JUNE, 2020

DYNAMIC WIRELESS POWER TRANSFER FEASIBILITY

Project ID: EEMS040
Pillar: AFI

2020 Vehicle Technologies Office
Annual Merit Review Meeting

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OVERVIEW

Timeline

- Start – 10/01/2016 (FY17)
- End – 09/31/2019 (FY19)
- Percent complete: 100%

Budget

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

Barriers/Challenges

- Complexity of large-scale integrated transportation networks
- 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
- Determining the value and productivity derived from new mobility technologies
- Difficulty in sourcing empirical real-world data applicable to new mobility technologies such as connectivity and automation

Partners

- ORNL (Project/Task lead)
- NREL
- INL

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

RELEVANCE / OUTCOME

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

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).

Outcome

- 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.
- Research insights and findings to support energy efficient local and regional transportation systems.

MILESTONES

Timeline and Deliverables

- **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):** Analyze a case study of a future highway where CAVs travel in coordinated groups, with each CAV in the group powered by the same DWPT section and minimize the infrastructure requirements and energy losses of the DWPT system by adjusting the power level, transmitter length, and the receiver loads as the distribution of light and heavy duty vehicles are varied in each group of CAVs **(completed) (Slides 6-11)**.

- **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 **(completed) (Slides 12-15)**.

APPROACH / OBJECTIVES

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.
- Utilize a test case with real data collected from CAVs in operation with a DWPT deployment scenario.

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 ACCOMPLISHMENT AND PROGRESS

Optimization Approach for Highway Driving Cases for LDV and HDVs

- Capital costs objective functions
  - $\mathrm{C_{inv}}$ – cost of the power electronics per mile
  - $\mathrm{C_{road}}$ – cost of the road construction per mile
  - $\mathrm{C_{coupler}}$ – cost of the coupler materials per mile
- $\eta_{coupler}(\ell_\mathrm{T})$ is the overall efficiency of the DWPT system

$$\min_{\mathbf{x}} \quad \mathrm{f}(\mathbf{x},\mathbf{p}) = \mathrm{C_{inv}}(\mathbf{x},\mathbf{p}) + \mathrm{C_{road}}(\mathbf{x},\mathbf{p}) + \mathrm{C_{coupler}}(\mathbf{x},\mathbf{p})$$

$$\mathrm{C_{inv}}(\mathbf{x},\mathbf{p}) = W_{inv} \times \frac{P_{sys}\beta_{road}}{\ell_T}$$

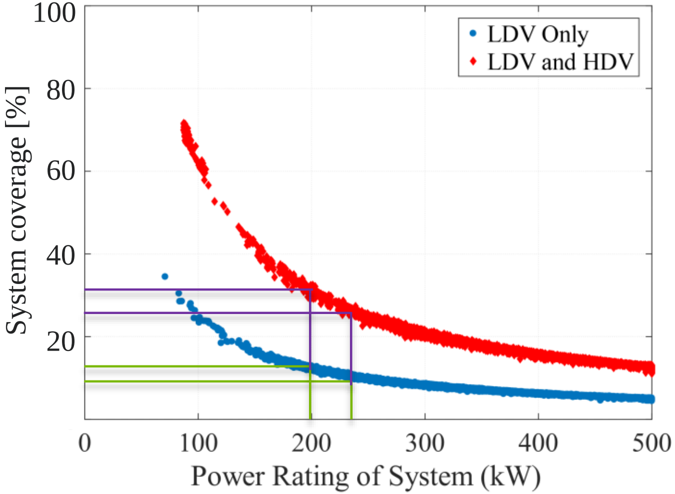
$$\mathrm{C_{road}}(\mathbf{x},\mathbf{p}) = W_{road} \times \beta_{road}$$

$$\mathrm{C_{coupler}}(\mathbf{x},\mathbf{p}) = W_{Litz} \times \frac{P_{sys}\beta_{road}}{\ell_T} \times (2\ell_T + 2W_{sys}) \times N_{turns}$$

$$\text{s.t.} \qquad \bar{P} + P_{aux} - P_{sys} \cdot \frac{\ell_{vehicle}}{\ell_T} \cdot \beta_{road} \cdot \eta_{coupler}(\ell_\mathrm{T}) \leq 0$$

