Connected and Automated Vehicles

Aymeric Rousseau (PI), John Smart,
Jeff Gonder, Andreas Malikopoulos

ANL, INL, NREL, ORNL

2016 DOE VTO Annual Merit Review
June 8, 2016, Washington DC

Project ID: VAN022

Project Overview

Timeline	Barriers
Start Date: September 2016 End Date: September 2019 Percent Complete: 10%	• Energy impact of connected and automated vehicles • Implication on VTO technologies and targets
Budget	**Partners**
Total project funding: $3M (100% DOE) Funding for FY 2016: $1M	National Laboratories (ANL, INL, NREL, ORNL) LLNL (VS006)

Relevance

Objective: How can connectivity and automation be leveraged to reduce total energy use?

Why DOE VTO? DOE has the key expertize to provide the analysis and quantify the potential benefits of CAVs in reducing energy usage and greenhouse gas emissions :

- Vehicle technology (what are the optimal powertrain designs for automated vehicles?)
- Vehicle control (=> using information to save energy)
- Traffic flow control (speed harmonization, intersection control, smoothing, cooperative driving)
- Traveler Behavior (Where, when, how people travel?)

Relevance

Great Uncertainty about CAVs Effect On Energy Consumption

Changes in traffic flows ⇒ Different Speeds

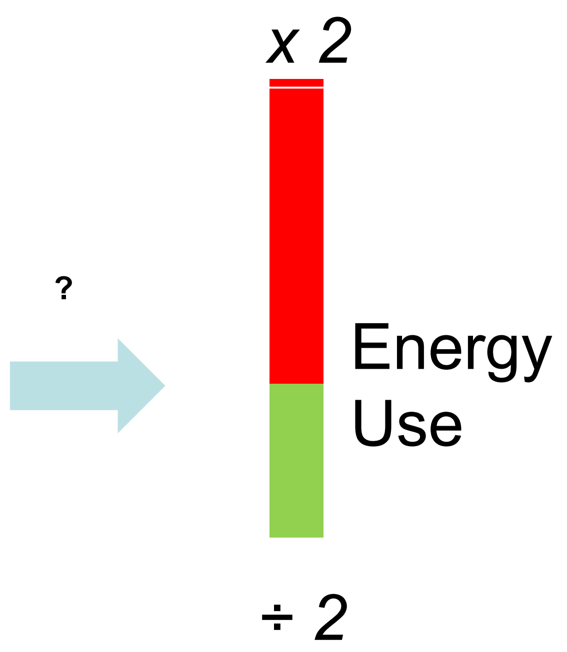
- Increased capacity
- Smoother speeds
- Potentially faster speeds
- Smart intersections

Travel behavior ⇒ +/- VMT

- Mode shifts (to/away from transit with automated shuttles)
- Increased access to mobility of underserved populations
- Changes in the value of time

Higher Vehicle Energy Efficiency

- Smoother driving
- Predictive energy management
- Reduced aero losses in platoons
- Downsizing (due to performance/safety)



+ Interaction with advanced powertrain technology!

Milestones

- Energy impact of CAV-specific speed profiles
- Estimation of ACC/CACC energy impact

- Fuel savings with predictive cruise control on highways
- Sensitivity of ACC/CACC to powertrain electrification

- Fuel savings with optimal speed/powertrain control on urban/arterial roads
- Impact of platooning on energy

Task 1: Energy Impacts at the Individual Vehicle Level

FY16 | FY17 | FY18

FY16

- Develop framework for evaluating ACC & CACC technologies

FY17

- Perform simulations to evaluate the impact of smart intersections at the regional level for advanced vehicle technologies

FY18

- Quantify the energy impact at the regional level of CAVs for VTO technologies

Task 2: Energy Impact at the Macro Level

FY16 | FY17 | FY18

FY16

- Perform simulations to quantify the energy impact of secondary effects (e.g., VMT) at the regional level
- Quantify the impact of VTO technologies on LDVs design and energy consumption

FY17

- Quantify the impact of VTO technologies on USDrive targets

FY18

- Quantify the impact of simultaneous CAVs technologies
- Quantify how VTO technologies can mitigate potential energy multiplier
- Quantify the impact of VTO technologies on MDVs & HDVs design and energy consumption

