Project ID: EEMS040
Pillar: AFI

U.S. DEPARTMENT OF ENERGY
SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

Dynamic Wireless Power Transfer Feasibility

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Oak Ridge National Laboratory
2019 Vehicle Technologies Office Annual Merit Review
June 11, 2019

Argonne National Laboratory · INL Idaho National Laboratory · Berkeley Lab · Oak Ridge National Laboratory · NREL National Renewable Energy Laboratory

OVERVIEW

Timeline

- Start – 10/01/2016
- End – 09/31/2019
- Percent complete: 65%

Budget

- Total funding $705k
  - 100% DOE
- Funding received in FY17: $235k
- Funding received in FY18: $235k
- Funding for FY19: $235k

Barriers / Challenges

- Complexity of large-scale integrated transportation networks that this technology will be applied to.
- Accurately measuring the transportation system-wide energy impacts of connected and automated vehicles
- Difficulty in sourcing empirical real-world data applicable to new mobility technologies such as connectivity and automation

Partners

- ORNL (Project lead)
- NREL
- INL

RELEVANCE

- Relevance
  - This task aims at developing new tools (dynamic wireless power transfer optimization model), techniques, and core capabilities to understand and identify the most important levers to improve the energy efficiency and productivity of future integrated mobility systems.
  - Promoting connected and automated vehicle (CAV) technology with automated refueling process.
  - Identify & support dynamic wireless power transfer (DWPT) systems as an early stage R&D to develop innovative approaches that enable energy efficient future mobility systems.
  - Utilize DWPT technology to refuel ride-shared vehicles or commercial fleets on-the-go with charge sustaining operation without any down time (providing high utilization factor for this capital cost intense technology).
  - Share research insights and findings to support energy efficient local and regional transportation systems.
- Outcome
  - The outcome of this task is to produce a design guideline applied to an example test case scenario for the optimal deployment of DWPT systems to support future roadway and electric power infrastructure planning.

MILESTONES

- **December 2018 (Q1):** Expand the vehicle energy consumption level analysis for connected and automated vehicles taking their vehicle specifications and auxiliary power consumption levels into account **(completed).**
- **March 2019 (Q2):** Grid requirements analysis of the DWPT systems considering multiple vehicles on route **(completed).**
- **June 2019 (Q3):** Identify multiple future scenarios and develop framework to identify optimum DWPT system designs, locations, and grid interfaces. Also analyze the impact of DWPT systems and architectures in advanced scenarios (including interference on CAVs, control mechanisms with track vs. coil approaches, vehicle detection systems, etc.) **(on track).**
- **September 2019 (Q4):** Expand the DWPT optimization analysis to include real data collected from operational connected and automated ride-shared vehicles for dynamic wireless power transfer feasibility analysis. Use WPTSim tool for optimal DWPT system deployment scenarios **(on track).**

APPROACH

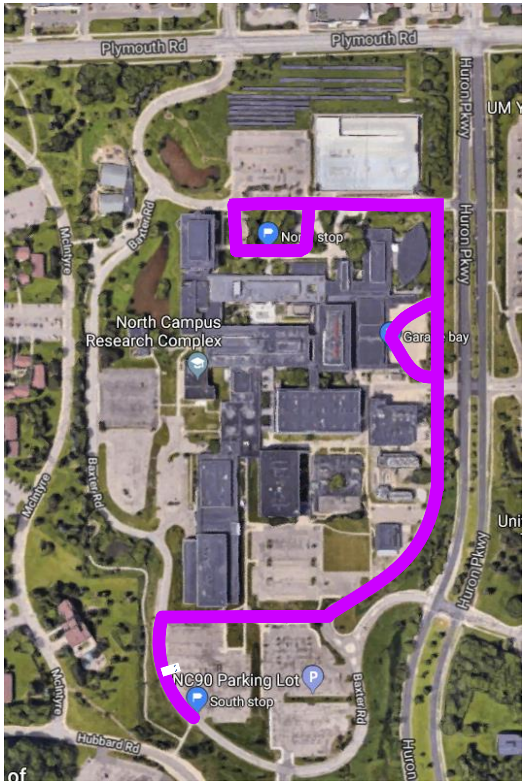
- **Approach**
  - Characterize vehicle energy consumption levels for automated vehicles based upon drive cycle and traffic constraints for possible deployment scenarios.
  - Create an optimization framework for optimal sizing and placement of the DWPT system.
  - Define grid requirements considering the grid impact of the DWPT systems with commonly used power distribution networks through test scenarios.

- **Overall Objective**
  - Investigate the feasibility of dynamic wireless charging systems for their infrastructure requirements and key deployment design parameters.
  - Generate an optimization framework and algorithms to optimize the dynamic wireless power transfer electrified roadway sections in terms of power levels, vehicle battery impact, and section lengths.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Energy Consumption Analysis of CAVs

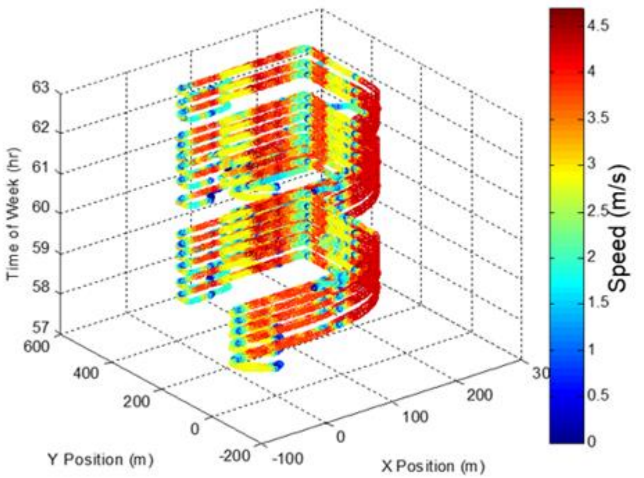
- Team investigated the energy consumption levels of connected and automated ride-shared vehicles on real-world routes in order to initiate the updated design of dynamic wireless power transfer systems.
- According to preliminary analysis, for low speed shuttles (15-25), the energy consumption varies from 0.24 miles/kWh (Navya at 15 mph) to 0.37 miles/kWh (Local Motors Olly at 15-20 mph).
- Therefore, for a given duty cycle or miles per day use and the route, dynamic wireless charging systems can be optimized for maximum range extension or charge sustaining operation.
- Consumption levels are being validated using the real-world use of Navya automated shuttles operational in M-City at the University of Michigan, Ann Arbor.