$\mathbf{x}$ – decision vector: $[P_{sys} \quad \ell_T \quad \beta_{road}]^T$
$\mathbf{p}$ – set constants and vehicle specifications

Pareto solutions for DWPT system sizing



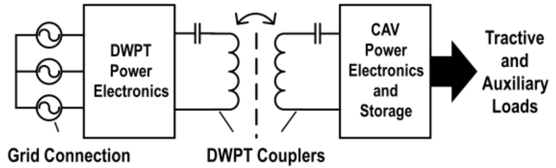
- Pareto front is found by varying the weights of each objective function
- Constant speed of 70 mph on highways
- **For about 8-12% coverage rate, 200-250 kW power is needed for the charge sustaining operation of LDVs on highways for 70 mph driving speed**
- **For the same power level, coverage should be increased to 25-30% to support HVDs as well.**

TECHNICAL ACCOMPLISHMENT AND PROGRESS

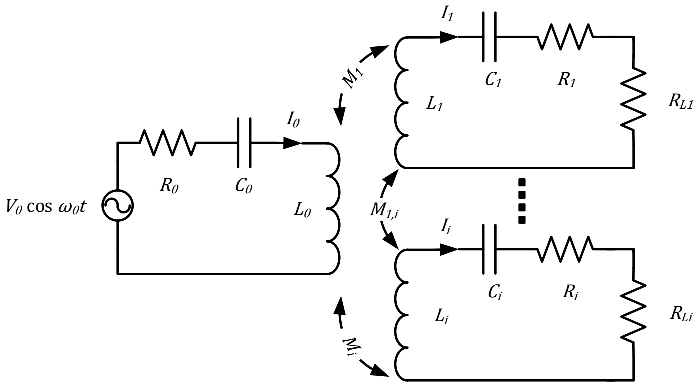
System Design of DWPT for an Automated Highway

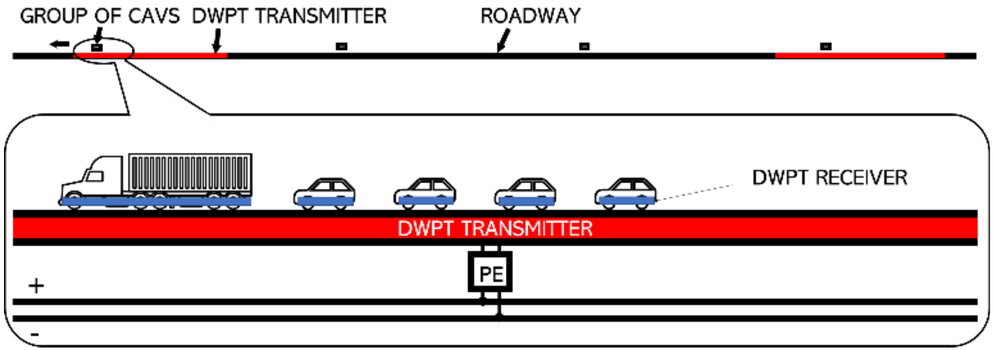
- Several impacts of automated highways and the integration of CAVs in the highways
- Longer passenger trips
- Freight with no hour-of-service restrictions
- Decrease in congestion and accidents
- Groups of platooning CAVs could improve the utilization of DWPT systems
- The number and type of CAVs in each platooning group can be used to optimize the DWPT system design and operation

