ENERGY EFFICIENT CAVS: WORKFLOW DEVELOPMENT AND DEPLOYMENT

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Argonne National Laboratory

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OVERVIEW

Timeline
- Nov. 2019 - Sep. 2023
- Percent complete: 20%

Budget
- FY21 Funding: $1,360,000
- FY20 Funding: $300,000

Partners
- Argonne National Laboratory (lead)
- George Mason University (partner)
- Clemson University (partner)
- Hyundai (CRADA)
- GM, Cummins, Nissan (stakeholders)

Barriers
- Many CAV technologies are nascent and require models
- Energy-efficiency not a factor in the development of Connected and Automated Vehicles (CAVs)
- Lack of methods to evaluate CAV energy benefits
- Lack of practical tools for energy-focused CAV controls development
- Demonstration w/ real vehicles challenging
RELEVANCE

RoadRunner and SVTRIP Essential Tools for SMART Research

ROAD RUNNER
☑ CAV Eco-driving Control
☑ CAV Energy Impacts
☑ Predictive Powertrain Control
➢ Simulink models
➢ Fast & Customizable
➢ Graph. interface + API
➢ MBSE (Sim. to VIL/XIL)

SVTRIP
☑ Naturalistic drive-cycle prediction
➢ Data-driven
➢ In-traffic conditions
➢ Flexible OD selection (HERE)

Objectives
▪ Develop professional-grade software & deploy to stakeholders
▪ Provide models balancing of fidelity and complexity
▪ Develop workflows that support SMART mobility research
**APPROACH**

- Integration with AMBER
- Graphical user interface
- Visualization
- Release

**SOFTWARE**
Maximize usability

**MODELS**
Enhance Fidelity

**WORKFLOWS**
Automate & Accelerate Research

- Exogenous Traffic
- HPC & Calibration
- XIL: real vehicle in virtual environment

Real-world data (Hyundai CRADA)
Real-world data (EEMS096)

- Human driver
- Lateral dynamics
- V2X and sensors
- Full CAV model validation

SMART CAV Controls
EEMS094

SMART Mobility workflow
EEMS093

Dynamometer & Vehicles
EEMS041

AMBER/Autonomie
EEMS013
MILESTONES

Q2

SOFTWARE

SVTRIP Integrated in AMBER w/ GUI

MODELS

V2V models in RoadRunner

WORKFLOWS

First XIL framework prototype

Q3

SOFTWARE

Human driver data analytics framework operational

MODELS

Lateral movement models in RoadRunner

WORKFLOWS

SVTRIP-RoadRunner integration for “native” traffic modeling in RoadRunner

Q4

SOFTWARE

Graphical RoadRunner scenario builder

MODELS

Prototypes of AI algorithms for speed prediction (SVTRIP)

WORKFLOWS

Deployment of RoadRunner to HPC to enable parameter calibration

ROADRUNNER

Release of RoadRunner

RoadRunner sensor models implemented and integrated

XIL workflow demonstration (go/no go)
ACCOMPLISHMENTS

1. Software
2. Models
3. Workflows
IMPROVED ROADRUNNER FLEXIBILITY

AMBER/Autonomie metadata system applied to RoadRunner

Entire simulation workflow now defined through metadata (previously hard-coded):

- **Model/system architecture**
  - how the subsystems are interconnected

- **File compatibility**
  - between files for: model, parameters, post-processing

- **Simulation workflow**, i.e. what to do when

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 ✓ Reusable code
 ✓ Faster dev
 ✓ New Workflows (e.g. XIL)
 ✓ Easier maintenance
 ✓ Customization
DEPLOYMENT TO STAKEHOLDERS

Integrated RoadRunner and SVTRIP into Existing Software Lifecycle Process ⇒ Reliable and Easy-to-Use Software

