2020 DOE Vehicle Technologies Office
Annual Merit Review

CIRCLES: Congestion Impacts Reduction via CAV-in-the-loop Lagrangian Energy

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June 2, 2020

Project ID: eems0083

Overview

Timeline

Start: January 1, 2020

End: December 31, 2022

15% Complete

Partners

Project Lead: UC Berkeley

- Rutgers University Camden
- Temple University
- Tennessee DOT
- University of Arizona
- Vanderbilt University

Industry Partner: Toyota

Barriers

- Rapid evolution of vehicle technologies and services enabled by connectivity and automation
- Accurately measuring the transportation system-wide energy impacts of connected and automated vehicles

Budget

Total Project Funding:

DOE: $3.5M / 3 years

CS: $1.5M / 3 years

Total FY2020 Funding: $1.7M

Relevance - Project Objectives

Overall Objective:

To develop and demonstrate AI and control algorithms that smooth traffic flow in stop-and-go traffic conditions capable of providing ≥10% energy savings

Objectives this period:

To achieve ≥10% energy saving traffic smoothing in simulation

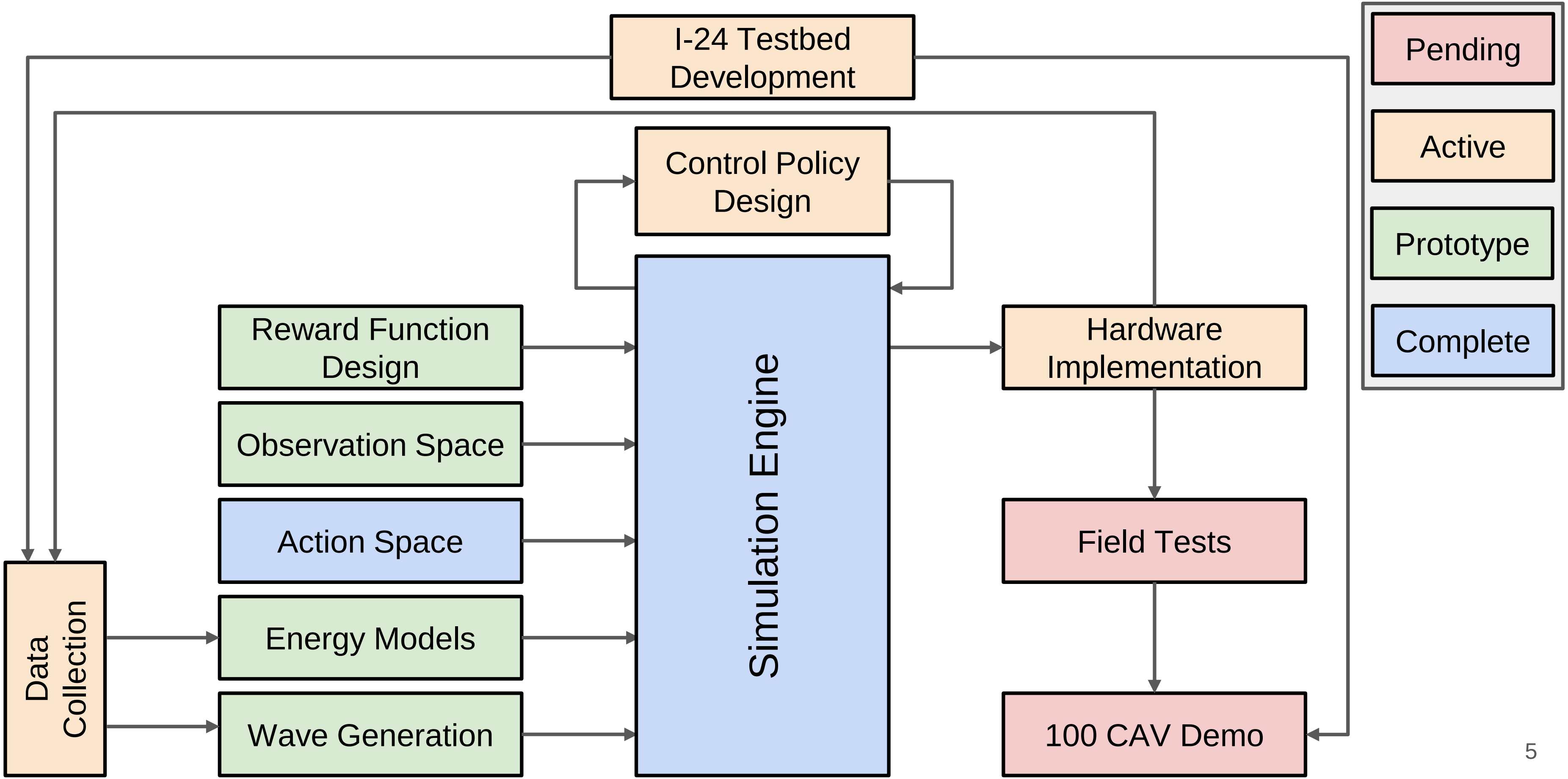
Impact:

- Enables the use of a few CAVs to save system-wide energy
- Advances CAV technology
- Directly facilitates system-wide energy measurement

