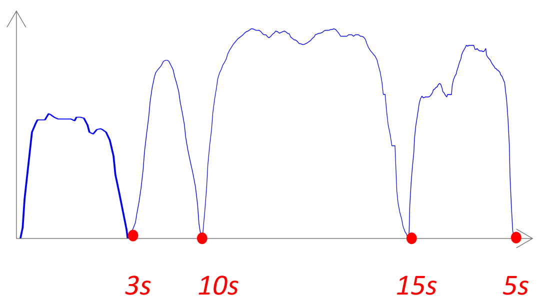
For each segment, the algorithm generates **stochastic speed profiles** iteratively until a solution that matches the segment constraints (**average speed, distance**, etc.) is found.

Entire Trip

The entire trip is then the concatenation of **stop periods** and **speed profiles** from all segments



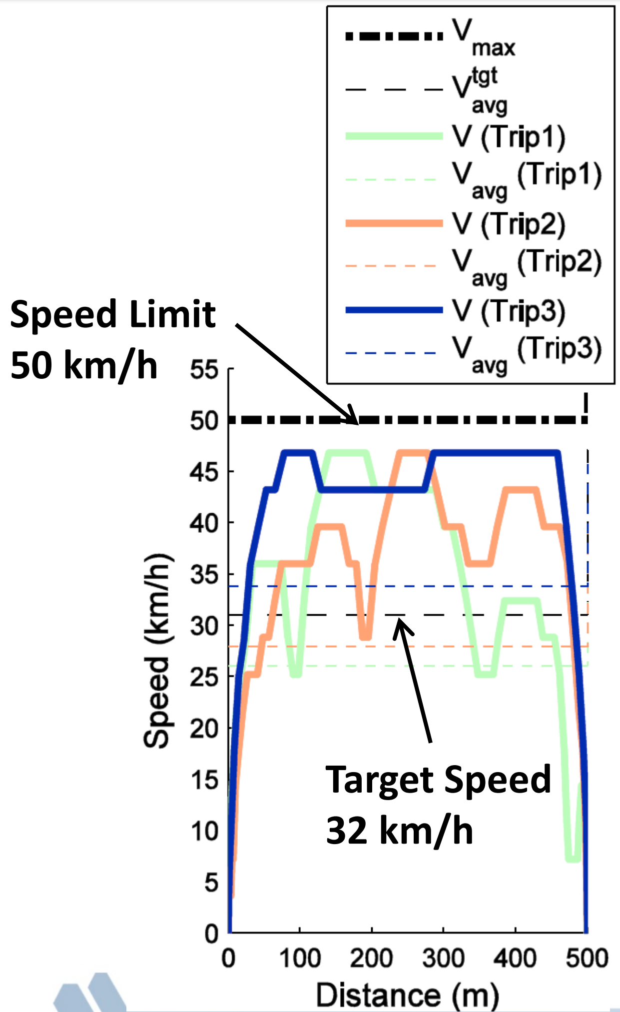




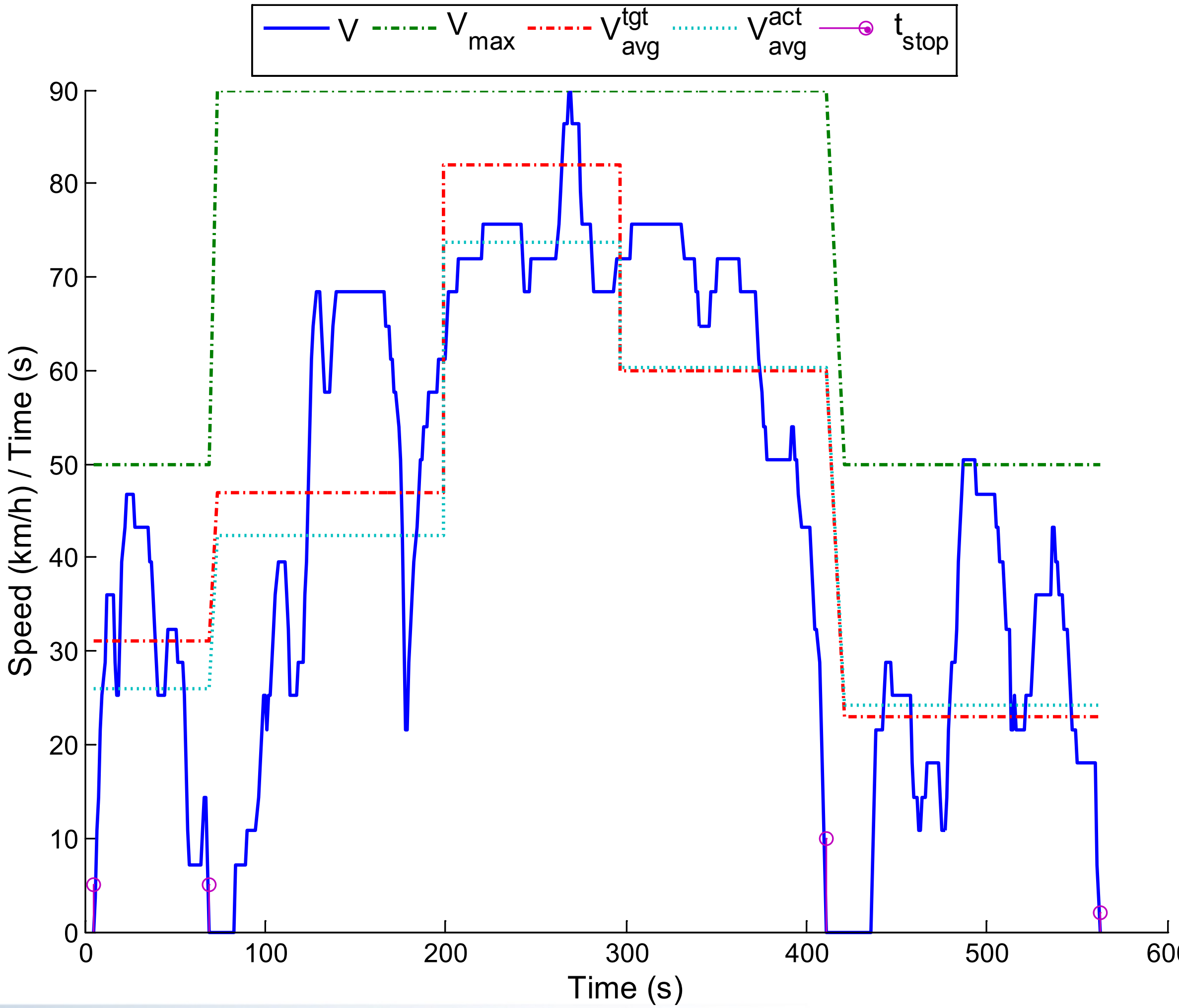
Technical Accomplishments

Examples of Synthetic Vehicle Speed Profiles

Multiple stochastic speed profiles for the same target micro-trip

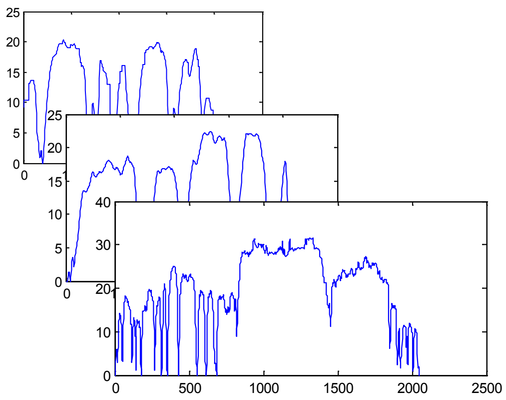


One synthetic speed profile for one entire itinerary



Technical Accomplishments
Markov Chains Defined Using Real-World Data

Database



- 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

$$\begin{bmatrix} P_{1,1} & \cdots & P_{1,n} \\ \vdots & \ddots & \vdots \\ P_{n,1} & \cdots & P_{n,n} \end{bmatrix}$$

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

$$P_b^* = \underset{P_b}{\operatorname{argmin}}\left(P_f(P_b) + r(t)\theta(P_b)P_b \right)$$