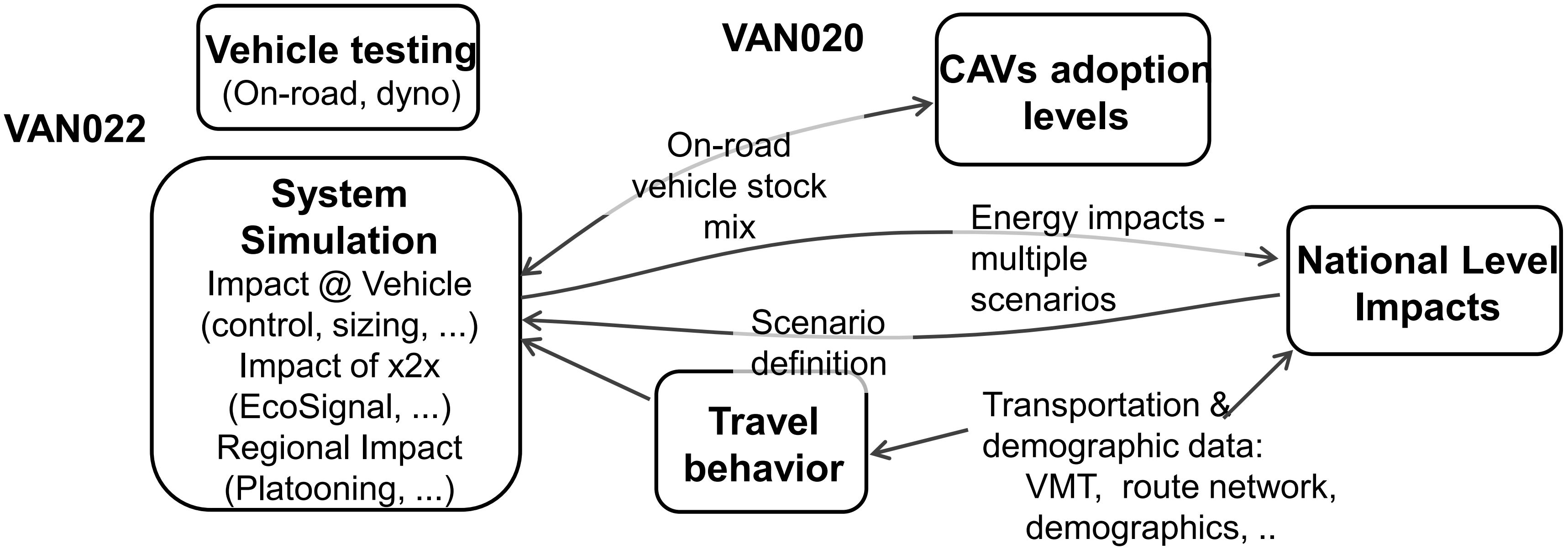
Task 3: Secondary Energy Impact

FY16 | FY17 | FY18

Approach

Interactions with National Level Impact (AOI 2C) Effort

- Energy impacts of CAV technologies at vehicle-, local- and regional-levels will be analyzed by the AOI 9E team (VAN022), with guidance on cases to analyze and assumptions from this (AOI 2C – VAN020) effort



- Results from AOI 9E analyses will be used to develop national-level estimates, to be refined as more results are available
- This effort will identify gaps and uncertainties for improved analyses by the AOI 9E team

Approach
Expertise of Each Laboratory Leveraged

- ANL
  - Vehicle energy modeling and control
  - Travel demand, flow and traveler behavior modeling
  - Vehicle [V2X] technology evaluation and analysis, dyno LD/MD
- INL
  - Define LD vehicle data collection requirements for model validation and identify data sources
  - On-road and on-track data collection and analysis – LD
- NREL
  - LD driving behavior; MD/HD on-road data collection and analysis
  - Impacts of vehicle design/operation & green routing on energy use
- ORNL
  - Decentralized control for optimizing traffic flow
  - Impact on VMT using geo-demographics

Approach

Different Resolution Tools Required

VAN022

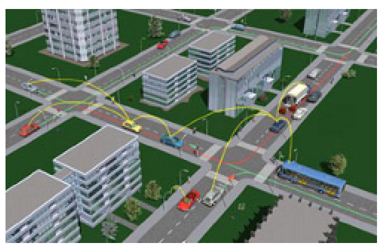
VAN020

Evaluating new vehicle technologies, developing new vehicle controls

Developing controls for connected and automated vehicles

Analyzing the impact of new infrastructure, control and new forms of transportation