Milestones

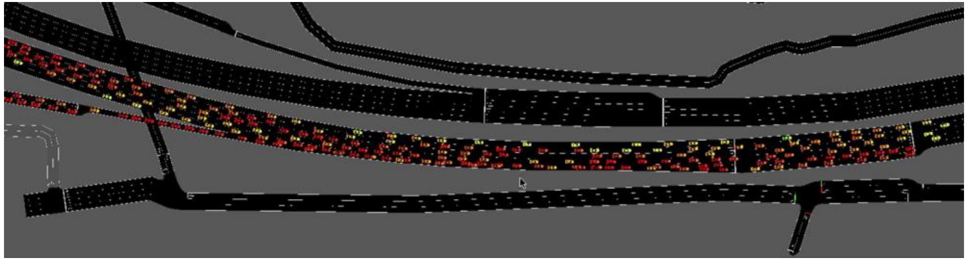
Year	Milestone	Status
2020	Computer vision tracking algorithm implemented	On track
2020	Reduced energy models from industry partners developed and made compatible with macroscopic traffic model framework	On track
2020	Control algorithm for large scale vehicle coordination validated and working in simulation	On track
2020	Stop-and-go traffic data collected via CAV vehicle	On track
2020	**Go/No Go:** Control algorithm demonstrates positive energy reduction at modest penetration rate in simulation	On track
2021	Successful calibration of the model and control algorithm over the demonstration site	Pending
2021	Prototype control algorithms implementation on small-scale vehicles safely executed on demonstration site	Pending
2021	Energy models validated	Pending
2021	**Go/No Go:** Medium-scale car test executed with computer commands	Pending

Components of the Approach



Technical Accomplishments and Progress:
Traffic Network Modeling

Goal: to develop simulation network with realistic demand and wave formation/propagation



https://youtu.be/GkDGHXNIssU

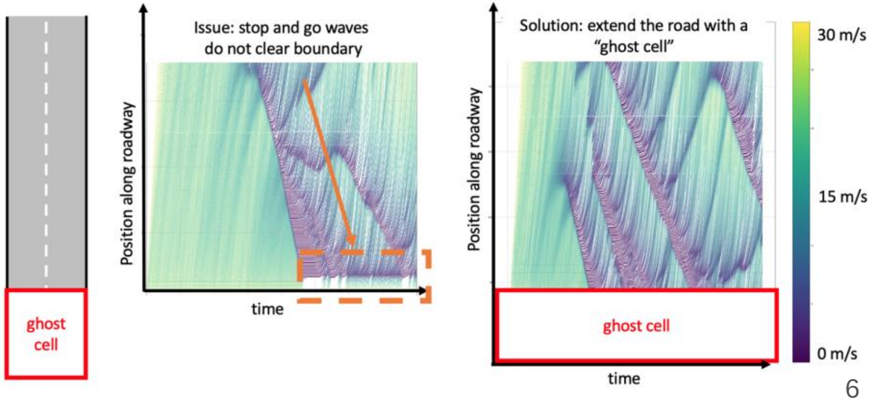
Progress: implemented I-210 model

Related accomplishments:

- Calibrated demand with loop data
- Seed wave formation with acceleration noise
- Implemented ghost cell as temporary fix for standing wave at boundary
- Ongoing development of I-24 model with road grade

In Progress (to improve model quality)**:**

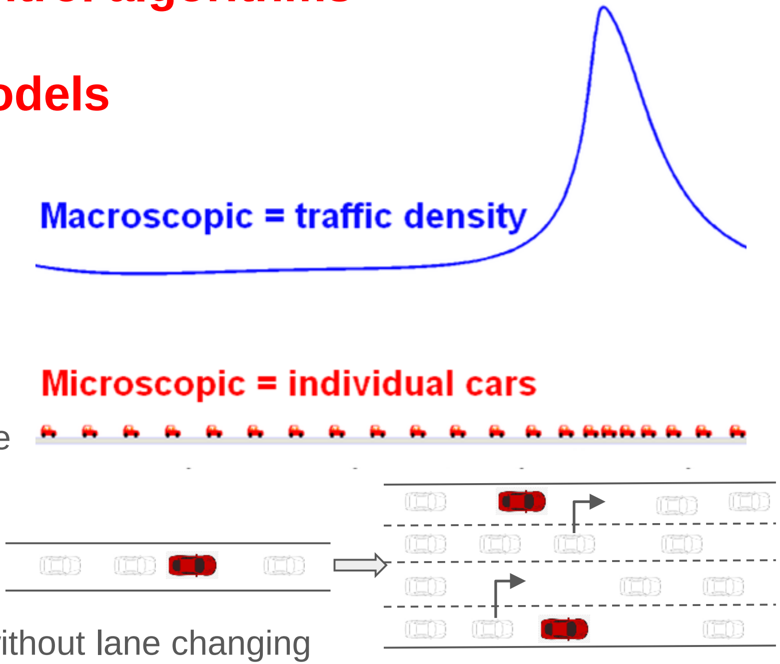
- Upgrade car following model to respond to road grade
- Alternate strategies for standing wave at boundary
- Develop diagnostic tools for assessing realism
- Calibrate on- and off-ramp demand for I-24 model
- Integrate new lane-changing model



Technical Accomplishments and Progress:
ODE/PDE & Mean-Field Models

Goal: to design robust and theory-based control algorithms

Progress: designed relevant traffic macromodels



Accomplishments:

- Two macromodels
  - A wave based ODE/PDE with relevant AV-traffic interactions
  - A mean-field model, limit of microscopic model, showing effects of AV and lane-changes at macroscale
- First control strategy on wave-based model

Next steps:

- Find traveling wave profiles for the mean-field model with / without lane changing
- Derive control strategies to smooth waves for the mean field model and algorithms from both models
- Design optimal control problems to the mean-field model, Derive optimal control algorithms