New Graphical User Interfaces

Formalized Software Lifecycle

Documentation

• Training
• HTML Help

*Enabled by XML
ACCOMPLISHMENTS

1. Software
2. Models
3. Workflows
IMPROVED HUMAN DRIVER MODEL

Human Driver Model Validated under Highway Car-Following Situations Using Real-World Driving Data

**Human driver model essential for CAV studies**
- Required for baseline when evaluating CAVs
- Needed to model mixed traffic scenarios

**Developed w/ OEM support (CRADA)**
- Hyundai provides data for training
- Model to be first deployed at Hyundai for ADAS & CAV modeling

- Improved the speed trajectory generation for car-following (analytical model)
- Validated the improved model w/ NGSIM data
- Speed and gap w/ preceding vehicle closer to real-world data by 20% and 42% (compared to IDM)

**Example: 1 vehicle**

- Illustration of speed and gap trajectory comparison between Data, aMPC, and IDM models

**524 vehicles in 5 lanes**

- Diagram showing RMSE for Speed and Gap with IDM and aMPC models

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RMSE: Root Mean Square Error | IDM: Intelligent Driver Model | aMPC: analytical Model Predictive Control | PV: Preceding veh.
DATA FOR HUMAN DRIVER MODEL

Extensive Real-World Data Provided by CRADA Partner (Hyundai) for Model Training

<table>
<thead>
<tr>
<th>1Hz Data from Customers</th>
<th>100Hz Data from Dedicated Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivers</td>
<td>Vehicle types</td>
</tr>
<tr>
<td>500+</td>
<td>6</td>
</tr>
</tbody>
</table>

Data from CAN:
- Driver: pedal pos., …
- Powertrain: eng. torque, …
- Dynamics: steering angle, …
- ADAS: gap with previous veh.

Dashcam Video + CAN Data + Coordinates

Large variety of driving situations & driving styles

Detailed understanding of the reasons behind driver actions
NEW V2V COMMUNICATION MODEL

Easy Setup of V2V Scenarios

Information transmitted via V2V: speed & position

- Standardized 2-way data exchange between vehicles using metadata
- Now possible to have any mix & match of V2V and non-V2V veh., for any number of veh.
- Parametrizable range
- Supports EEMS094 task on connectivity-enabled controls

Vehicle wrapper (one for each vehicle)
ACCOMPLISHMENTS

1. Software
2. Models
3. Workflows
AUTOMATED CALIBRATION

Fast and automated workflow to optimally calibrate controller parameters

Accomplishments: Workflows

Manually calibrated controllers +

Scenarios + Controller parameters to calibrate + Cost function to minimize

Optimization
grid search, pattern search

Controllers optimized for better performance

Faster and Less energy

Optimized parameters

Baseline parameters

BEV

Computer cluster

Energy Saving [%]

Travel Time Saving [%]
XIL – ANYTHING-IN-THE-LOOP
Combines Real and Virtual Systems w/ Closed Feedback Loop

Virtual World
Road and other vehicles simulated in RoadRunner

CAV Control
Controls the real vehicle driving in a virtual world

Real vehicle
on chassis dynamometer

Objectives
Calibrate
Evaluate
Demonstrate
Validate
energy-saving of CAV controls

Accomplishments: Workflows
- Calibrate
- Evaluate
- Demonstrate
- Validate
energy-saving of CAV controls
XIL – ANYTHING-IN-THE-LOOP

Combines Real and Virtual Systems w/ Closed Feedback Loop

Virtual World
Road and other vehicles simulated in RoadRunner

CAV Control
Controls the real vehicle driving in a virtual world

ANL XIL Workflow

Real vehicle on chassis dynamometer

BOLT (EV)
OR
BLAZER (ICE)

EEMS089 Focus:
Develop an automated workflow centered around RoadRunner that connects all the pieces

EEMS041
EEMS089
EEMS094
XIL WORKFLOW DEMONSTRATED
XIL Enables Fast Evaluation of CAV Controls in Laboratory Setting

CAV Controls (EEMS094)  XIL Hardware (EEMS041)