Evaluating energy impacts at the national level



Single Vehicle

Eco-driving
Eco-Routing
Predictive Control

Small Network

Connected Intersections
V2X
ACC, CACC & Platooning

Entire Urban Area

Connected Intersections
Platooning & Eco-lanes
Low-emission zones
VMT changes

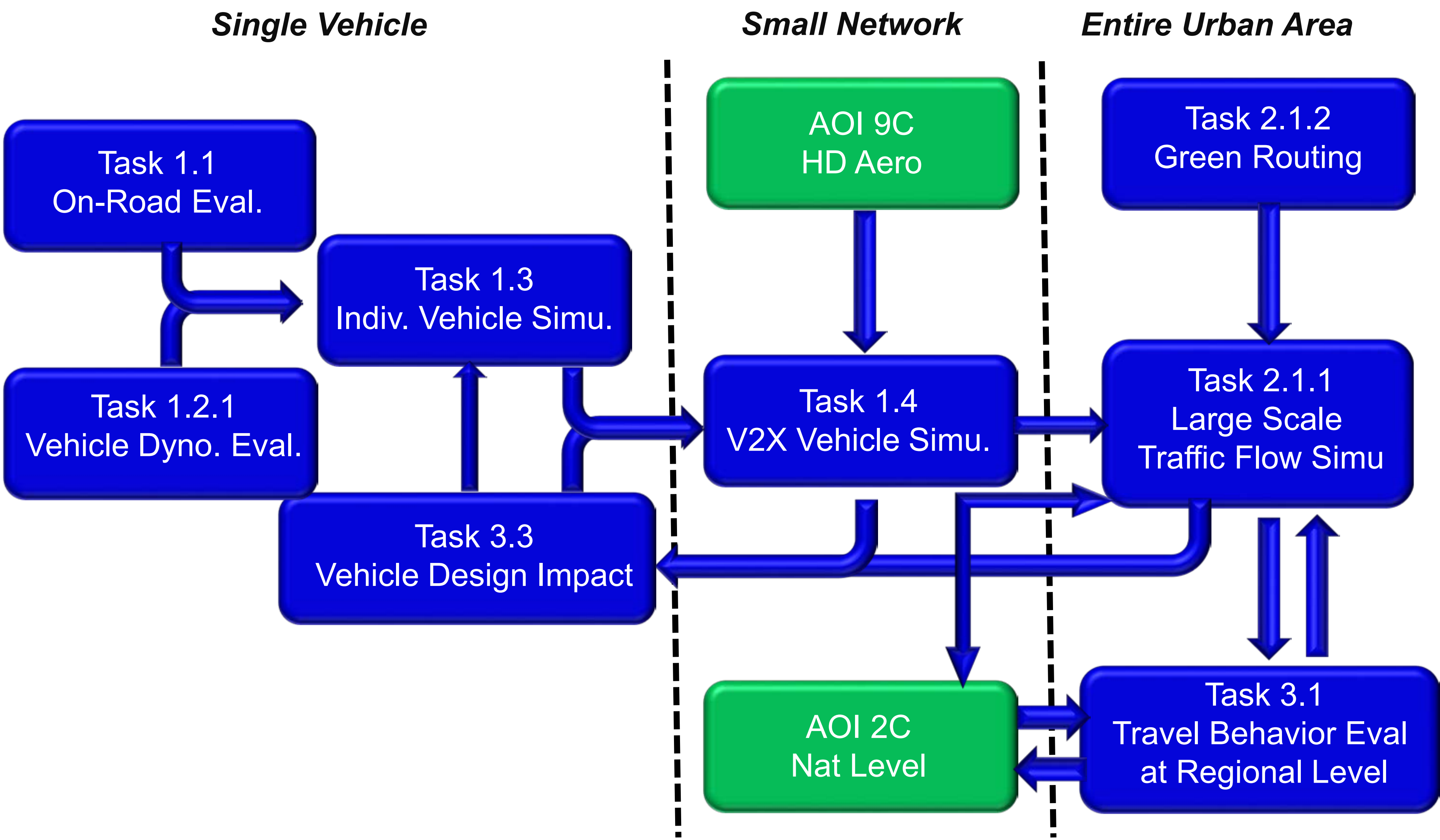
National Level

Approach
Project Organization Leverages Tool Resolution

Task	Description
1	Energy Impact at the Vehicle Level
1.1.1	On-Road Light Duty Vehicle Evaluation (INL)
1.1.2	On-Road Medium & Heavy Vehicle Evaluation (NREL)
1.2.1	Light duty chassis dynamometer evaluation (ANL)
1.2.2	Heavy Duty Powertrain Dynamometer Evaluation (ORNL)
1.3	Individual Vehicle Simulations (ANL)
1.4	Connected Vehicle Simulations (ANL)
2	Energy Impacts at the Macro Level
2.1.1	Larger-Scale Traffic Flow Impacts (ANL)
2.1.2	Green routing (NREL)
2.2	Control for Improving Traffic Flow with CAVs (ORNL)
3	Secondary Impacts that Could Enhance or Inhibit Energy Benefits
3.1	Travel Behavior Evolution at the Regional Level and its Energy Impact (ANL)
3.2.1	Evolution of Vehicle Miles Traveled at the Nat. Level (ORNL)
3.2.2	Impacts on Heavy-Duty Freight Demand (NREL)
3.3.1	Impact on Vehicle Design (ANL)
3.3.2	Impact on Vehicle Design (NREL)