Goal: formulate an energy model portfolio compatible with the simulation and data framework of this project

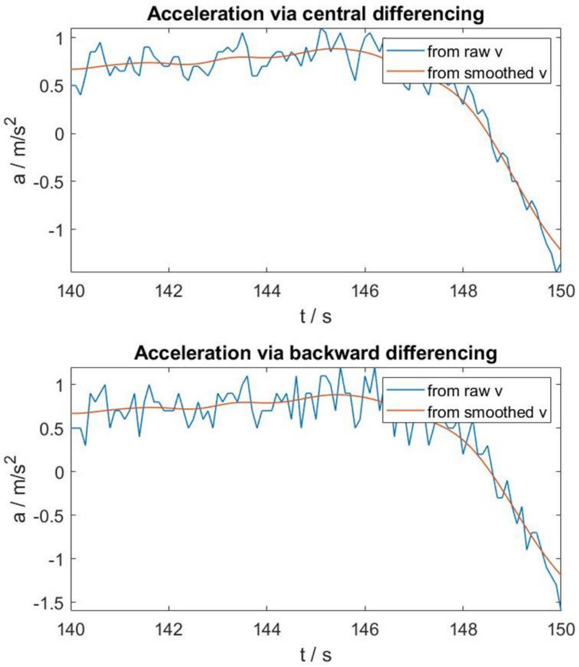
Progress: reduced models from Toyota; incorporated into software pipeline

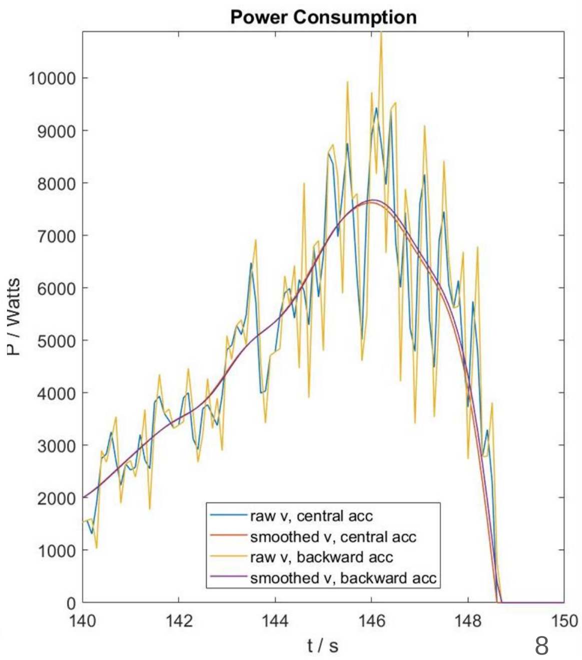
Accomplishments:

- Model reduction of Toyota models (averaging away unknown quantities: SOC, gear, etc.)
- Incorporated baseline power demand model and two Toyota models (combustion, electric) into Flow
- Initiated data pipeline for automatic robust post-processing of energy models within noisy simulation data

Next steps:

- Work with Toyota on further energy models
- Integrate energy modeling workflow into Flow (including useability in RL reward modeling)

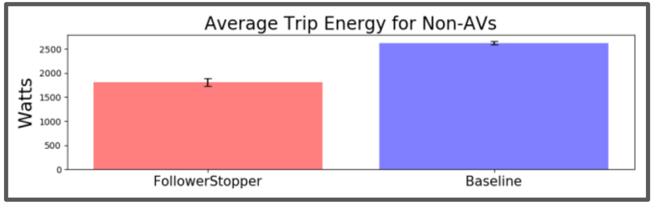




Technical Accomplishments and Progress:
Reinforcement Learning Control Algorithms

Goal: **design RL algorithms capable of saving energy**

Progress: **implemented & testing six different approaches**



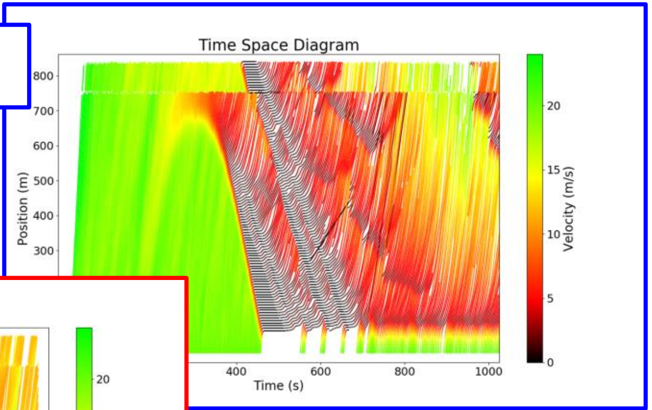
Accomplishments:

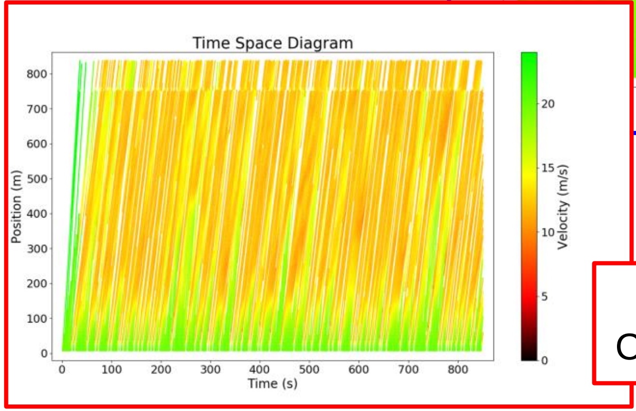
- Implemented single-agent, multi-agent, and hierarchical RL strategies
- Some preliminary controllers able to dampen waves (e.g. time-space diagrams on right)