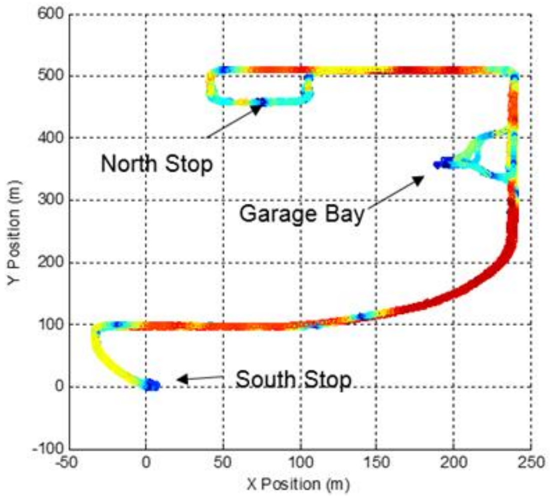
Actual route of the M-City Navya automated shuttle on Google Maps



TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Energy Consumption Analysis of CAVs

- The level-2 charger of the Navya vehicle is instrumented on the AC grid side to analyze the vehicle charge power and energy.
- Vehicle travelled 19 miles daily on average and used about 34 kWh from the AC terminals of the plug-in charger.
- Assuming 90% on-board charger efficiency from grid to the vehicle battery terminals, vehicle receives 30.6 kWh of charge power going into the battery.
- Therefore, vehicle consumes about 0.62 kWh/mile on this route which is higher than the manufacturer claimed energy use possibly due to loaded passengers, use of air conditioner, and the energy use of other CAV specific components.



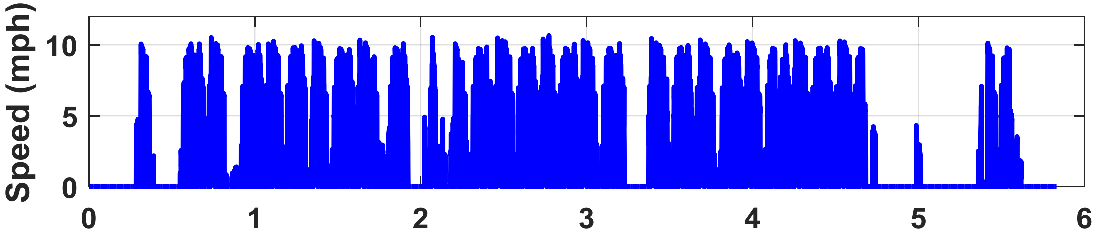


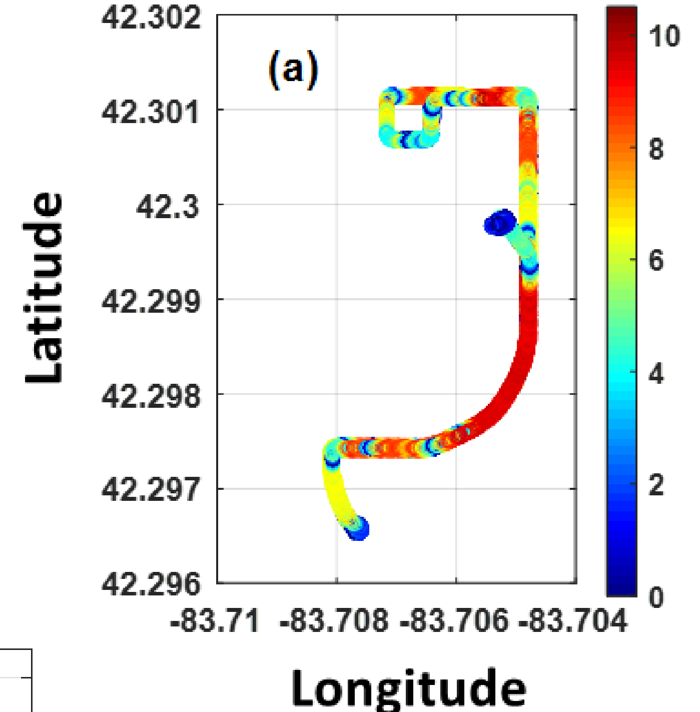
Speed and route data for the Navya automated shuttle operating in M-City

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Energy Consumption Analysis of CAVs

- 2 circulator fixed-route autonomous shuttles (Navya Arma)
- Data for July 16, 17, and 19 are collected and analyzed
- GPS data (speed, latitude, longitude)
- Energy consumption on AC side (AC kWh/mile)

A typical speed profile for Navya automated electric shuttle





A typical route profile for Navya automated shuttle

U.S. DEPARTMENT OF ENERGY SMARTMOBILITY Systems and Modeling for Accelerated Research in Transportation

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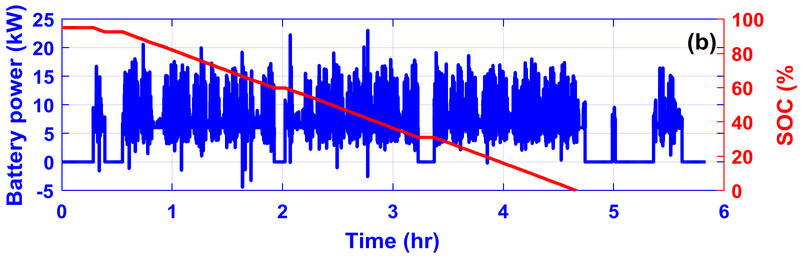
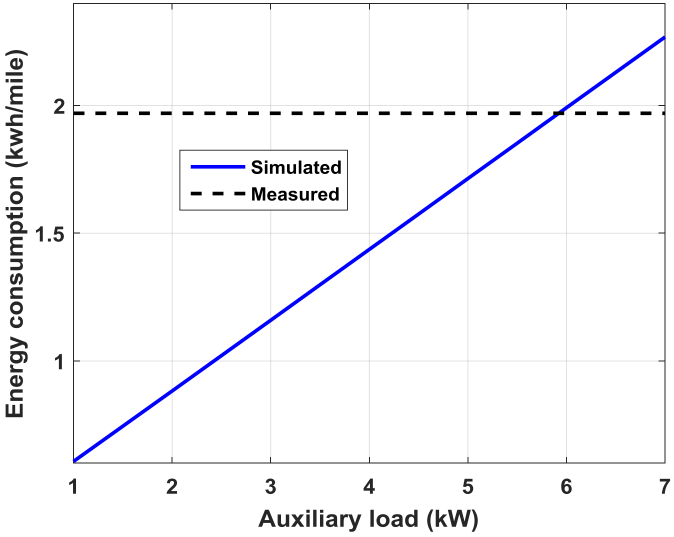
TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Energy Consumption Analysis of CAVs

- Auxiliary loads are analyzed to match the measured values (simulated auxiliary loads for up to 7 kW)
- Considering ~90% efficiency for the on-board charger, the auxiliary loads are then around ~6 kW.
- Results show that automated shuttle can drive for 5 hours continuously with around 16 miles range.
- With on-route dynamic wireless charging infrastructure, vehicle can be operated in charge sustaining mode or with significant range extension.