Block diagram of DWPT system



System design with single transmitter and multiple receivers





The automated highway concept with DWPT integration

Optimization Formulation for an Automated Highway with Multiple CAVs

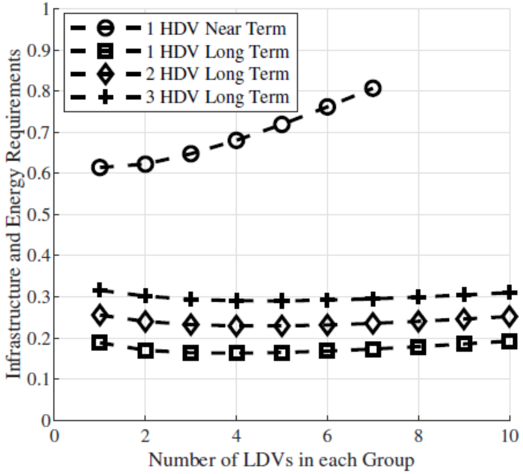
- Two sets of bounds: near-term and a long-term
- The constraints represent
  - Tractive power required by the LDV and HDVs
  - Length of the DWPT section vs. CAV group
- Objective function of energy and infrastructure requirements formulated and minimized (refer to the technical backup slide)

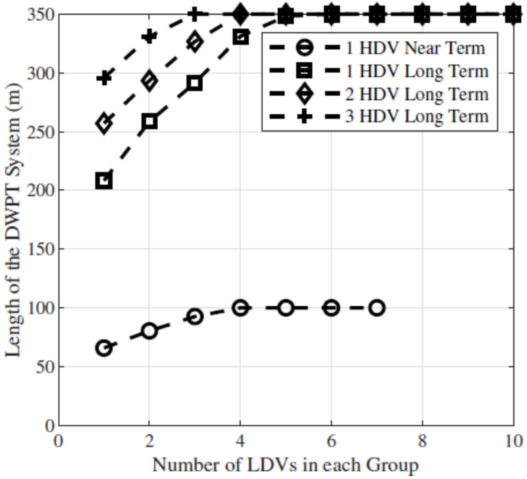
Variable Definitions and Upper Bounds		
Variable Definitions	Near Term	Long Term
P_{sys} = DWPT section power level	200 kW [16], [17]	2 MW [6]
l_{sys} = DWPT transmitter length	100 m [6]	350 m
β_{road} = coverage ratio per mile	100%	100%
Optimization Parameters		
v = constant travel speed of CAVs	55 mph, 70 mph	
I_0 = constant inverter current	200 A	
ω = frequency of DWPT system	2π*85 kHz [12]	
z = system air gap	162 mm [13]	
n_{LDV} = LDV numbers in group	1:10	
n_{HDV} = HDV numbers in group	1:3	
w_{sys} = width of DWPT couplers	1.5 m [14]	
Y_{LT} = lifetime of DWPT system	5 years	
$AADT$ = average daily traffic	150,000 per day [15]	
N_t = equivalent turns in transmitter	1 turn	
N_{LDV} = turns in LDV couplers	4 turns	
N_{HDV} = turns in HDV couplers	4 turns	

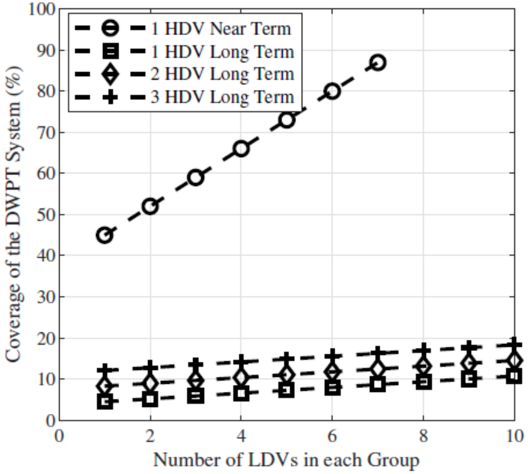
TECHNICAL ACCOMPLISHMENT AND PROGRESS

Optimization Results for DWPT Integrated Automated Highway with multiple CAVs

Results for 55 mph







- Pathways to higher system power levels and longer DWPT sections may increase the feasibility of DWPT
- There is synergy between CAV coordination and DWPT infrastructure deployment and operation
- There is work to be done to establish the ideal implementation of DWPT for future electrified and automated highways