Next steps:

- Reward function design utilizing energy models
- Implement observation space correspond-ing to real hardware specification
- Continue to decrease penetration rate while maintaining wave reduction

Baseline





FollowerStopper Controller @ 12 m/s

Technical Accomplishments and Progress:
Traffic Data Collection

Total Collected: 871 miles, 30GB

Estimated Stop-and-Go Miles: 50-100

Related accomplishments:

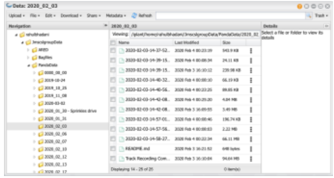
1. Have 4 available vehicles for data collection
2. Automatic data collection scripts
3. Data uploaded to CyVerse (cyverse.org)
4. Decoding techniques for lead vehicle distance/velocity, engine RPM

In Progress:

1. Automatic metadata extraction from data based on input parameters
2. Automatic data upload at end of data collection trips
3. Further CAN message decoding for vehicle states of interest for control algorithms and energy consumption

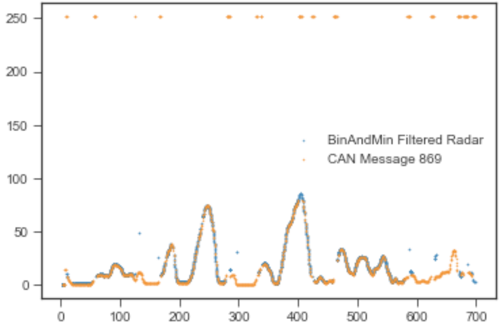
RPM Over Time

CyVerse Discovery Environment



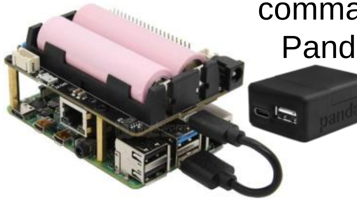
3x Toyota Rav4, 1x Camry

Lead Vehicle Distance



Hardware

comma.ai Panda



Raspberry Pi 4 w/Power

Technical Accomplishments and Progress:
Testbed Development

Goal: to build I-24 phase-1 sensor network

- 18 4K resolution video cameras
- 110’ mounting position
- 1600 ft of continuous video coverage

Progress: construction on track for Fall 2020

- TDOT finalizing engineering design for poles and site
- Camera mount, lowering device, and network layout finalized

110’ pole with six 4K cameras

18 camera network built by Fall 2020

Technical Accomplishments and Progress:
Computer Vision Tracking Algorithm

Goal: to develop vehicle tracking algorithms for continuous data extraction

- Capable of tracking 180k+ highway vehicles per day
- High-accuracy vehicle trajectory data possible with 4K resolution cameras

Progress: prototype tracking algorithm developed, under continued improvement

- Preliminary algorithms published at *Design Automation for CPS and IoT* (DESTION 2020) at CPSWeek 2020
- Processed data achieves 10% of milestone data volume
- Continuing refinement of algorithm pipeline and individual vehicle trajectories

https://youtu.be/XKXKmtgp9-M

Response to Previous Year Reviewers' Comments

Not applicable. This is the first year this project has been reviewed.

Collaboration and Coordination

Partner	Relation	Type	Extent of Collaboration
University of California, Berkeley	Prime	Univ.	PI Bayen and researchers at UC Berkeley provide expertise in reinforcement learning applied to microsimulation. Researchers also support efforts at other campuses, including energy modeling, hardware, and mean-field models.
Rutgers University Camden	Sub	Univ.	Co-PI Piccoli and researchers at Rutgers develop of control algorithms for microscopic, macroscopic, multiscale and mean-field models; researchers also contribute to the development of simulation models exhibiting realistic and stable traffic waves.
Temple University	Sub	Univ.	Co-PI Seibold oversees work in the area of energy modeling and co-leads (with Co-PI Work) the research effort of developing microsimulation models that reproduce realistic traffic flow instabilities and waves.
University of Arizona	Sub	Univ.	Co-PI Sprinkle and researchers at Arizona work in the area of hardware interfacing, software drivers and recording, and vehicle platforms and integration. Researchers are responsible for prototyping the hardware interfaces to be used by high-level controllers.
Vanderbilt University	Sub	Univ.	Co-PI Work oversees I-24 testbed planning and construction; he and Vanderbilt researchers develop vehicle tracking algorithms for trajectory extraction, implement microsimulation models for traffic flow with instabilities, and work on instrumentation of test vehicles.
Tennessee DOT	Sub	Gov’t	Tennessee DOT is working on the development of the I-24 testbed.
Toyota	Partner	Industry	Toyota’s role includes, but is not limited to, providing vehicle energy consumption models, vehicle interfacing expertise, and financial support.