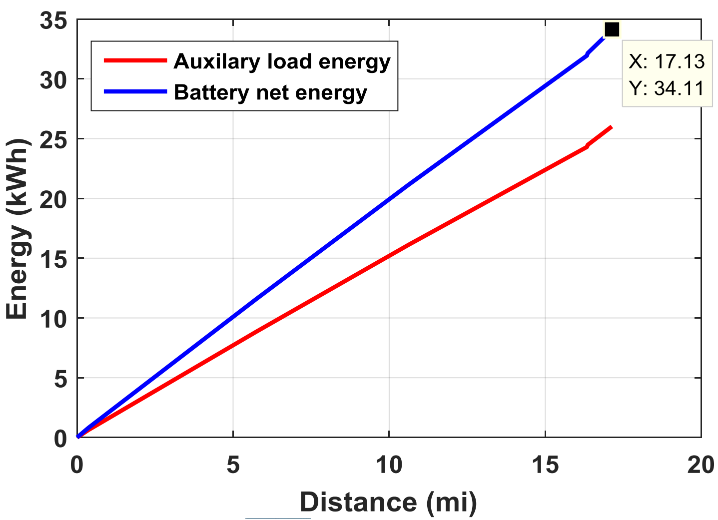


Driving performance considering 6 kW aux. load



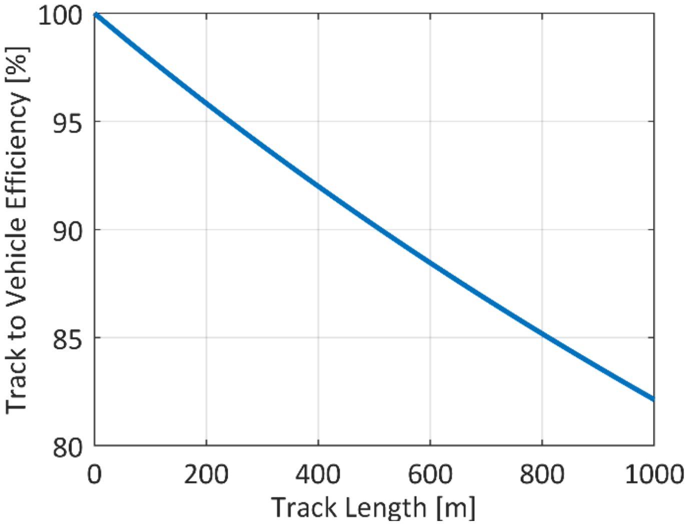
Auxiliary load analysis; at 6 kW measured energy consumption matches the simulated

Energy profiles considering 6 kW auxiliary load

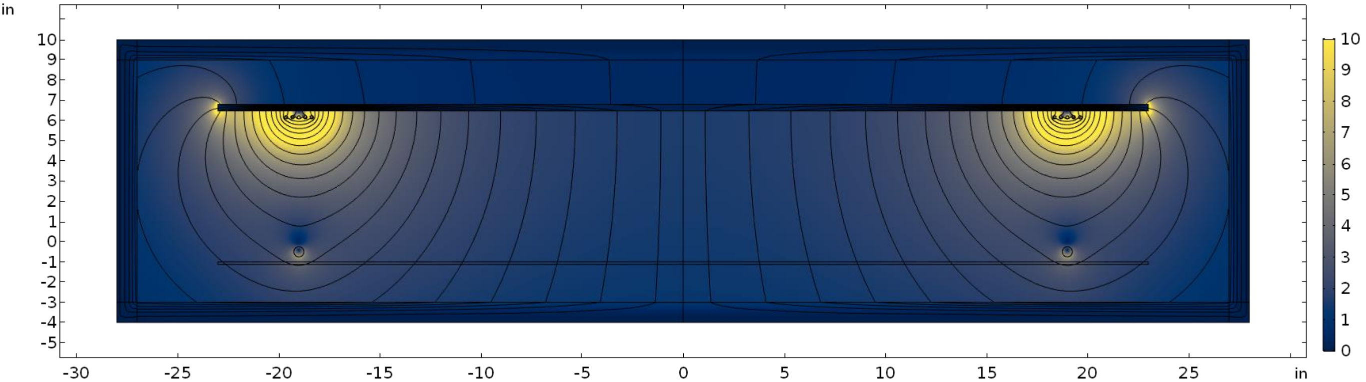


TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Analysis of Power Transfer Characteristics

- Computing track-to-vehicle efficiency
- Finite Element Analysis (FEA) validation of the previous assumptions on power transfer profile, trapezoidal variation of power transfer and mutual inductance.
- Verified power transfer continuity along the track designed for 100kW power transfer.
- Analyzed for a ferrite-free track
- Track-to-vehicle efficiency as a function of the track length



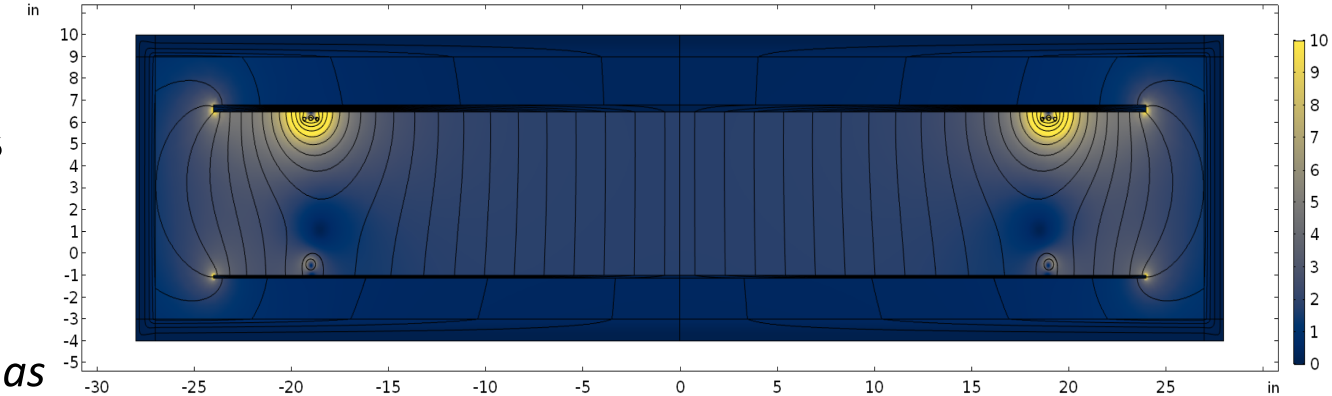
Track-to-vehicle efficiency as a function of the track length for a ferrite-less design



FAE model of the DWPT system

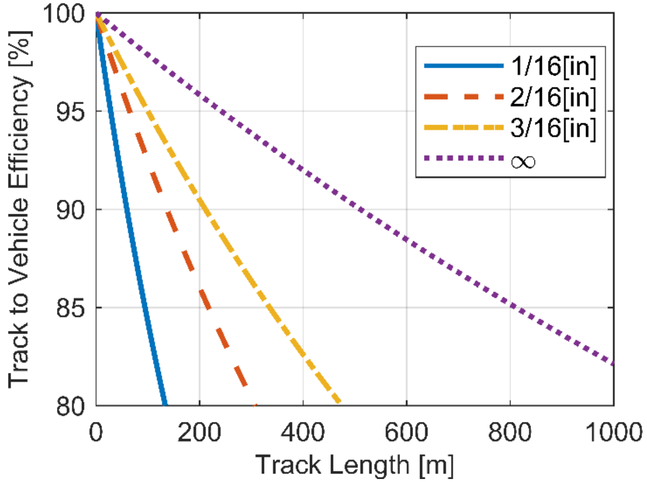
TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Analysis of Power Transfer Characteristics