≈1

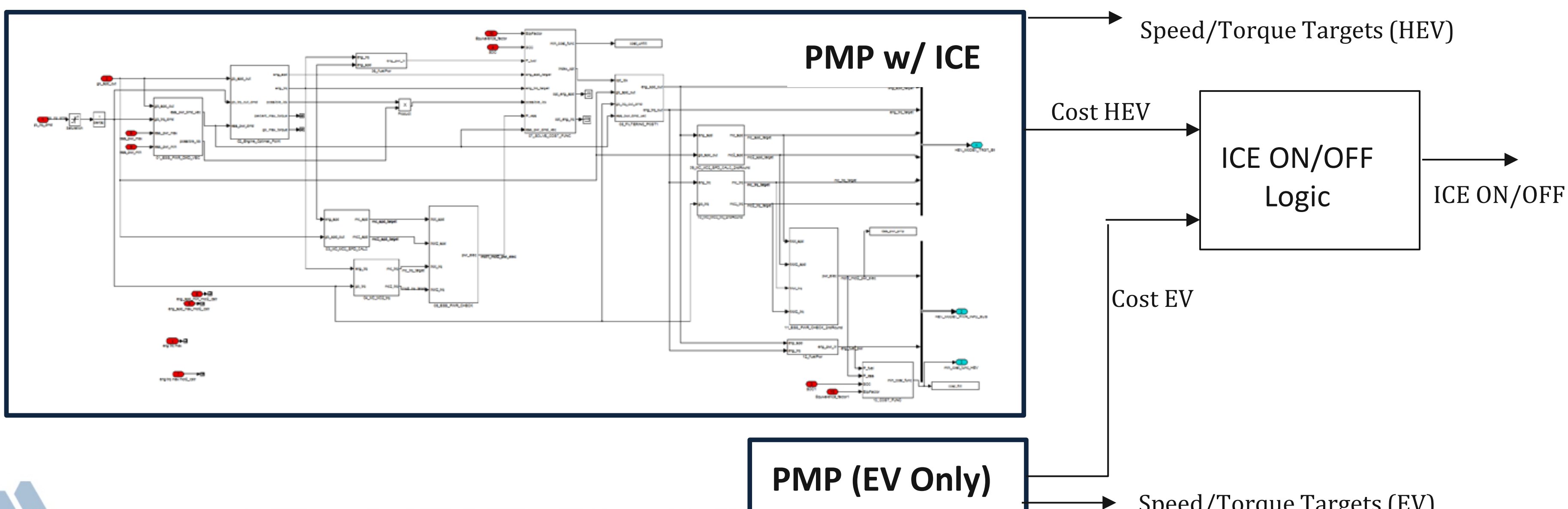
Fuel Power *Function of   through optimal operation maps*

Equivalence Factor (depends on trip!)