Remaining Challenges and Barriers

- Good controllers may not only improve energy efficiency of traffic, but actually improve road throughput — thus inducing fundamental policy questions.
- Non-convex energy functions of combustion engines $\Longrightarrow$ Energy-optimal controllers may yield non-intuitive driving. Compromises needed.
- Energy models and controllers needed that are robust w.r.t. uncertainties in data (on-vehicle, camera, etc.).
- Research challenge: Advance non-equilibrium traffic flow theory to develop microsimulation models that can correctly reproduce traffic waves.
- Research challenge: Calibrating microsimulation models to real traffic instabilities/waves. So far, dampening these features only proof-of-concept.
- Research challenge: Method to automatically detect and process stop-and-go traffic characteristics from hours of collected driving/traffic data.
- Research challenge: Algorithmic enhancements to improve speed and accuracy of the computer vision algorithms

Proposed Future Research - FY 2020

Milestone 1.1

- Installation of first set of high-res cameras slated for August 2020
- Continue development of computer vision tracking algorithms

Milestone 1.2

- Continue understanding and adding energy models to inventory

Milestone 1.3

- Continue refining control algorithms and reward/penalty function designs

Milestone 1.4

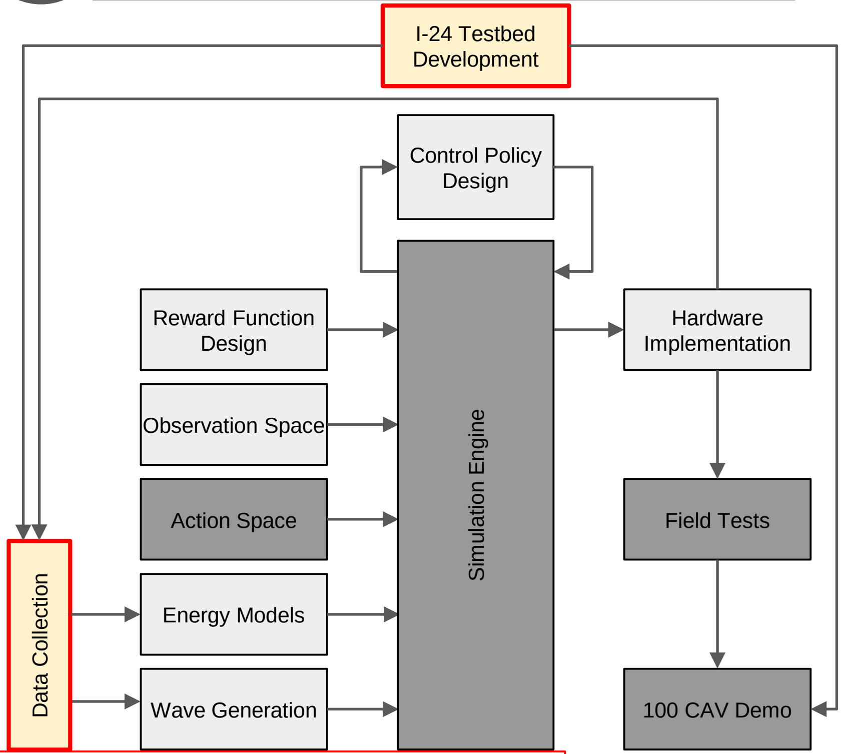
- Continue traffic data collection via CAV
- Develop traffic data analysis methodology

Milestone 1.5

- Improve simulation boundary conditions
- Development of analysis/visualization tools for traffic simulation validation

1.1

Milestone 1.1: Computer vision tracking algorithm implemented



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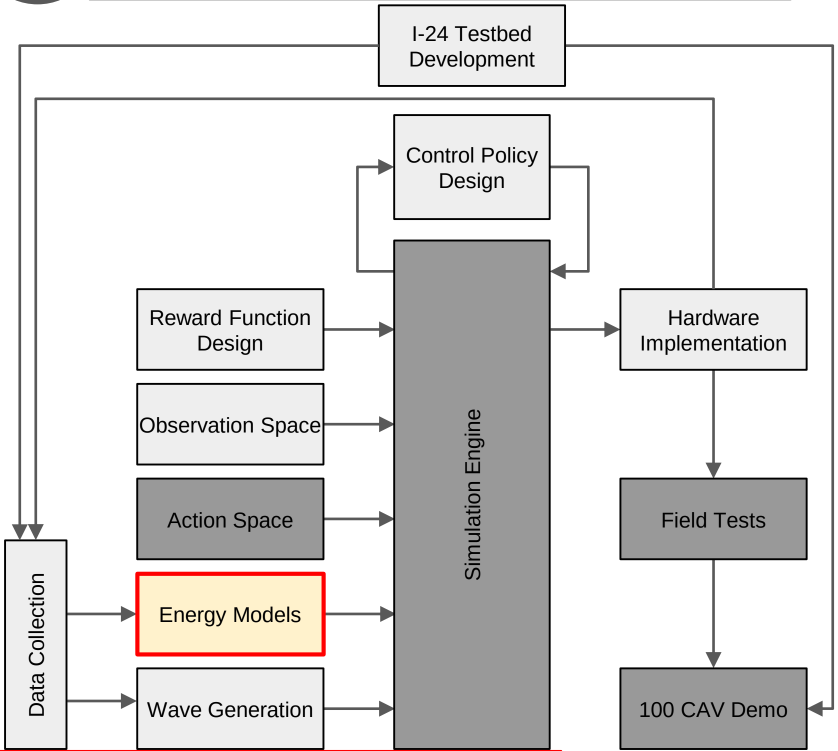
1.2

Milestone 1.2: Reduced energy models from industry partners developed and made compatible with macroscopic traffic model framework



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Proposed Future Research - FY 2020

1.3

Milestone 1.3: Control algorithm for large-scale vehicle coordination validated and working in simulation