TECHNICAL ACCOMPLISHMENT AND PROGRESS

Optimization Framework with WPTSim Tool

Optimization variables

- Number and locations of DWPT tracks/transmitters
- DWPT power levels
- Track length
- EV battery size

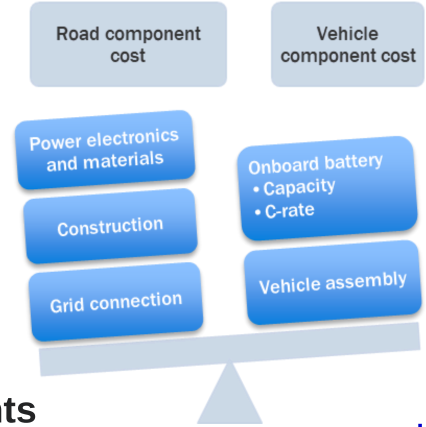
Optimization objective

- Minimum overall system cost

Optimization constraints

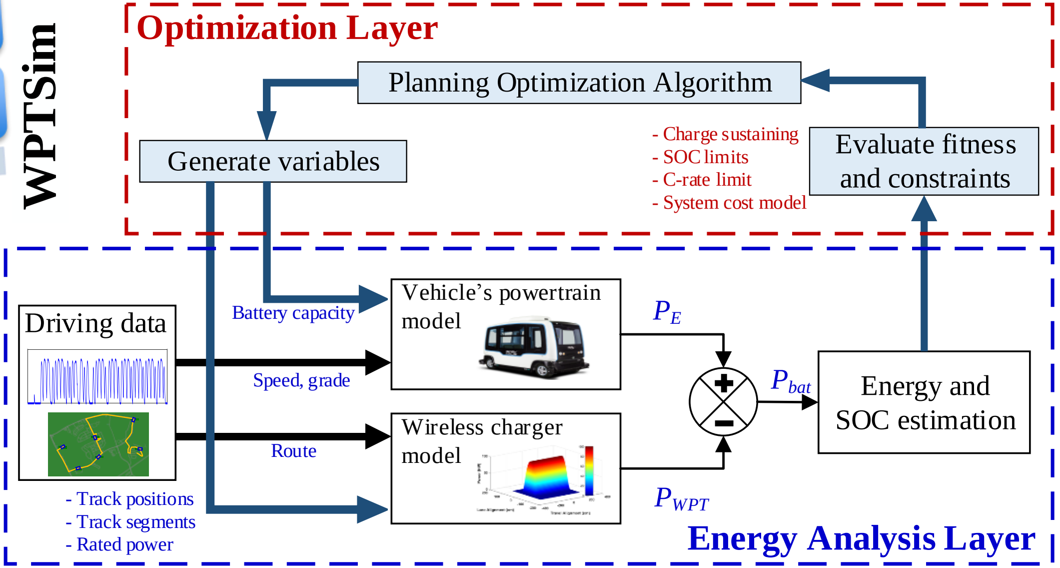
- Charge-sustaining operation
- Charge rate (C-rate) limit
- State-of-charge (SOC) limit

Overall system cost model



WPTSim tool

- Planning optimization tool for defining the system key design parameters.
- Vehicle powertrain model,
- Wireless charger power model,
- Automatic search algorithm,
- Overall system cost model