Battery Power Command

IMPLEMENTATION

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

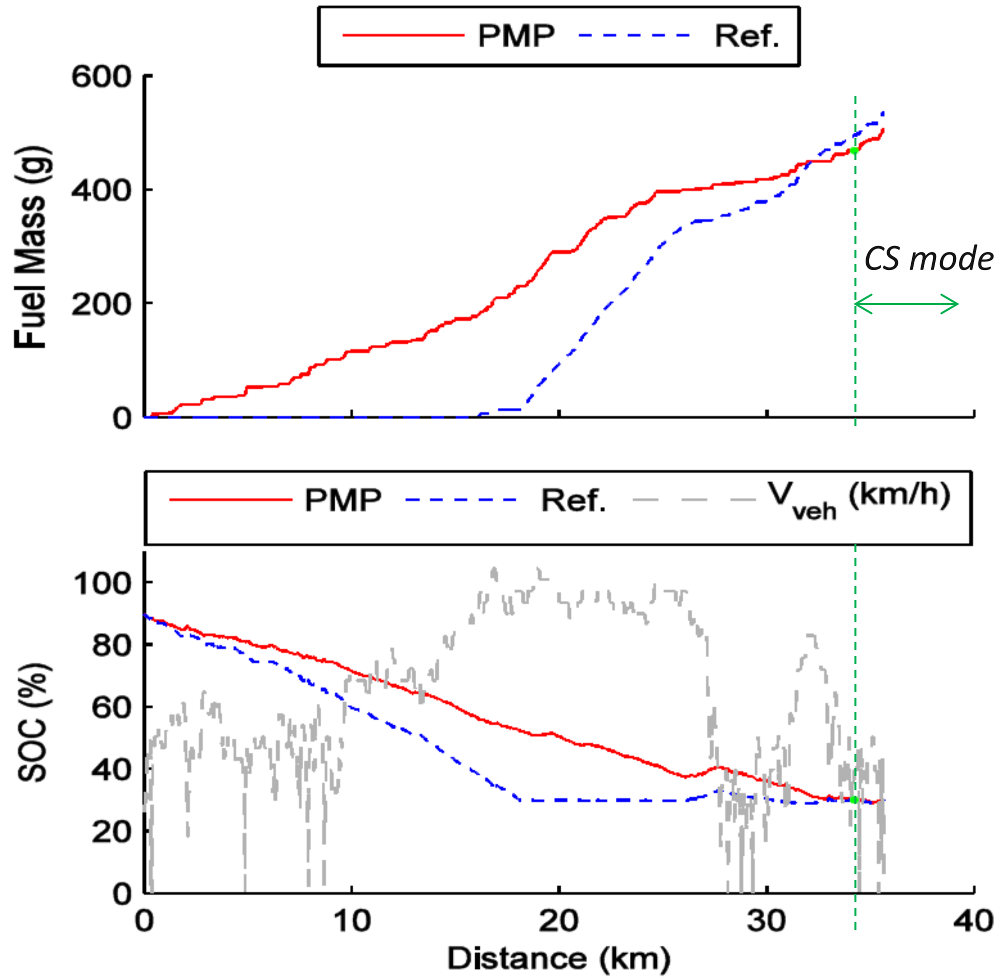


Technical Accomplishments

Benefits of Optimal Energy Management Evaluated

- Simulation environment: A**utonomie**, 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

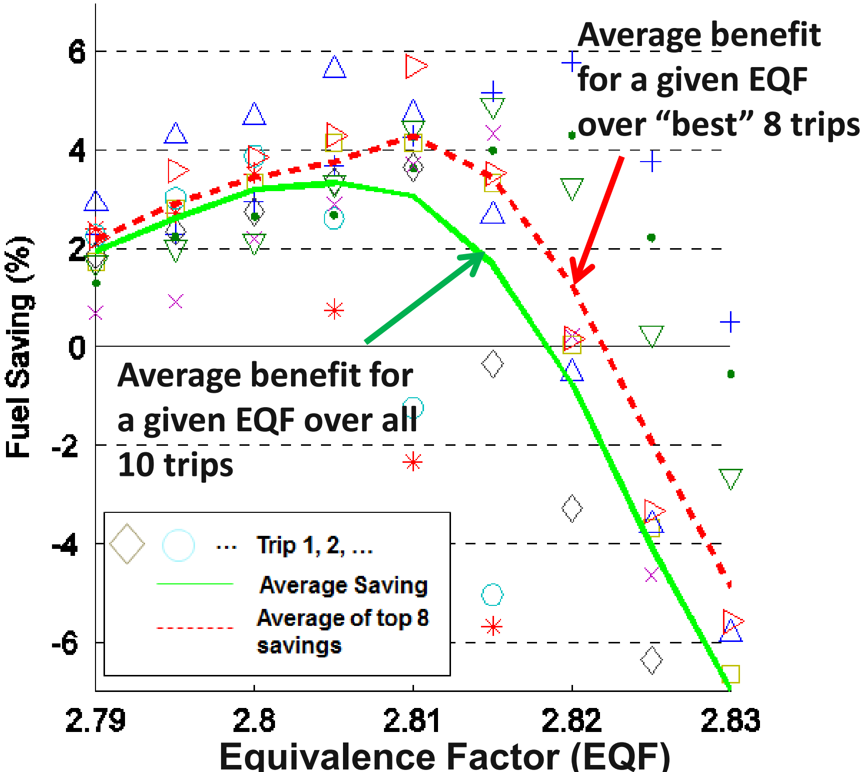
Example of operations



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



- **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

FY 2014

- **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.

FY 2015 and beyond (proposed)

- 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.).