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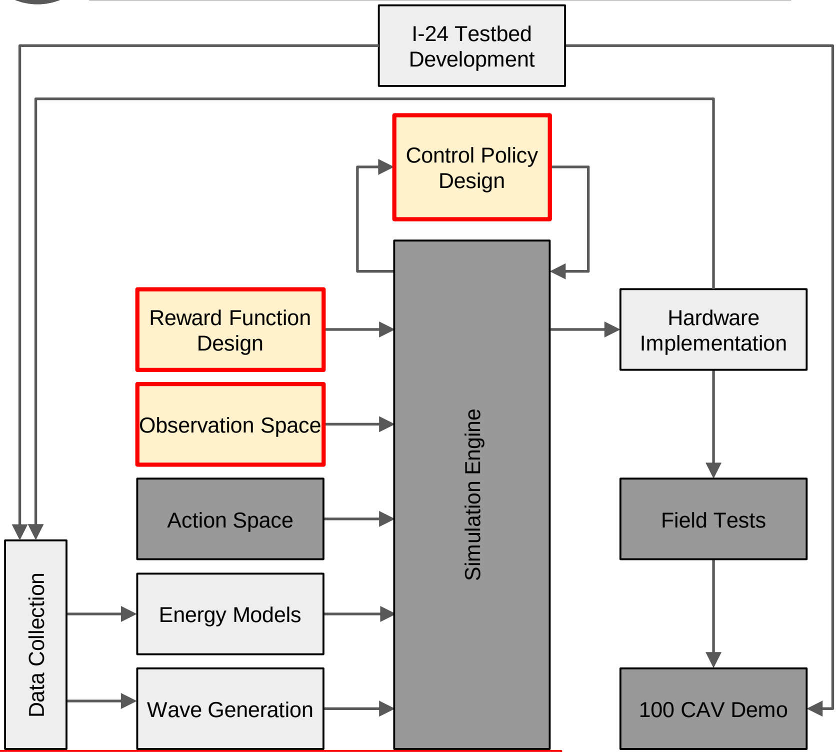

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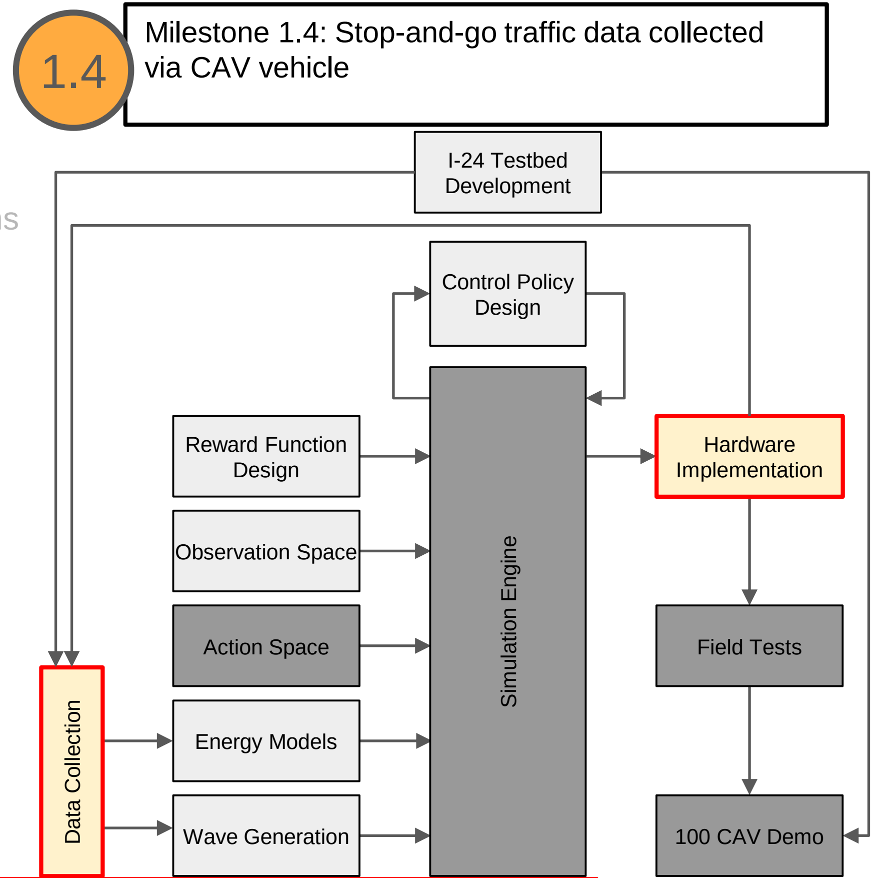