Block diagram of WPTSim optimization work

TECHNICAL ACCOMPLISHMENT AND PROGRESS

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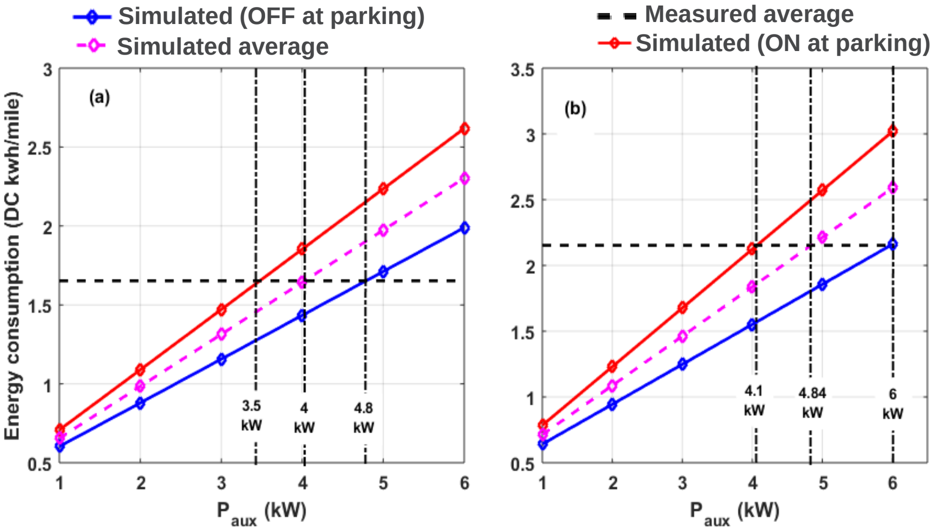
M-City NAVYA Arma Automated Shuttle Project

- Two circulator fixed-route NAVYA Arma shared automated electric vehicles (SAEVs) at the University of Michigan.
- Run in a ~1-mile route with two designated stops—south (S) and north (N)
- Data for 16, 17 and 19 of July 2018 are collected.
  - Energy consumption (AC Wh/mile)→ used for vehicle modeling
  - GPS travel data (speed, latitude, longitude)→ used for system planning

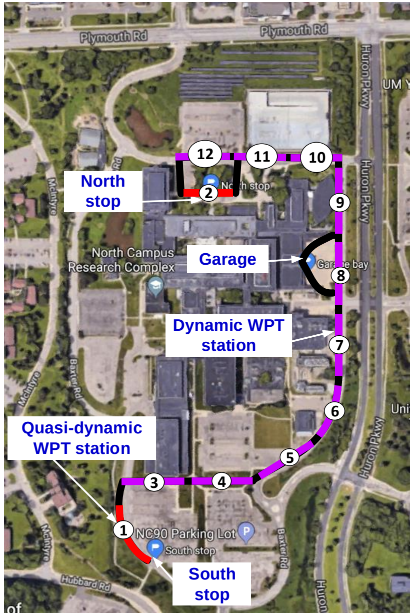
Auxiliary load estimation

- Charger efficiency of 90% from grid-to-battery
- Present auxiliary loads
  - Arma1 → 4 kW
  - Arma2 → 4.84 kW
- Futuristic additional auxiliary load estimation
  - Arma1 → 1.4 kW
  - Arma2 → 1.7 kW



Energy consumption variation with auxiliary loads Arma1 (left) and Arma2 (right)