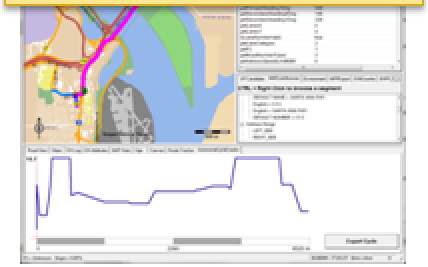
Summary

- 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**

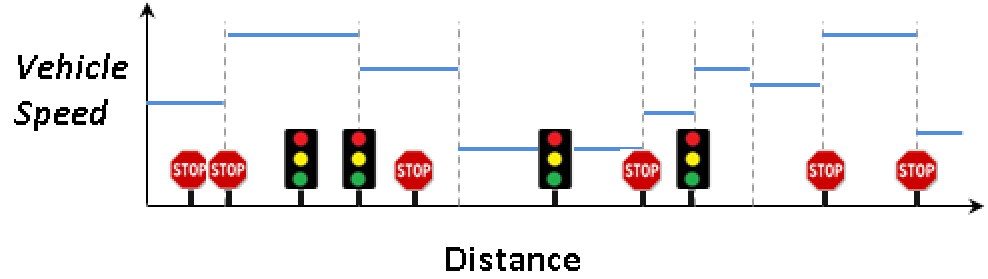
Back-up Slides

Combining Markov Chains and Geographical Information

Itinerary in GIS (ADAS-RP)

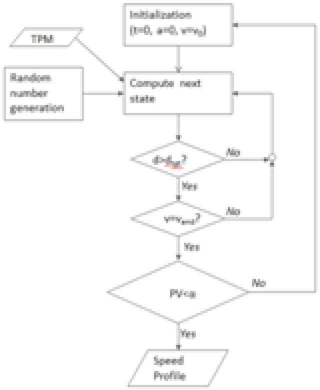


Raw Data Formatting + Segmentation



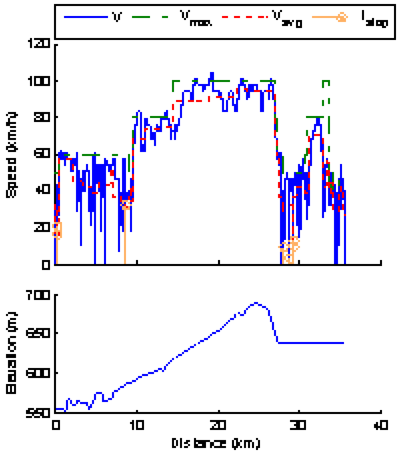
Iterative Stochastic Generation for each Segment