- Analysis repeated for a 100kW track designed with ferrites

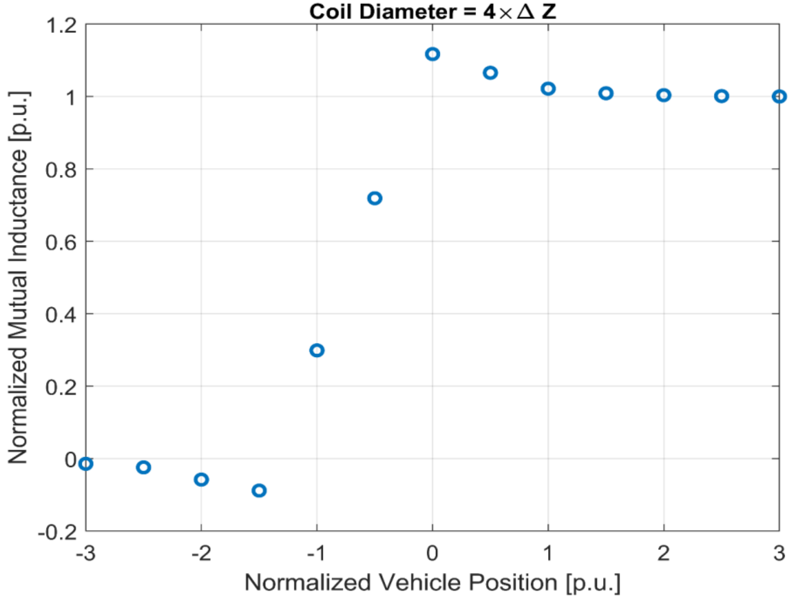


FAE model of the DWPT system

Track-to-vehicle efficiency as a function of the track length for a track with ferrites



Mutual inductance profile as a function of the relative vehicle position



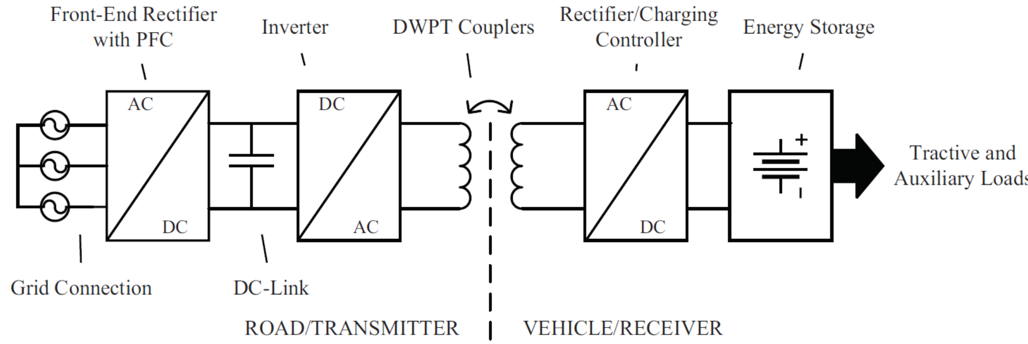
TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Grid Impact and Requirements Analysis for DWPT Systems

- Evaluated the impact of DWPT systems on the power grid using electromagnetic transient studies → Identifying infrastructure requirements (stability, voltage variations, etc.).
- For the DWPT models, the DWPT system requirements were quantified based on the charge-sustaining mode of operation for the vehicles.
- Road electrification data:

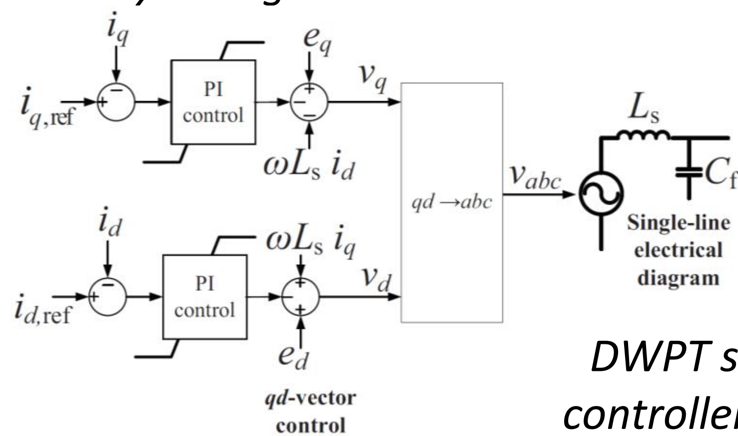
Parameter	Value/Information
Route distance	30 miles
Vehicle type on road	Light-duty
Speed of vehicles	70 MPH
Vehicle length	16’ each
Distance between vehicles	4×16’
Penetration of EVs	100 %
Coil / Track length	8’