Flexible
- 2 vehicles (Bolt, Blazer)
- 22 unique scenarios:
  - w/ speed limits, stop signs, traffic lights
  - w/ or w/o V2I and eco-approach
  - Empty road and car-following

Fast & Efficient
- Formalized workflow for cross-team, cross-capability collaboration
- 63 tests in 3 (2+1) days,
- 280 km total
- ~2 days pre-test prep time
- Simulation results validated

Accomplishments: Workflows

Flexible

Fast & Efficient

Custom-controlled CAV follows rules of the road
**XIL – KEY ENABLERS**

- New dedicated RoadRunner **XIL architecture**
- Hardware-oriented code integrated into RoadRunner (EEMS041)
- Easy switch between 100% simulation and XIL

**Accomplishments: Workflows**

- Standardized workflow with **automated** steps for speed and robustness
- From test plan design to real-time code generation to quick post-test data processing

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**1. INTEGRATION**

- 1.1 Test plan design
- 1.2 Controller preparation
- 1.3 XIL model integration

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**2. PREPARATION**

- 2.1 RT software preparation
- 2.2 Vehicle preparation

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**3. EXPERIMENTATION**

- 3.1 Test
- 3.2 Data-processing
CONCLUDING REMARKS
## RESPONSES TO PREVIOUS YEAR REVIEWERS’ COMMENTS

<table>
<thead>
<tr>
<th>Reviewer Comment</th>
<th>Response</th>
</tr>
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<tbody>
<tr>
<td>“a tool that enables the quantification and improvements of CAVs with respect to energy efficiency is relevant to DOE”</td>
<td>“CAV+Energy” space is a core focus for RoadRunner development</td>
</tr>
<tr>
<td>“The reviewer suggested that the team work on alpha release and GUI”</td>
<td>Public alpha/beta release with GUI planned for Sep. 2021</td>
</tr>
</tbody>
</table>
| “Traffic is not considered” | Exogenous traffic will be added to RoadRunner through:  
  - A lead vehicle that represents traffic dynamics via SVTRIP (FY21Q3)  
  - A robust and automated linkage with traffic flow micro-simulation (FY22) |
## COLLABORATIONS

<table>
<thead>
<tr>
<th>Organization</th>
<th>Role</th>
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</thead>
<tbody>
<tr>
<td>George Mason University</td>
<td><em>project partner</em> Al for calibration and driver modeling (SVTRIP)</td>
</tr>
<tr>
<td>Clemson University</td>
<td><em>project partner</em> Extension of XIL capabilities to on-track testing</td>
</tr>
<tr>
<td>ANL/NREL</td>
<td><em>EEMS096</em> Use real-world CAV data collected in this project to develop CAV-related models in RoadRunner</td>
</tr>
<tr>
<td>ANL</td>
<td><em>EEMS041</em> Colleagues in this project develop and run the hardware for XIL</td>
</tr>
<tr>
<td>Hyundai</td>
<td><em>CRADA</em> Provide real-world data for human driver model development and validation, early testers of RoadRunner</td>
</tr>
<tr>
<td>GM</td>
<td>Stakeholders for XIL and RoadRunner workflow</td>
</tr>
<tr>
<td>Cummins</td>
<td><em>EEMS109</em> Interested in using RoadRunner when released</td>
</tr>
<tr>
<td>Nissan</td>
<td><em>SPP</em> Adopting SVTRIP for online, in-vehicle applications</td>
</tr>
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FUTURE RESEARCH

SOFTWARE
Maximize usability

MODELS
Enhance Fidelity

WORKFLOWS
Automate & Accelerate Research

- Integrate exogenous traffic with RoadRunner (e.g., automate connection with traffic flow microsimulation)
- Enhance XIL workflow (e.g., integrate direct vehicle override controls, add grade/aero emulation, expand process automation...)
- Develop Al-based control calibration process

Any proposed future work is subject to change based on funding levels.