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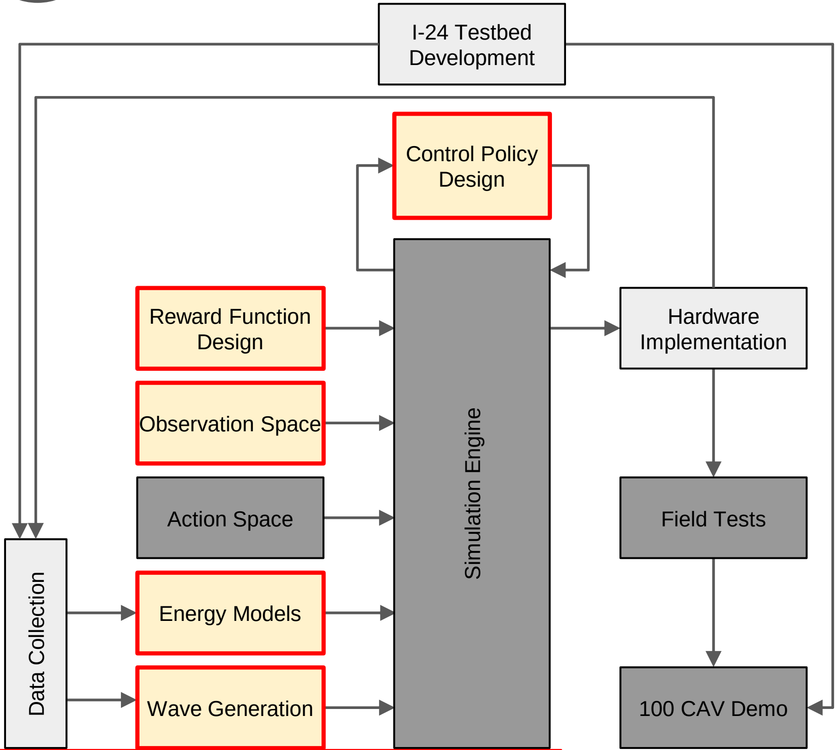
Milestone 1.5: Control algorithm demonstrates positive energy reduction at modest penetration rate in simulation



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Proposed Future Research - FY 2021

Milestone 2.1

- Calibration of simulation models and control algorithms with collected data

Milestone 2.2

- Transfer prototype control policies to hardware
- Execute small scale field test
- Confirm physical effects as expected

Milestone 2.3

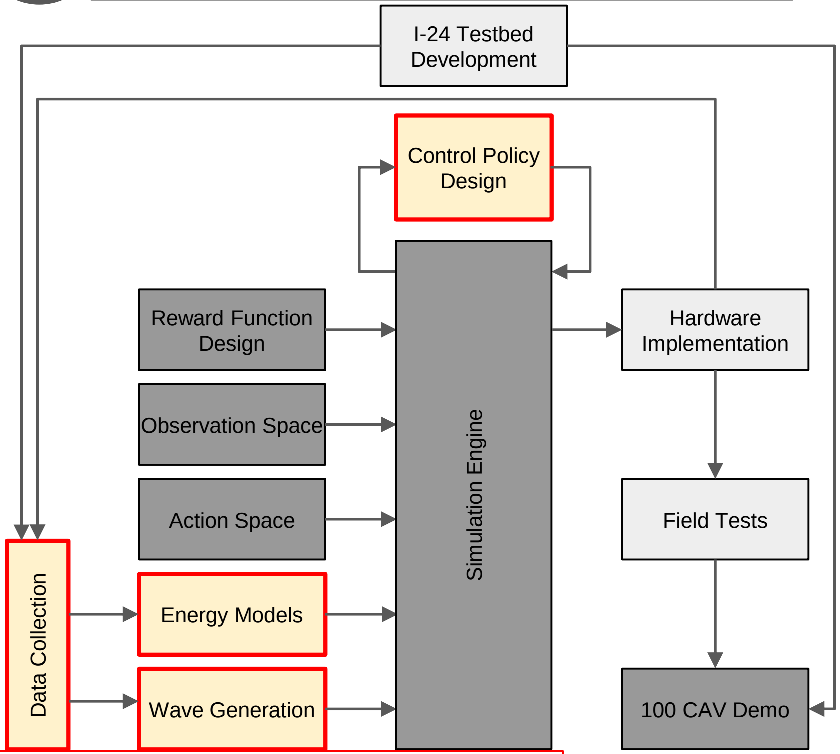
- Develop aggregate energy model from inventory
- Validate energy model against collected datasets

Milestone 2.4

- Transfer updated control policies to hardware
- Execute medium scale field test
- Confirm 10% energy savings are feasible

2.1

Milestone 2.1: Successful calibration of the model and control algorithm over the demonstration site



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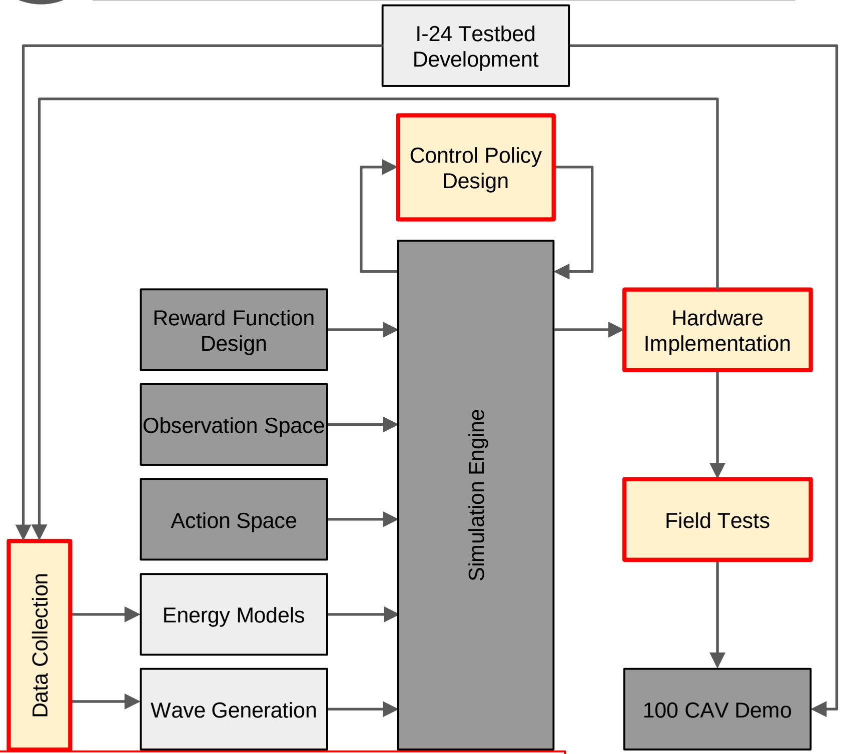
Milestone 2.2: Prototype control algorithms implementation on small-scale vehicles safely executed on demonstration site