- 50% roadway coverage of 82.5kW DWPT systems

Case study for smart autonomous highway with DWPT



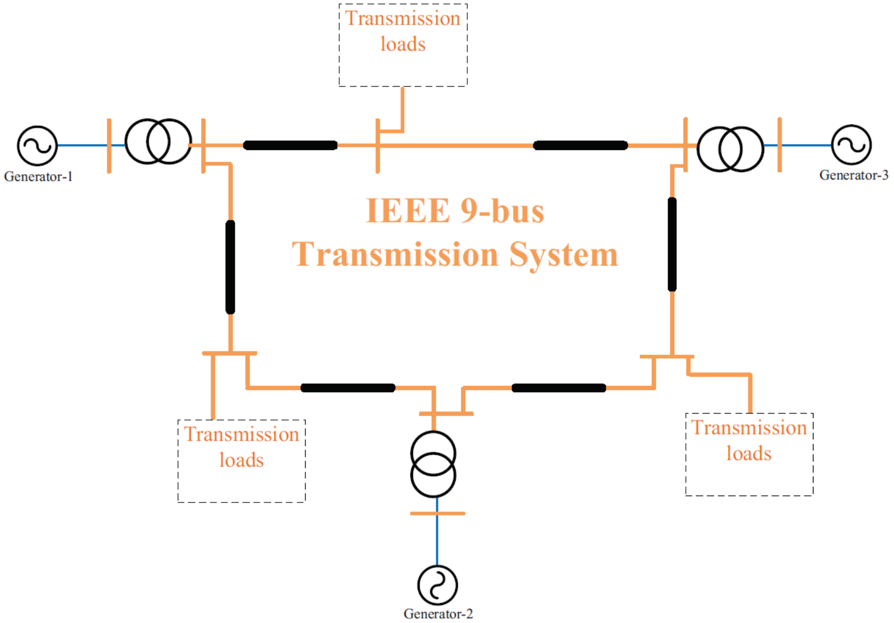
DWPT system grid interconnection scheme



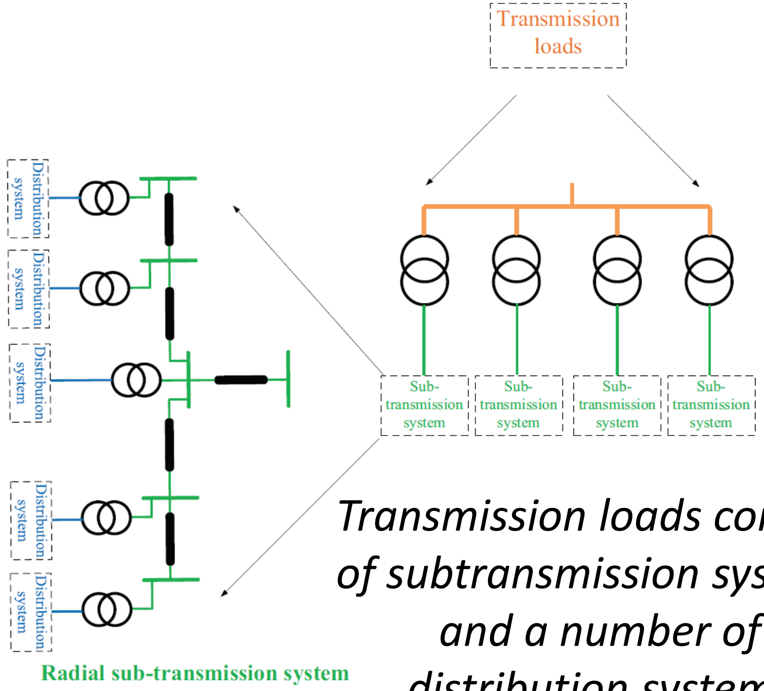
DWPT system controller model

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Grid Impact and Requirements Analysis for DWPT Systems

- For the analysis, the standard IEEE 9-bus 3-generator, 230 kV transmission system is used.
- The power system is super-imposed over the considered 30 mile road section with DWPT loads.



IEEE 9 bus system feeding transmission loads

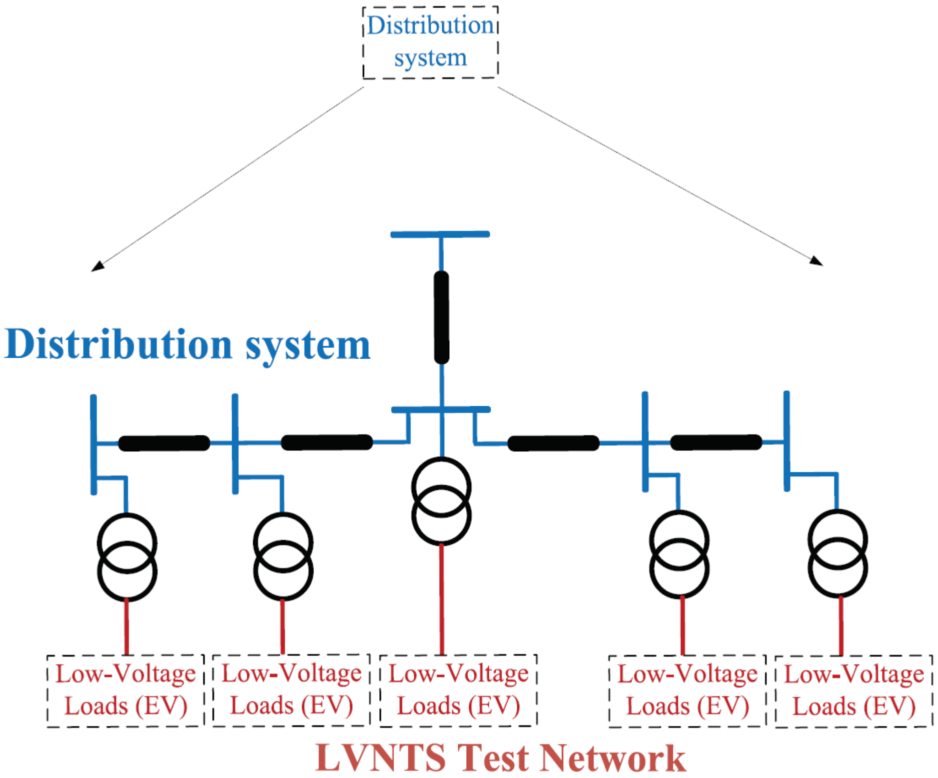


Transmission loads consists of subtransmission systems and a number of distribution systems

- The three load buses in the IEEE 9 bus system are converted to detailed subtransmission (5 node 4.16 kV) – distribution – low voltage grid and DWPT system loads.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Grid Impact and Requirements Analysis for DWPT Systems

- Scenario 1: Each node in the distribution system is connected to 8 active DWPT systems connected to 480V low-voltage networked test system.

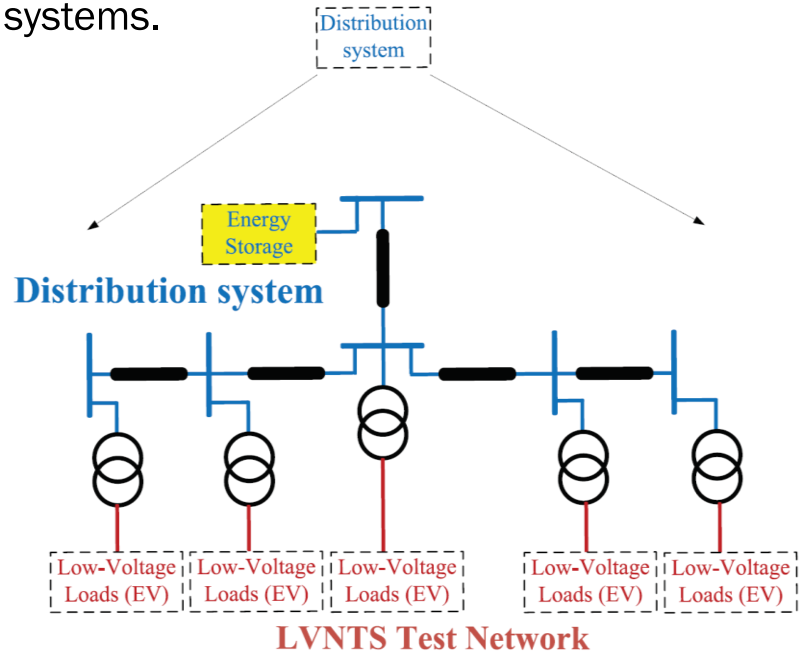


- With each active DWPT system rated at 82.5 kW, the low-voltage system processes a maximum of 660 kW based on the vehicle penetration.
- The low-voltage system transformer is rated at 1 MVA 4.16 kV/ 480 V.
- The distribution transformer is rated at 6 MVA 32 kV/ 4.16 kV, and the sub-transmission transformer is rated at 25 MVA 230 kV/ 32 kV.