Approach

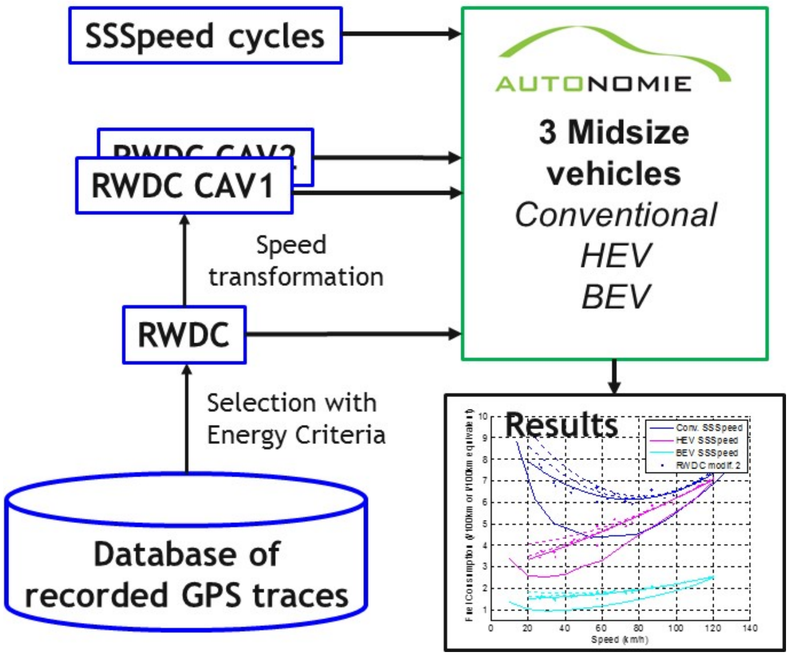
Project Subtasks Dependency



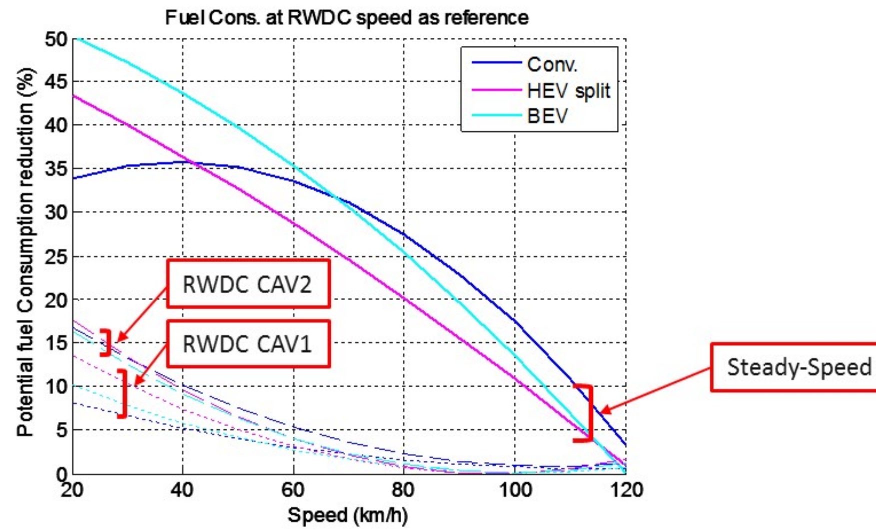
Technical Accomplishments

Task1.3: Energy Impact of Individual Vehicles

Process



Results

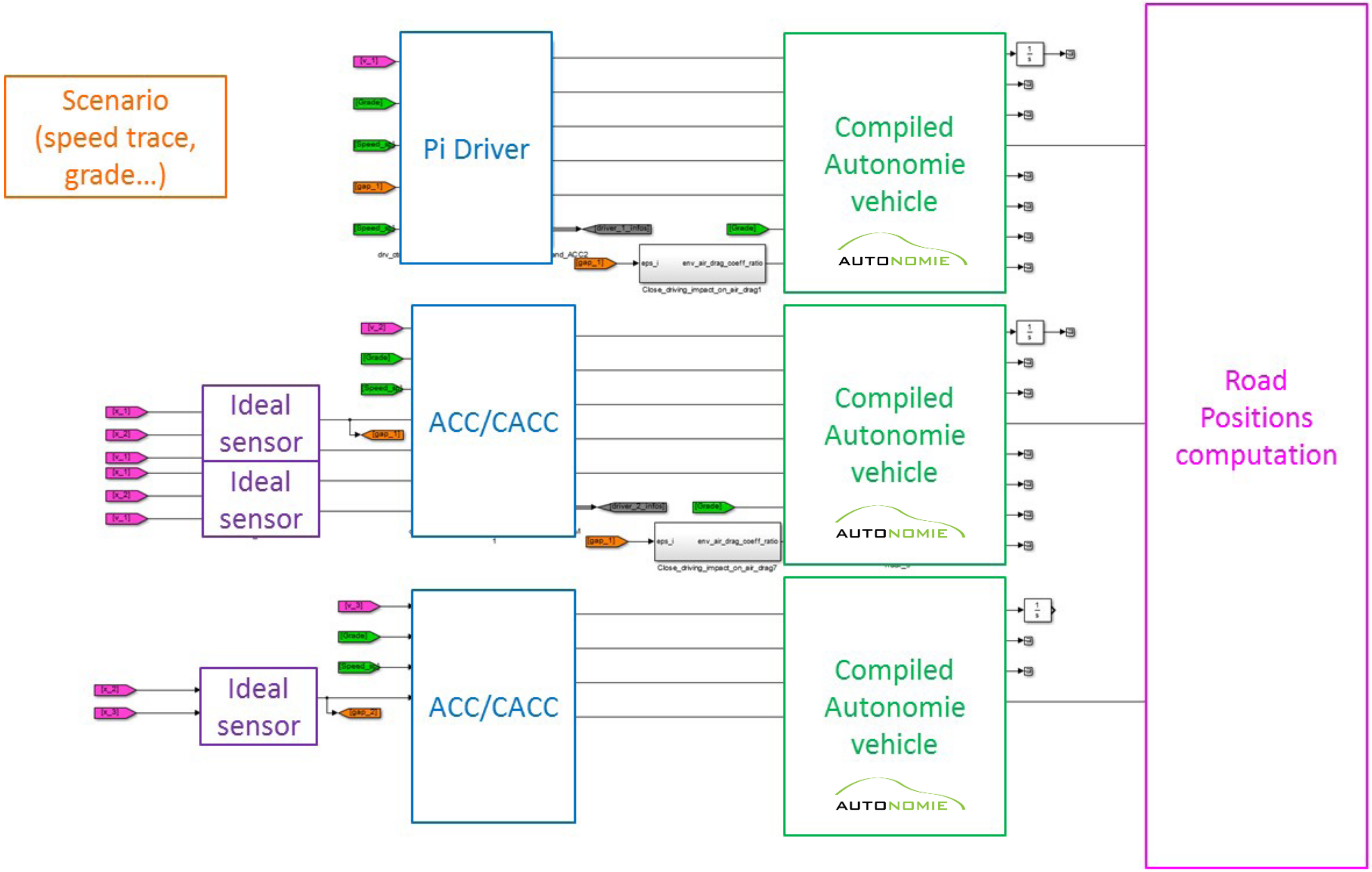


- 35 to 50 % potential fuel savings at low vehicle speed
- BEVs have biggest potential at low vehicle speed

Technical Accomplishments

Task1.4: Connected Vehicles Simulations

Started Development of Multi-Vehicle Simulation Framework Using Autonomie



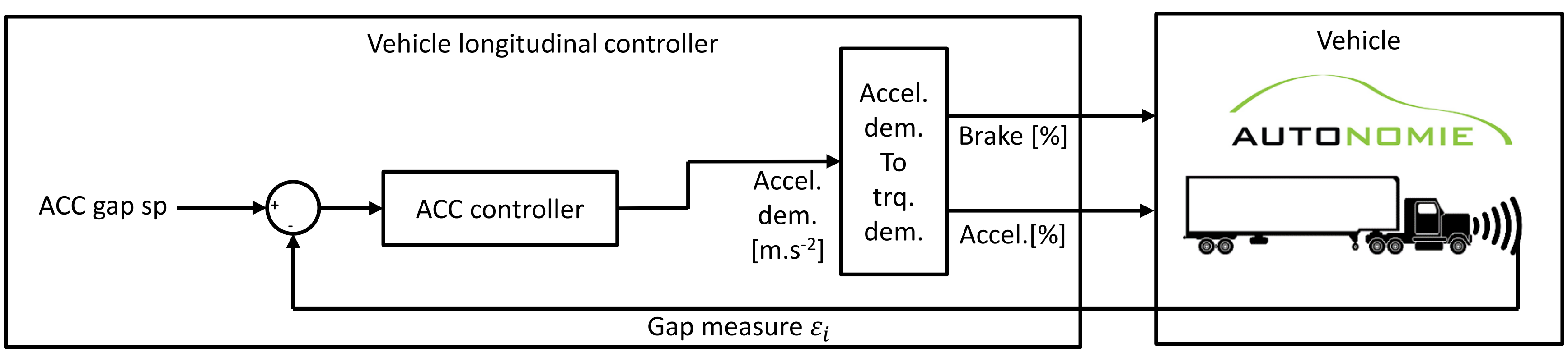
Truck platoon example

Technical Accomplishments
Task1.4: Connected Vehicles Simulations

Longitudinal vehicle dynamic control - ACC concept

- ACC
  - Vehicles are equipped with sensor(s) to measure
    - The inter-vehicle gap
    - The preceding vehicle speed