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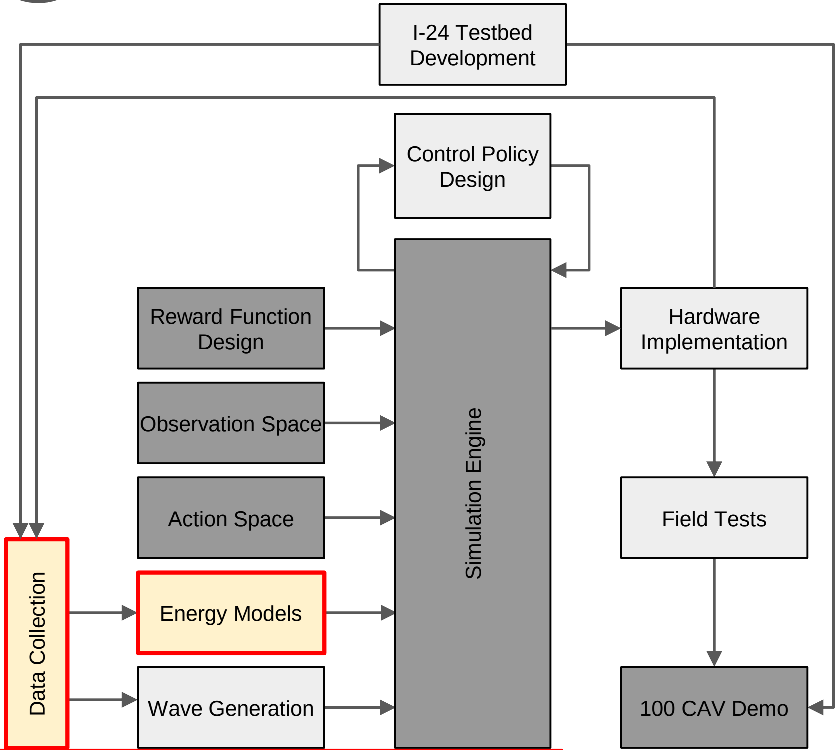
2.3

Milestone 2.3: Energy models validated



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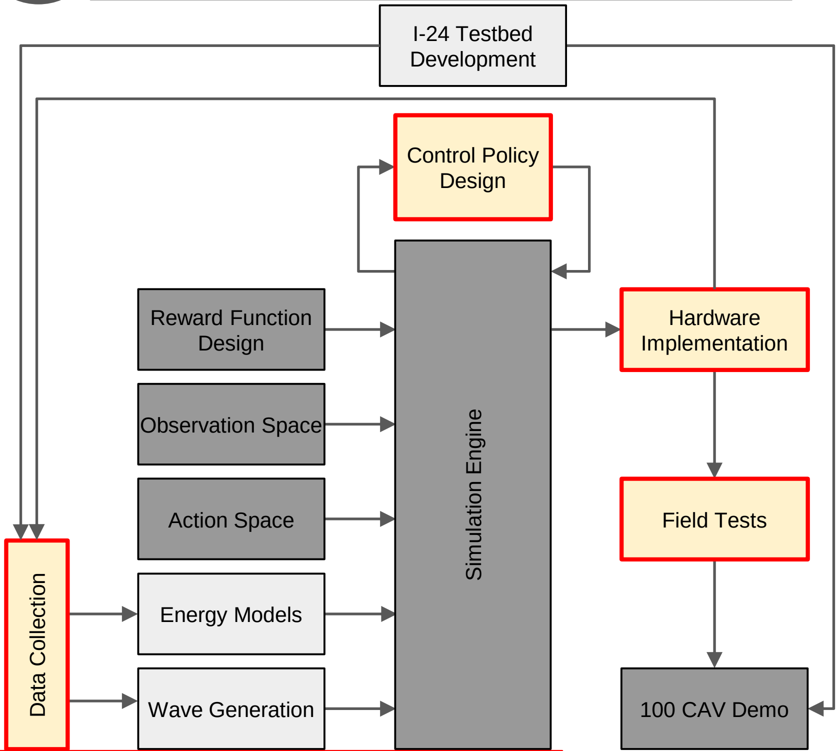
2.4

Milestone 2.4: Medium-scale car test executed with computer commands



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Summary

- Task force assembled to generate waves in simulation environments
  - Various environments developed; developing analysis tools
- Multiple control algorithms to smooth waves and save energy
  - Algorithms span classical control and RL-trained; need to experiment with reward function
- Working weekly with Toyota to expand energy model inventory
- Most essential CAN bus messages decoded
- Designed vehicle interfacing using comma.ai
  - Collected 800+ miles of driving data; need to standardize analysis to filter for stop-and-go
- Prototype computer vision tracking algorithm implemented
- First 18 camera network going up in Fall 2020

Technical Backup Slides