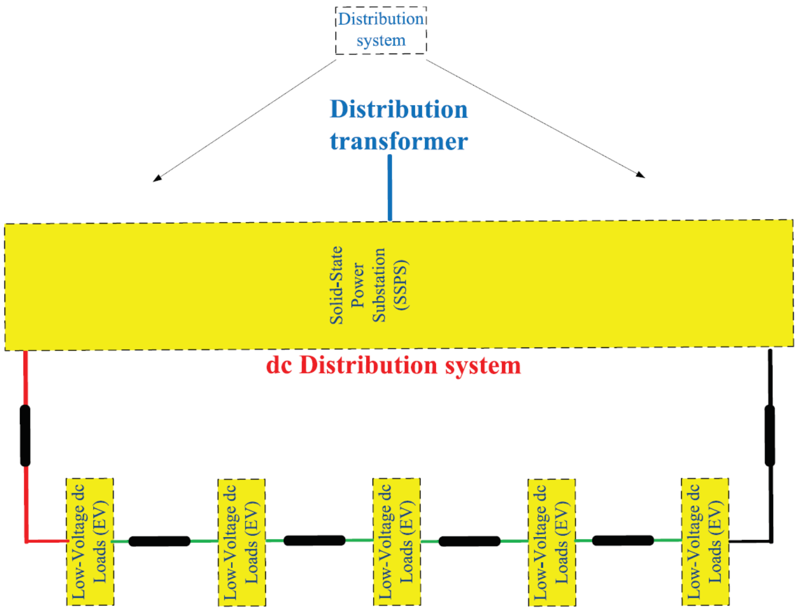
Grid infrastructure to support DWPT systems (Scenario 1, distribution and low-voltage systems)

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Grid Impact and Requirements Analysis for DWPT Systems

- In Scenario-2, distributed energy storage is connected to the secondary side of the distribution transformer to avoid the pulsating DWPT system power being transferred to the distribution and sub-transmission systems.
- In Scenario-3, a DC infrastructure is considered to reduce the voltage variation without including energy storage. Solid-state transformer converts 4.16 kV AC to 8 kV DC, feeding 40 active DWPT systems.



Distribution system with distributed energy storage system (Scenario-2)



DC distribution system with solid state transformer (Scenario-3)

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Grid Impact and Requirements Analysis for DWPT Systems

- In Scenario-1, there are two studies performed:

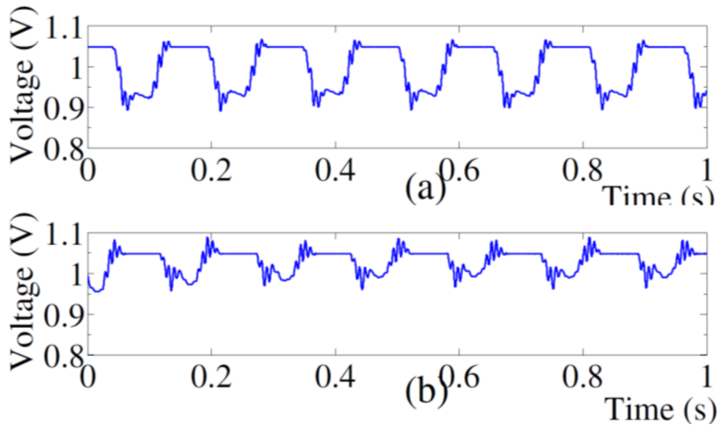
(i) DWPT system connects to the basic infrastructure, and

(ii) DWPT system consists of smart inverters that can provide Volt-VAr support to the basic infrastructure.

- Similar studies are performed in Scenario-2 with non-smart and smart inverters considered connected to the energy storage.
- The final study is performed on Scenario-3 with dc distribution infrastructure.
- The normalized voltages at the sub-transmission buses are analyzed.

(a)

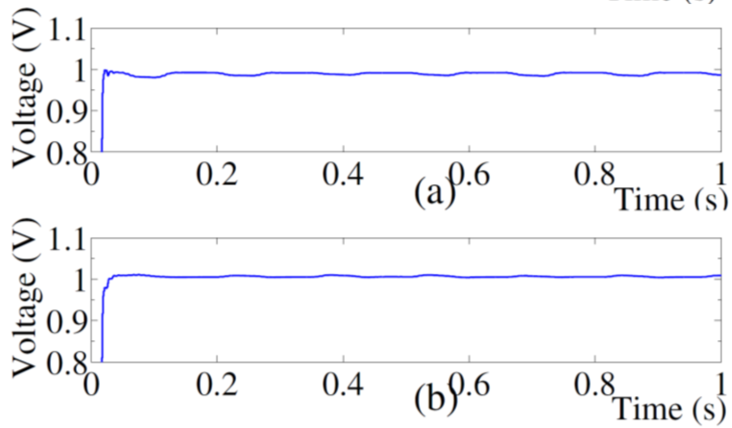
(b)



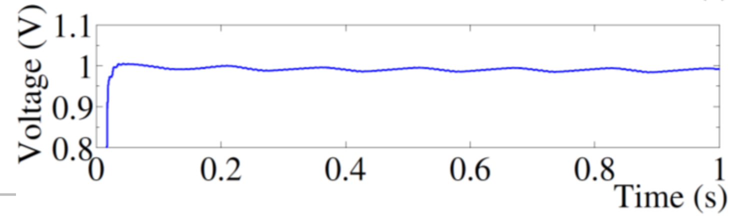
Normalized voltage in a sub-transmission bus in Scenario-1: (a) Without smart inverters (relatively large voltage variations), and (b) With smart inverters (reduced voltage variations).

(a)

(b)