for segment= 1 to n

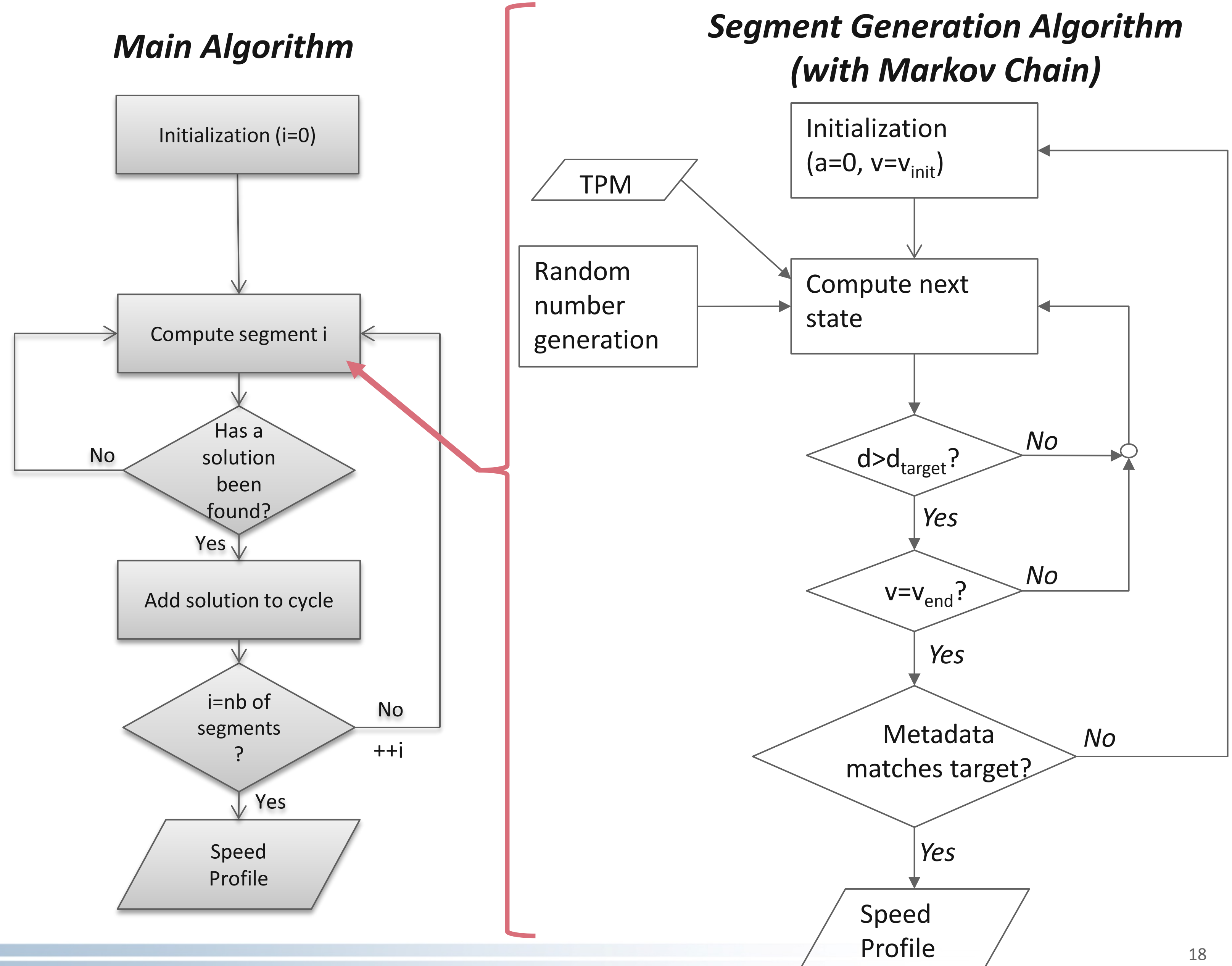


end

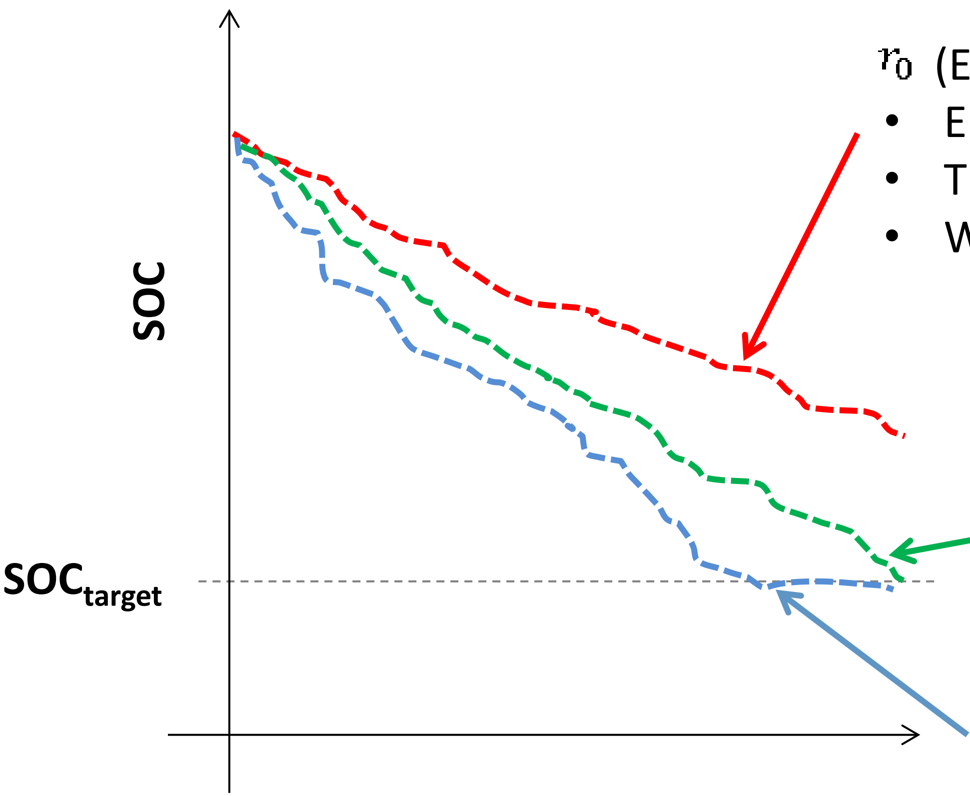
Synthesized Trip



Algorithm to Generate Speed Profiles



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

too low:

- Electricity is too "cheap"
- Battery is discharged too early
- Missed opportunity to displace more fuel