- Deploy tools and workflows to stakeholders
- Develop graphical scenario builder (road, traffic signs, etc.)
- Develop a visualization module to replay simulations on road map and synchronize with time-series data
- Develop new workflows

- Al-based speed prediction algorithm (SVTRIP)
- Model the impact of lateral dynamics (turns, curves) on longitudinal speed
- Improve sensor & radio models (range, delays, etc.)
- Complete light-duty vehicle human driver model
- Validate CAV models (Data from EEMS096)
## SUMMARY

### SVTRIP
- SVTRIP integrated within AMBER GUI, and new AI-based algorithm development underway

### ROAD RUNNER
**Release, Models, Workflows**
- Significant progress made towards *RoadRunner release*: closer integration with AMBER, first GUI, software lifecycle in place.
- Improved *RoadRunner models*, incl. V2V and human driver, with data from CRADA partner (Hyundai) to ramp up into FY22.
- On-going addition of new workflows, e.g. *calibration* or *exogenous traffic*

### XIL
- Developed & demo’d *XIL workflow* ahead of schedule (despite COVID!)
- Automated and efficient process to experiment CAV controls on real veh.
- Fast, flexible, robust
- Applied to 2 different vehicles, with a variety of scenarios (incl. V2I, car-following); simulation validated within 5% in first try

### Supporting SMART Mobility R&D
- All new developments and features support CAV research, and will be progressively deployed to stakeholders
Energy Efficient CAVs: Workflow Development and Deployment

FOR MORE INFORMATION
Dominik Karbowski
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THANK YOU!
TECHNICAL BACK-UP SLIDES
ROADRUNNER GUI

Developed First GUI, and Packaged it for 02/2021 Internal Alpha Release of RoadRunner

1. Select Autonomie powertrains, order and position

2. Select Route

3. Launch Simulations
XIL WORKFLOW

0. DEVELOPMENT
- Control development
- Vehicle instrumentation

1. INTEGRATION
1.1 Test plan design
1.2 Controller preparation
1.3 XIL model integration

2. PREPARATION
2.1 RT software preparation
2.2 Vehicle preparation

3. EXPERIMENTATION
3.1 Test
3.2 Data-processing

4. IN-DEPTH ANALYSIS
Test comparisons, Validation, etc.

Way ahead → Ahead
Just before
During
Back at the office

Collaboration with EEMS041
XIL KEY COMPONENTS

XIL Workflow Combines 3 Major Capabilities

Virtual Environment

Digital twin vehicle

Perf. env. info.

Embedded Automated Driving Software

Perception

Powertrain State

Control

Grade, aero load

Speed

Real Vehicle on dyno, with control override

- Control
- Powertrain State
- Perception
- Real Vehicle on dyno, with control override
- Embedded Automated Driving Software
- Perfect env. info.
XIL EXPERIMENTAL SETUP

- **Real-time SOFTWARE (dSpace Micro-Autobox)**
- **Robot Driver**
- **Robot Driver Controller**
- **Automated Driving Controller**
- **Virtual Environment**
- **Vehicle Info**
- **Vehicle**
- **Chassis Dynamometer**
- **Control Room with dedicated HMI**

- **Real Time CAN Connection**
  - Vehicle States (Speed, SOC, etc.)

- **Perceived Environment**
  - APP, BPP Demand

- **Send Commands/Monitor Feedback**

- **CAN**
  - Analog
  - Ethernet

- **APP [V]**
- **BPP [V]**

- **Demand**

- **Grade/aero load**

- **Automated Driving Controller**
- **Vehicle**

- **Real Time CAN Connection**

- **Vehicle States**

- **Control Room with dedicated HMI**

- **Virtual Environment**

- **Grade/aero load**

- **Speed**

- **Robot Driver Controller**

- **Vehicle Info**

- **Robot Driver**

- **Chassis Dynamometer**

- **Sending Commands/Monitor Feedback**