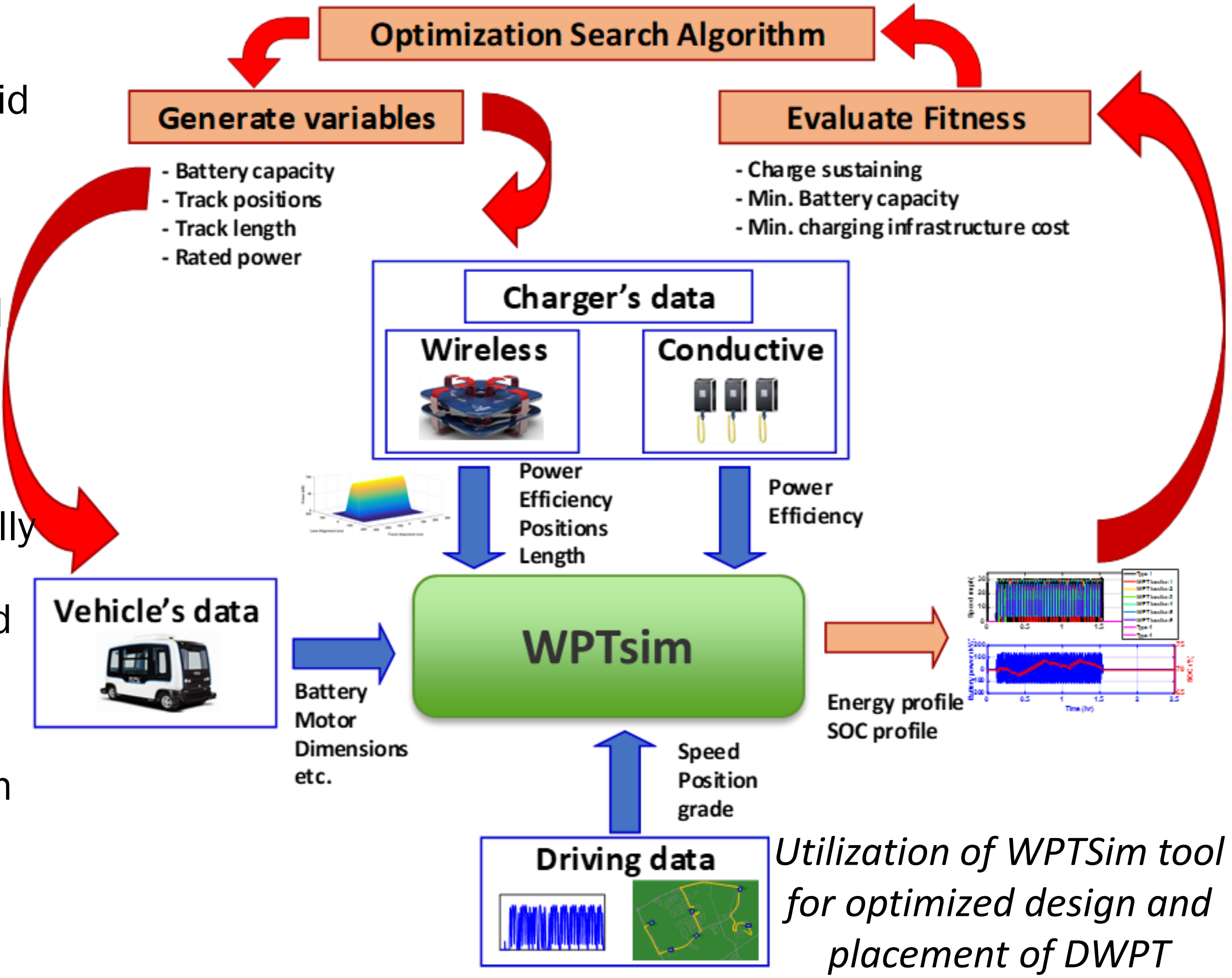
Normalized voltage in a sub-transmission bus in Scenario-2: (a) Without smart inverters (smaller voltage ripples compared to Scenario-1 but larger voltage than (b)), and (b) With smart inverters (reduced voltage ripples)



Normalized voltage in a sub-transmission bus in Scenario-3.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Optimization with WPTSim Tool (work in progress)

- With the CAVs energy consumption information and grid requirements are identified, we are currently optimizing the system using WPTSim tool.
- It generates the final energy and SOC profiles based on input variables.
- It is enhanced with an optimization layer to automatically search the optimum key design parameters based on predefined objectives and constraints.
- Objectives: minimum infrastructure cost and minimum battery cost.
- Constraints: charge sustaining operation and better battery performance.



Utilization of WPTSim tool for optimized design and placement of DWPT systems.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS – Cost Function Formulation for Optimization of DWPT Systems

- During FY18, the optimization was around the power rating and section length of the DWPT systems.
- FY19 includes analysis on parameterized cost of the system.
- DWPT total cost = Cost of road-side components + Cost of vehicle side components

c_r (\$.lane^{-1}.mile^{-1}): road retrofitting cost coefficient

c_e (\$.lane^{-1}.mile^{-1}.kW^{-1}) : power electronics and material cost coefficient

c_g (\$.lane^{-1}.mile^{-1}.kW^{-1}) : grid connection cost coefficient

c_i (\$/position) is the installation cost coefficient.

c_{VA} (\$.kW^{-1}) is the vehicle assembly cost coefficient,

c_{GA} (\$.kW^{-1}) is the ground assembly cost coefficient

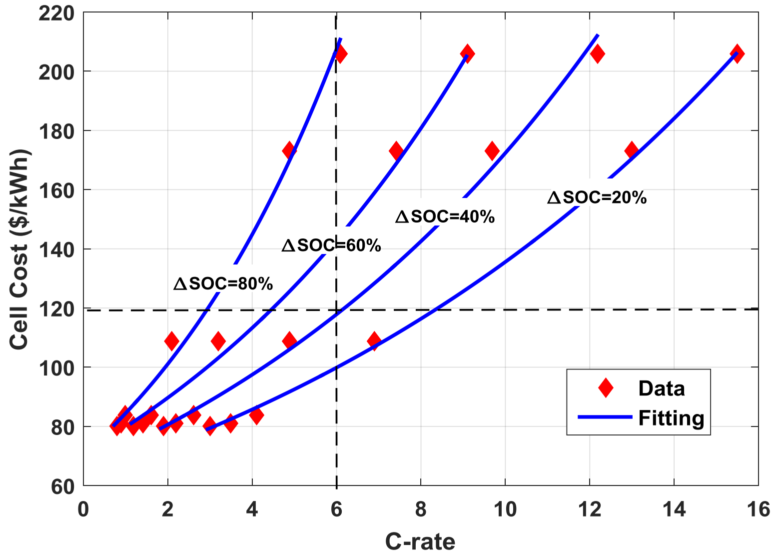
c_{iSWPT} (\$/port) is the installation cost coefficient.

c_{DCFC} (\$.kW^{-1}) is the DCFC unit cost,

c_{iDCFC} (\$/port) is the installation cost coefficient, and

c_b (\$.kWh^{-1}) is the battery cost coefficient, which is function of C-rate and SOC window.

Battery cost as function of C-rate and ΔSOC (NMC622-Graphite, 85 kWh pack, 900 DCV).



"Enabling Fast Charging: A Technology Gap Assessment," U.S. Department of Energy; Office of Energy Efficiency & Renewable Energy, Oct. 2017

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

- **Comment:** *"The reviewer found that overall, the project is well-designed. The main barrier of obtaining real-world data does not appear to have a solution, which is a major concern, because the validity of the models relies on the performance of the new technology."*

Response: Now the project has data from M-City project as well as it has some data from the Greenville AMD scenario that are being utilized in our models.

- **Comment:** *"The reviewer commented that the project is well-designed with supporting calculations. The 90% power transfer assumption should be reviewed to ensure that is the correct value and that no additional technical barriers exist with an implementation that delivers 90%."*

Response: This important issue is addressed by modeling an example track based dynamic wireless charging system using finite element analysis tool. The results showed that we can achieve about 90% efficiency from electrified roadway segments to the vehicles.