- ACC controller



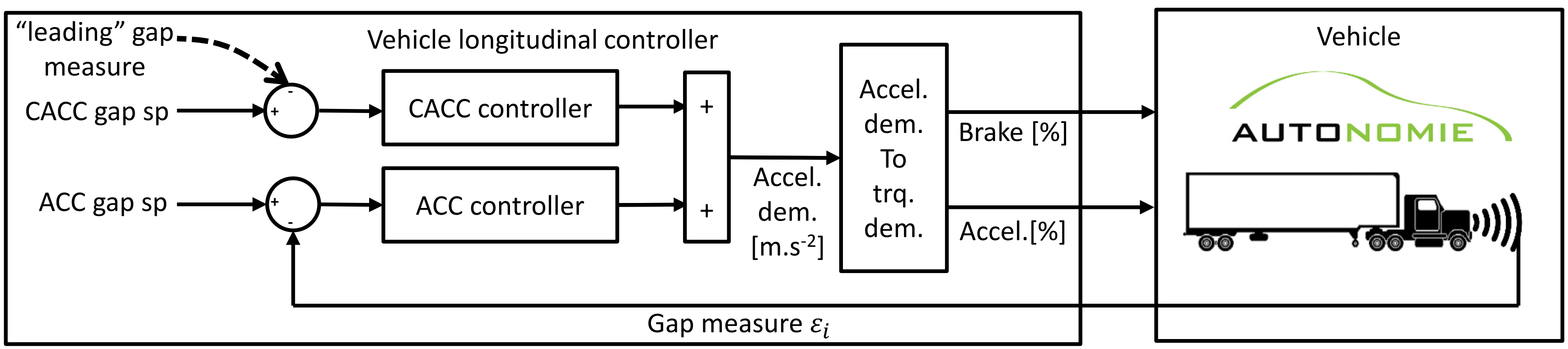
Aerodynamic data for following trucks provided by LLNL (VS006)

Technical Accomplishments

Task1.4: Connected Vehicles Simulations

Longitudinal vehicle dynamic control - CACC concept

- CACC
  - Vehicles are equipped with sensor(s) to measure
    - The inter-vehicle gap
    - The preceding vehicle speed
    - The leading-vehicle gap
    - The leading vehicle speed
- Siplified CACC controller

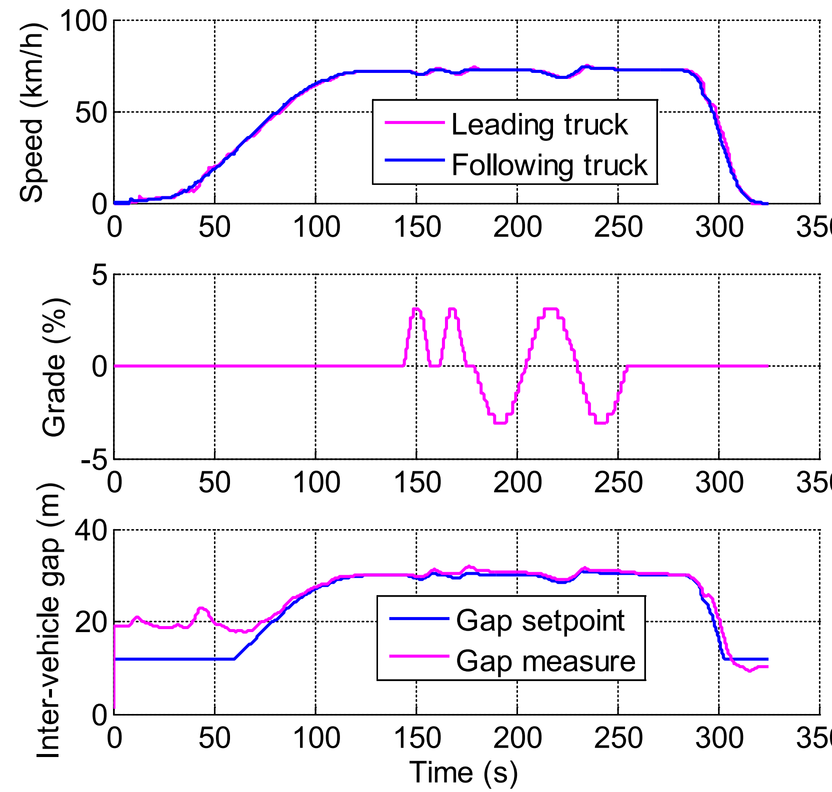


Aerodynamic data for following trucks provided by LLNL (VS006)