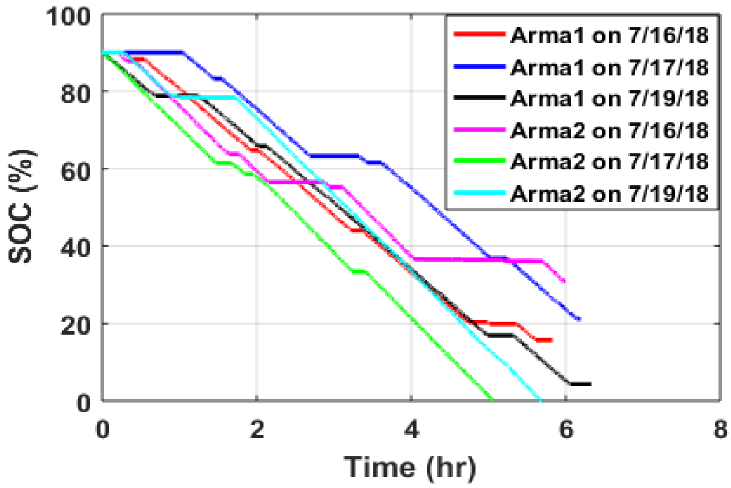
Map of the Arma shuttle route in M-City



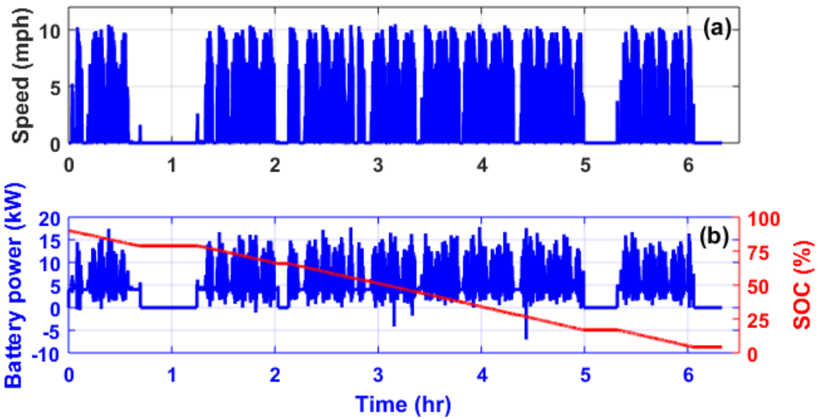
TECHNICAL ACCOMPLISHMENT AND PROGRESS

Operation of Arma SAEVs at M-City

- Real GPS travel data are used considering a 33-kWh onboard battery for each shuttle.
- A full battery charge allows Arma1 to run for ~ 6.5 hours with long intermittent stops (~ 5 hours of continuous operation).
- Three day of data for two Arma shuttles shows a range of 5–7 h of total operating hours.
- Therefore, to extend the vehicles range without interrupting the service, in-route automatic charging capability is needed—either dynamic or quasi-dynamic inductive charging.



SOC of Arma1 and Arma2 on July 16, 17, 19, 2018



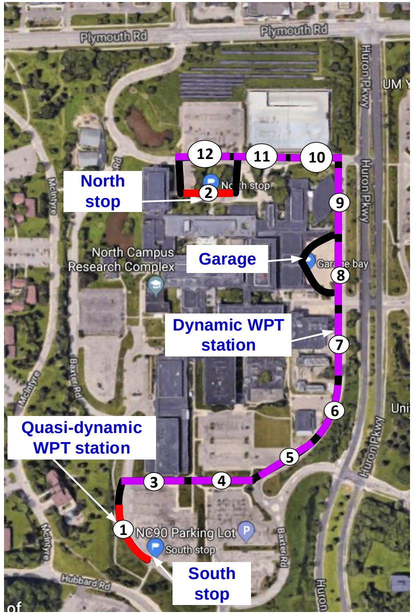
Arma1 operation on July 19, 2018
Vehicle speed (top) and battery power and SOC (bottom)

TECHNICAL ACCOMPLISHMENT AND PROGRESS

Optimization Analysis for In-Route Wireless Charging

- Three different optimization problems are formulated and solved, considering
  - Quasi-dynamic WPT (QDWPT) chargers (at stops only [red positions])
  - Dynamic WPT charging (DWPT) (in the entire route [purple positions], one segment is electrified at a time)
- Each problem is solved considering present-day and future vehicle and cost assumptions.
- Solving for dynamic chargers provides the same results as the quasi-dynamic solutions only, since targeting stops for installing the system provides the most cost-effective solutions.
- For present-day, one 100kW or two 50 kW chargers are needed for charge-sustaining.
- For future, one 40-50 kW charger might be sufficient with higher vehicle efficiencies.
- All solutions show reduced battery size (12-57%) compared to the current size.

	Present-day			Future		
Technology	QDWPT		DWPT	QDWPT		DWPT
Solution #	S1	S2	S1	S1	S2	S1
# chargers	2	1	1	1	1	1
Location	S & N	N	N	N	N	N
Power (kW)	50	100	100	40	50	40
Number of segments	1	1	1	1	1	1
Battery size (kWh)	29	28	28	29	14	29
Charge rate (C-rate)	1.55	3.2	3.2	1.24	3.2	1.24
kWh/mile	1.647	1.647	1.647	0.792	0.785	0.792