- **Comment:** *"The reviewer remarked there were only internal DOE collaborations. This project would require real-world input from transportation planners, from systems people, or from DWPT systems providers. The reviewer commented that the project needs external industry partners, especially to support the goal of establishing a plan for a wireless roadway. The reviewer remarked a partner from DOT or a civil engineering university program would provide benefit to the project."*

Response: Both reviewers are right, and we started discussions with potential partners to get their input on roadway construction and installation issues, communications, related vendors, and automotive OEMS.

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- More collaborations with all pillars and projects.
- Closely coordinating with NREL with regular and on the need basis teleconferences.
- INL to provide data on real use cases (field data collected) from connected and automated shuttle vehicles.
- NREL to use our input in the WPTSim tool to do more analysis on use case scenarios and system impact on transportation networks.

- **Inputs**:
  - Multi-Modal Freight Pillar → Electrified MD/HD truck energy usage
  - CAVs Pillar → Energy consumption of CAVs (Aux.)
  - Urban Science (US) Pillar → AMD traffic volume/energy requirements
- **Outputs**:
  - DWPT infrastructure requirements, CAVs refueling deployment scenario with DWPT → US Pillar, CAVs Pillar

REMAINING CHALLENGES AND BARRIERS

- Complexity of large-scale integrated transportation networks that this technology will be applied to.
- Accurately measuring the transportation system-wide energy impacts of connected and automated vehicles.
- Difficulty in sourcing empirical real-world data applicable to new mobility technologies such as connectivity and automation.
- Lack of field collected real use case data.

PROPOSED FUTURE RESEARCH

- Identify multiple future deployment scenarios and develop framework to identify optimum DWPT system designs, locations, and grid interfaces. Also analyze the impact of DWPT systems and architectures in advanced scenarios.
  - On track for this FY
- Expand the DWPT optimization analysis to include real data collected from operational connected and automated ride-shared vehicles for dynamic wireless power transfer feasibility analysis. Use WPTSim tool for optimal DWPT system deployment scenarios.
  - On track for this FY
- Long-term potential research:
  - Expand the analysis to cover quasi dynamic wireless charging scenarios (i.e., city shuttles with known routes, WPT installed at bus stops)
  - Perform a larger scale deployment scenario analysis to identify larger scale energy savings, cost, and benefit comparisons (i.e., comparisons with conventional chargers or DC fast chargers).

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

SUMMARY SLIDE

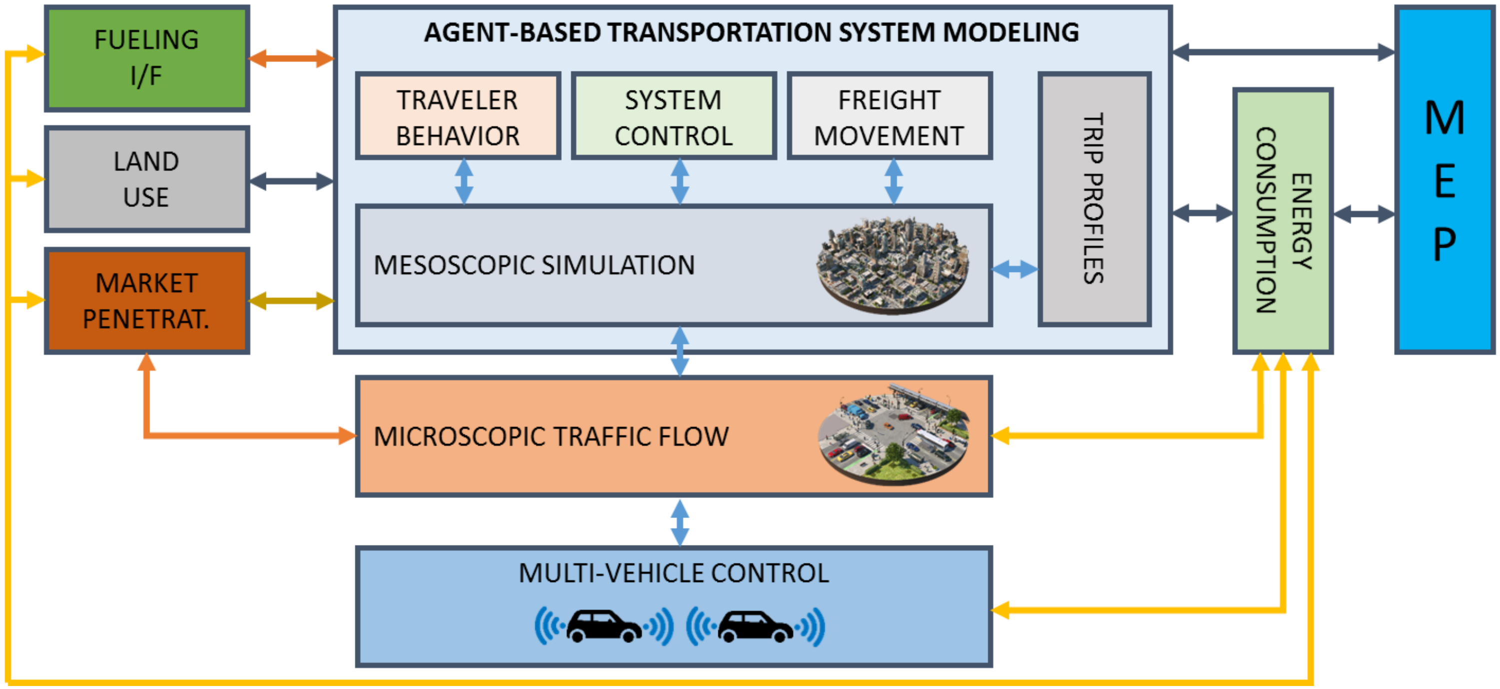
- **Approach:**
  - Characterize vehicle energy consumption levels for automated vehicles based upon drive cycle and traffic constraints for possible deployment scenarios.
  - Create an optimization framework for optimal sizing and placement of the DWPT system.
  - Define grid requirements and analyze grid impact of the DWPT systems with commonly used power distribution networks through test scenarios.

Collaborations: NREL, INL.

- **Technical Accomplishments:**
  - Evaluated vehicle energy consumption levels and identified DWPT system requirements as well as grid and infrastructure requirements.
- **Future Work:**
  - Identify multiple future deployment scenarios and develop framework to identify optimum DWPT system designs, locations, and grid interfaces.
  - Expand the DWPT optimization analysis to include real data collected from operational connected and automated ride-shared vehicles for dynamic wireless power transfer feasibility analysis. Use WPTSim tool for optimal DWPT system deployment scenarios.

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

END-TO-END MODELING WORKFLOW



- Project models utilize the energy consumption data of CAVs.
- Project defines the grid and infrastructure requirements and generates an optimization framework for optimal deployment of DWPT systems (minimal capital cost and energy use with highest range extension or charge sustaining operation)
- Project generates DWPT system specs and parameters considering multi-vehicle interactions.

QUESTIONS?