Technical Accomplishments

Task1.4: Connected Vehicles Simulations

Developed Adaptive Cruise Control Algorithms

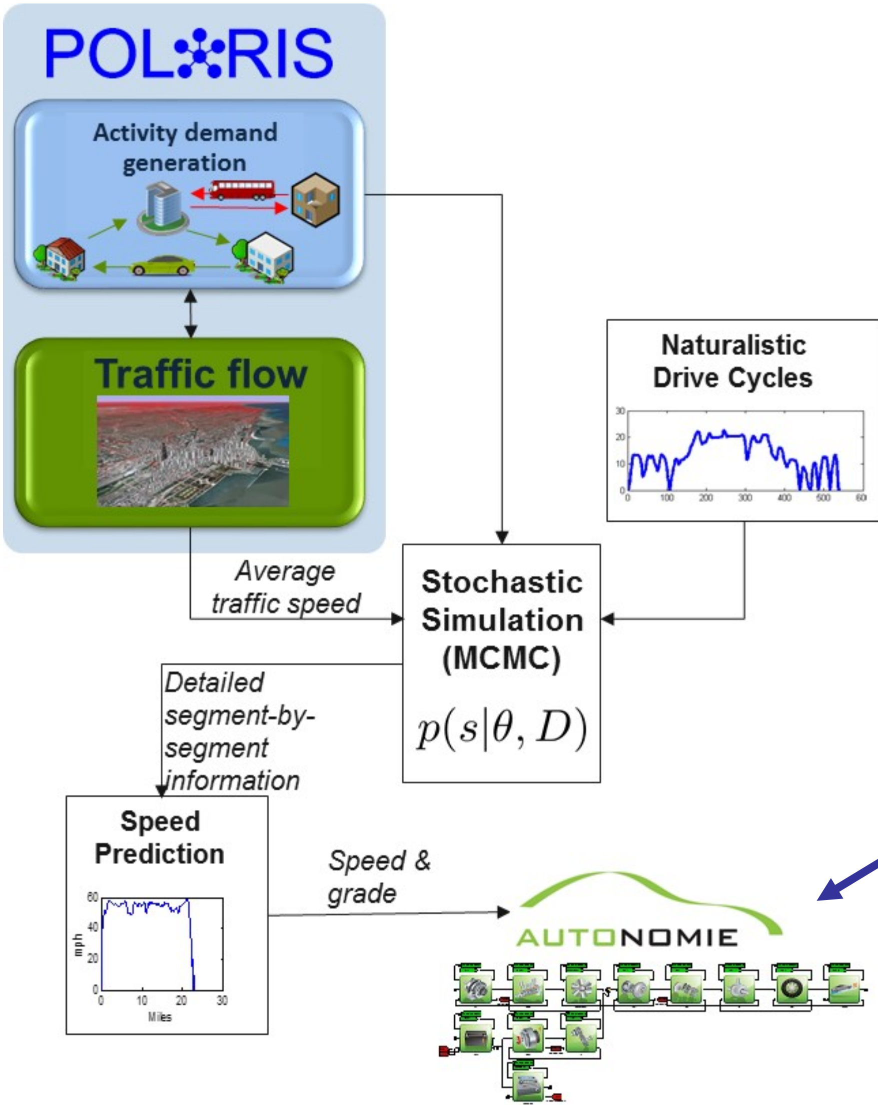


Grade robust ACC for line haul

Technical Accomplishments

Task2.1.1: Large Scale Traffic Flow Impact

Developed a linkage between MA3T outputs that allows fleet definition using Autonomie vehicles



MA3T
(ORNL Market Penetration Tool)

Fleet distribution

Technical Accomplishments
Task 2.2: Control for Improving Traffic Flow with CAVs

- Developed a scalable optimization framework for coordinating CAVs to optimize traffic flow in designated transportation segments, e.g., intersections, merging roadways.
- Formulated the centralized control problem for CAVs merging at highway on-ramps. Developed the decentralized control framework that will allow each vehicle to solve the optimal control problem independently.

Optimization Problem:

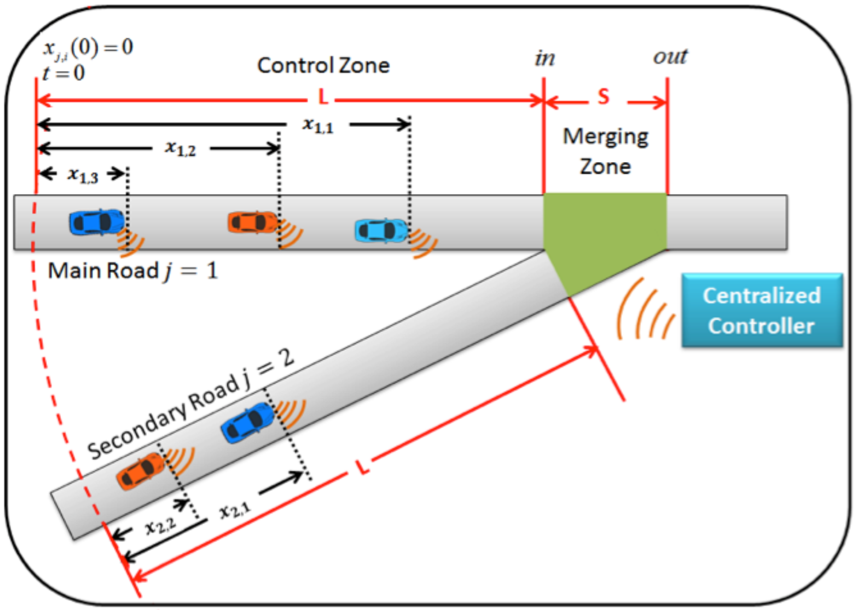
$$\min_{u_{j,i}} J = \min_{u_{j,i}} \frac{1}{2}\sum_{j=1}^{m}\sum_{i=1}^{n}\int_{0}^{t^{f}_{j,i}} u_{j,i}^{2}\,dt$$

Subject to:

$$\dot{x}_{j,i} = v_{j,i}$$

$$\dot{v}_{j,i} = u_{j,i}$$

- *Safety Constraints*
  - *Rear-end collision avoidance*
  - *Lateral collision avoidance*

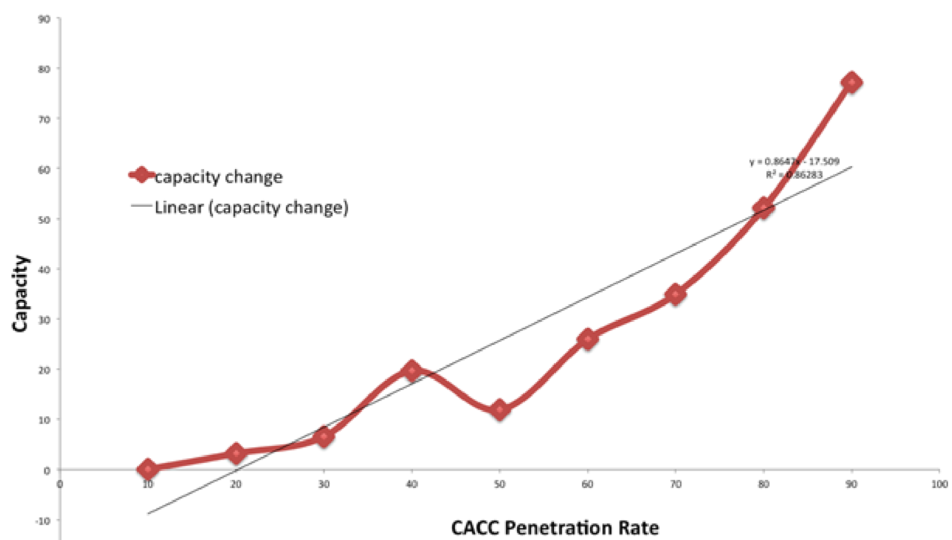


Technical Accomplishments

Task 3.1: Travel Behavior Evolution at the Regional Level and its Energy Impact

- Preliminary analysis of potential range of secondary effects at the regional level
- Simplified models of behavioral and traffic flow response to CACC deployment:
  - Changes in travel behavior come only from assumed changes in value of time (ranges drawn from literature)
  - Modeled by reducing travel time parameters in the utility functions for destination choice, mode choice, etc.
  - ex: $V_{in} = \beta_T T_{in}(1 + \gamma_{vt}) + \cdots$, where V_{in} = utility, β_T=travel time parameter, γ_{vt} = % change in travel time value
  - Traffic flow impacts modeled as link capacity changes for given penetration level derived from literature review:

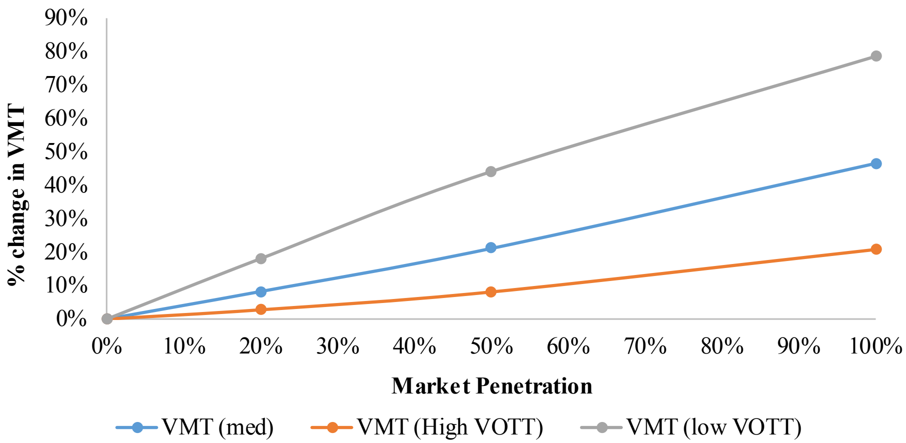
- Analyzed over a range of market penetration values
- CACC technology randomly distributed to drivers according to penetration level
- Link capacity changes uniformly applied across network



Technical Accomplishments

Task 3.1: Travel Behavior Evolution at the Regional Level and its Energy Impact

- Baseline model + 18 scenarios evaluated, including:
  - 3 with only capacity changes
  - 6 with only value of travel time changes at different penetration levels
  - 9 with all effects, including turning off intersection control at 100% penetration



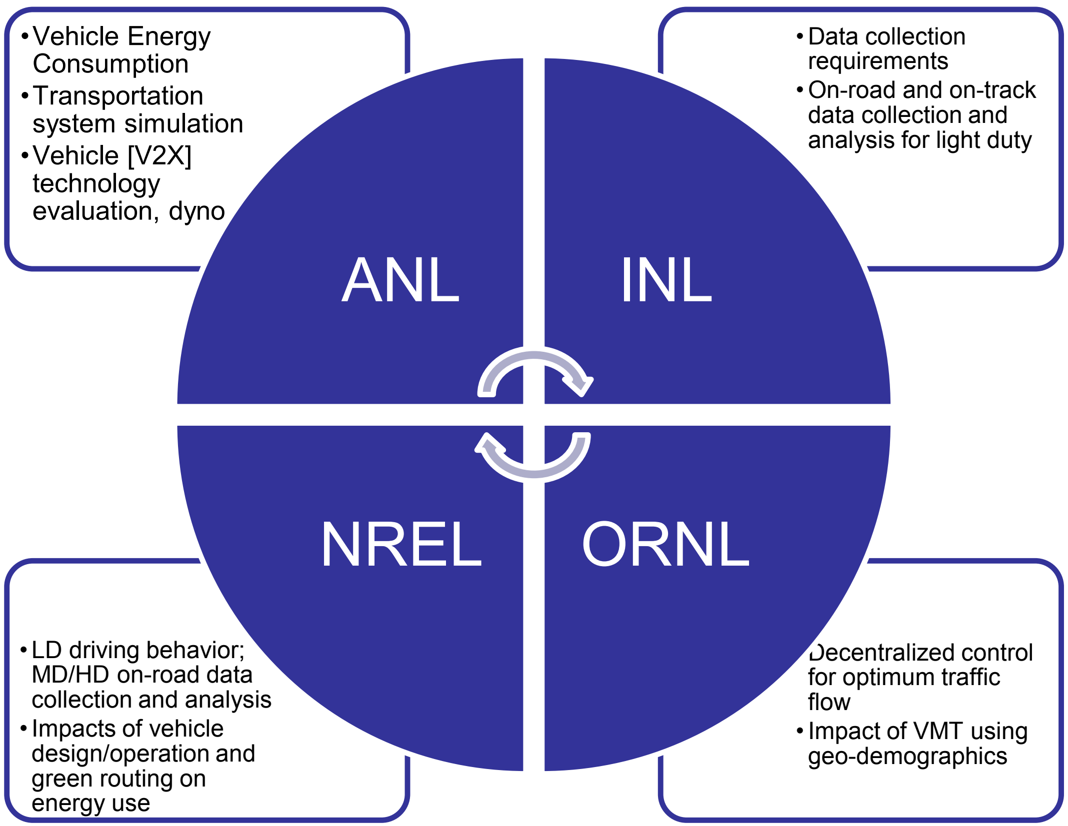
Scenario setup and analysis results

Scenario type	Market pen.	VOTT ratio	Capacity increase	Auton. Inter.	VMT (in MM)
baseline	0%	0%	0%	no	275.9
Capacity increase only	0%	0%	12%	no	278.5
Capacity increase only	0%	0%	50%	no	283.7
Capacity increase only	0%	0%	77%	no	287.2
VOTT only - low pen.	20%	-25%	0%	no	283.1
VOTT only - low pen.	20%	-50%	0%	no	298.8
VOTT only - low pen.	20%	-75%	0%	no	324.9
VOTT only - high pen.	75%	-25%	0%	no	310.2
VOTT only - high pen.	75%	-50%	0%	no	372.1
VOTT only - high pen.	75%	-75%	0%	no	437.9
All effects - low pen	20%	-25%	3%	no	283.5
All effects - low pen	20%	-50%	3%	no	298.6
All effects - low pen	20%	-75%	3%	no	325.7
All effects - med pen	50%	-25%	12%	no	298.2
All effects - med pen	50%	-50%	12%	no	334.1
All effects - med pen	50%	-75%	12%	no	397.5
All effects - high pen	100%	-25%	77%	yes	333.2
All effects - high pen	100%	-50%	77%	yes	404.2
All effects - high pen	100%	-75%	77%	yes	492.5

- Wide range of potential outcomes:
  - Difference largely driven by VOTT
  - Worst case of ~80% increase in VMT at high deployment/low VOTT
- Preliminary model with several potential behavioral responses unaccounted for and simplified impact of CACC on traffic flow

Collaboration and Coordination with Other Institutions

The project has been developed with collaboration in mind due to the multiple partners



Numerous other projects leveraged including:

- LLNL (Aero. VS006)
- MTC FOA (Data VS173)
- TARDEC (Advanced controls)
- CERC (MaaS)
- Detroit (Transportation system modeling)
- FTA (Transit modeling)
- ARPA-E TRANSNET (Connected traveler)

Future Work

FY16

- Collect data requirements for model validation and determine possible data sources, and contact data owners to find out if data can be shared.
- Complete ACC, CACC control impact along with the new multi-vehicle framework.
- Quantify the benefits of CAVs in fuel consumption in merging at highways on-ramps.
- Assess the impact of CAVs at the regional level to quantify positive (e.g., platooning, green routing) as well as negative impacts (e.g., VMT evolution).