Map of the Arma shuttle route in M-City with DWPT and QDWPT systems

TECHNICAL ACCOMPLISHMENT AND PROGRESS

Stationary Charging Options: Level-2 and DCFC

- Stationary charging technologies are explored for the Arma shuttles:
  - Level-2 AC chargers
  - DC fast chargers (DCFCs)
- Target driving ranges for present-day and future operation are 6 h and 12 h, respectively
- Continuous driving for 6 h in present-day technology requires about a 36.7-kWh battery capacity, while 12 h of driving with future technology requires a 30.2-kWh battery. This is due to the expected efficiency improvement assumption for SAEVs in future
- A 132-kW (for present-day) or 109-kW (for future) DCFC is required to fully recharge the batteries of both shuttles within 30 min (15 min each).
- Two 4.1-kW (for present-day) or two 3.4-kW (for future) L2 chargers are needed to fully recharge the batteries of two shuttles within 8 h.

	Present		Future	
Technology	DCFC	L2 charger	DCFC	L2 charger
# chargers	1	2	1	2
Location	garage	garage	garage	garage
Power (kW)	132	4.1	109	3.4
Battery size (kWh)	36.7	36.7	30.2	30.2
Charging time	15 min	8 h	15 min	8 h
C-rate	3.24	0.1	3.24	0.1
kWh/mile	1.911	1.91	0.7865	0.7865

TECHNICAL ACCOMPLISHMENT AND PROGRESS

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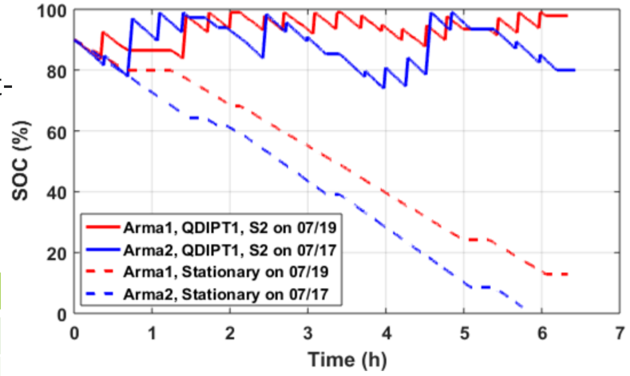
Systems and Modeling for Accelerated Research in Transportation

Charging Technology Comparisons

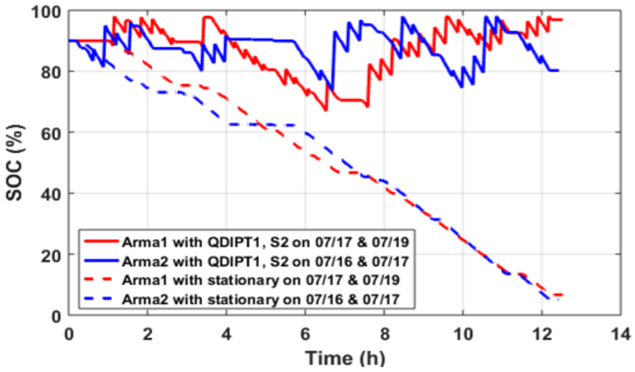
- The quasi-dynamic optimum solution (QDWPT, S2) is compared with Level-2 and DCFC.
- QDWPT solution shows charge-sustaining operation (|SOCf-SOCi|≤ 10%).
- DCFCs & Lelvel-2 chargers allows the vehicle to run for a limited range (6 h for present-day and 12 h for future).
- QDWPT requires less battery size, however, DCFCs & Level-2 require larger battery.
- QDWPT solution can be cost-effective compared to the DCFC.
- Level-2 chargers with an 8-h charging time are the least expensive.

Characteristic	QDWPT	DCFC	Level-2 charger
Driving range	Unlimited	Limited (6–12 h)	Limited (6–12 h)
Recharge time	Zero	30 min	8 h
Vehicle components cost	Relatively higher	Depends on the on-board components	Medium
Stationary components cost	Depends on section length and power level	High	Low
Overall system cost	Depends on section length and power level	High	Medium
Service interruption	Low	Medium	Medium
Land requirement	Low	High	
Automated	Yes	No	
User discomfort	Low	High (plug-in and wait)	
Hazards	Magnetic/Electric fields	Mechanical connection, cable wear, etc.	