FY17

- Perform data availability gap analysis.
- Design on-road evaluation program using AVTA resources to fill gaps.
- Assess the energy impact of CAVs for multiple technologies at different scales including uncertainties.
- Collect data and determine resources specific traffic scenario of heavy-duty vehicles for model validation.

Summary

- Connected and automated vehicles (CAVs) have the potential to disrupt the transportation system as it currently stands.
- While a significant amount of work has been reported related to safety, only limited qualitative analysis has been performed so far related to energy.
- This multi-year multi-national laboratory project expands existing expertise related to energy consumption, GHG and cost for CAVs.
- Multi-scale approach (single vehicle, small network, region and nation) combined with vehicle test data already showed promising results.
- Project currently being expanded to be part of Smart Mobility which will include decision science, infrastructure, multi-modal and urban in addition to CAVs

ADDITIONAL SLIDES

Current State of Research

- Current focus has been on safety and feasibility
  - Autonomous vehicles demonstrated for automated features (i.e., GM supercruise, Magna EYERIS…) as well as for self-driving cars (i.e., Google car, DARPA grand challenge…)
  - Regarding connected vehicles,
    - DSRC rule making is in progress. Cars will likely soon be equipped with V2V communications capabilities (ANPRM out).
    - Safety pilot performed at University of Michigan
- Government agencies, led by DOT/AERIS, universities and research institutions (I.e., ITS America) have performed preliminary work related to CAVs energy consumption potential. Several programs also on-going in Europe (i.e. amitran, compass4D) and Japan (i.e. nedo).

Qualitative foundational work performed so far for energy

Current State of Research – Energy Benefits

Researchers have performed *preliminary* estimations of *some* benefits

Examples of DOT/AERIS - *Estimations per Vehicle*

Technology	Benefit
Eco Approach & Departure	• 5-10% fuel reduction for an uncoordinated corridor • Up to 13% fuel reduction for a coordinated corridor
Eco-Traffic Signal Timing	• 5% fuel reduction when optimizing for the environment (e.g., CO2) • 2% fuel reduction when optimizing for mobility (e.g., delay)
Eco-Traffic Signal Priority	• Eco-Transit Signal Priority provides up to 2% fuel reduction benefits for transit vehicles • Eco-Freight Signal Priority provides up to 4% fuel reduction benefits for freight vehicles

The accelerated introduction of advanced vehicle technologies will allow for mobility optimization => **advanced technologies allow us to decouple energy from mobility**

While safety benefits can be extrapolated, **energy benefits cannot be generalized as they completely depend on the network and scenario**

Limitations of Current Research – Energy Benefits

A long list of next steps has already been identified by leading researchers, focusing on:

- **Different fleet distributions** (i.e.," *More aggressive assumptions of electric and hybrid fuel vehicles could be considered in future modeling efforts*")
- **Improved algorithms** (i.e., "*Trajectory planning algorithm used to make priority determinations can be improved to better estimate the arrival time of buses at intersections*")
- **Different travel demand and traffic flow** (i.e. "*Additional modeling [for EcoSignal] could be considered on different corridor demand configurations (e.g., a corridor with higher demands on the side streets, an urban grid, etc.)*")
- **Larger networks** (i.e., "*Evaluate [benefits of connected EcoDriving] on a larger network (interconnected arterial and freeway segments)")*
- **Integration of multiple benefits** (i.e. "*Integrate modeling of the Eco-Approach and Departure Application with other Eco-Traffic Signal Applications to determine composite benefits*")

Quotes from AERIS Program Webinars

Limitations of Current Research – Energy Benefits

Energy consumption analysis

Current Research Limitations

- Vehicle energy consumption based on average values (VMT), on vehicle speed binning (MOVES) or simplified vehicle models.
- These methodologies can be limited, especially for advanced vehicles
- Connectivity (X2X) not consistently leveraged for vehicle control optimization (AERIS sponsored “glide-path” research at Turner Fairbanks)

Leveraging DOE Expertise

Leverage high fidelity vehicle simulation tool to estimate:

- Advanced control benefits
  - Include full vehicle connectivity (i.e. V2V, V2I, I2V, V2G)
  - Take into account advanced controls (i.e. trucks use variable target speeds when going up & down grades)
  - Assess route based control
- Take into account powertrain specificities (i.e. different vehicles have different optimum speeds).
- Impact on vehicle design:
  - Component downsizing (i.e., impact on battery sizing due to efficient driving)
  - Light weighting
  - Impact of aerodynamic / thermal management for platooning

Limitations of Current Research – Energy Benefits

Travel Behavior, Traffic Flow Simulation & Fleet Definition

Current Research Limitations

- Rely on microscopic traffic flow simulations (very data hungry & hard to calibrate)
- Focus on small portions of roads (i.e. urban, highway) rather than the network
- Shift in travel behavior unaccounted (i.e. multi-modal, vehicle ownership models, demographic changes…)
- Leverage today's fleet distribution for their baseline
- Estimations based today's vehicle technologies (i.e. focus on anti-idling gains)

Leveraging DOE Expertise

- Leverage mesoscopic traffic flow simulators designed for ITS
- Leverage market penetration tools to estimate future fleet distribution
- Leverage expertise to define behavioral models of individual decision-maker
- Leverage expertise to estimate increased VMT, behavioral shift (i.e. mode shift…)

In addition, several of the benefits have not been quantified (i.e., Eco-traveler information, Eco-Smart Parking, Wireless Charging…)