SAEV performance for present day operation



SAEV performance for future operation



RESPONSES TO PREVIOUS YEAR'S REVIEWERS' COMMENTS

- **Comment**: *The idea of evaluating energy consumption level for AVs and developing an optimization framework to locate the placement of the dynamic wireless power transfer (DWPT) system looks appealing. Reviewer suggested that team can consider fixed route applications to study the feasibility.*

Response: We agree with the reviewer that the fixed route options would make the most sense for the automated shuttles due to predictability of energy consumption information. Fixed routes are the natural operation areas of automated shuttles as well.

- **Comment**: *Reviewer stated that the project is narrow in scope and lacks inclusion of real-world use cases. Collaborations with potential users of DWPT would be needed to make this work pertinent to any potential real-world application development.*

Response: We tried to keep the scope as wide as possible with the analysis of power transfer characteristics (FY19 work), grid impact analysis, and finding the optimal deployment scenarios of the DWPT technology. Team is working on real-world application development with the support of OEMs and a deployment of a prototype system at the American Center for Mobility under a different VTP project.

- **Comment**: *The reviewer stated that the project has good results and progress. Also, that explanation of how the scenarios were chosen would have been helpful.*

Response: The chosen scenarios are based on the very limited CAVs deployment in the real world.

- **Comment**: *The reviewer suggested considering air-gap variation between loaded and unloaded vehicles.*

Response: Airgap variations would slightly change the efficiency and the power transfer. Team is working on interoperable solutions for LDVs and HDVs under a different VTO project involving technology development and integration.

- **Comment**: *The reviewer said that the project could use a commercial drive cycle and measure how DWPT could be utilized to achieve functional, cost, and energy efficiency improvements on that cycle.*

Response: This is exactly what the project team has targeted and used a drive cycle based on the Arma shuttles operational at M-City.

- **Comment**: *The reviewer observed that the project is in line with DOE targets to improve the energy efficiency and productivity of future integrated mobility systems.*
- **Comment**: *The reviewer remarked that this is an important technology that will aid in increasing market share of electrified vehicles. Also, the reviewer encourages that the DOE continues research in this area.*
- **Comment**: *The resources appear sufficient for the work defined. However, the reviewer commented that the work needed to be expanded to achieve real project success.*

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- More collaborations with all pillars and projects.
- Closely coordinated with NREL with regular and on the need basis teleconferences.
- INL provided data on real use cases (field data collected) from connected and automated shuttle vehicles.
- NREL used our input in the WPTSim tool and performed 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
- 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
- Determining the value and productivity derived from new mobility technologies
- Difficulty in sourcing empirical real-world data applicable to new mobility technologies such as connectivity and automation

PROPOSED FUTURE RESEARCH BEYOND THIS PROJECT

- Experimental validation of the findings of this study with a dynamic wireless power transfer emulator or a dyno system with a vehicle or equivalent load profile for a given drive-cycle to analyze the potential range extension or charge sustaining operation.

- Acquire a real CAV for the integration of wireless charging technology with a real-world deployment to understand and evaluate real-world operation challenges, design improvements, data collection, and analysis.

- Perform a larger scale deployment scenario analysis to identify larger scale energy savings, cost, and benefit comparisons.

- Explore additional use cases for wireless charging technology, including full-size public transit buses, quasi-dynamic charging at intersections and traffic signals, and freight trucking applications.

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

SUMMARY

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 (Q1 and Q2 of FY19, covered in FY19 AMR presentation).
- Implemented in-route DWPT and QDWPT chargers for SAEV with the following findings:
    - A fully automated system can be realized with vehicles and chargers
    - Charge sustaining operation can be provided with unlimited range and zero downtime
    - Number of vehicles in service can be reduced with no downtime for charging
    - Battery size can be dramatically reduced up to 57%
    - Overall cost effectiveness is possible compared to DCFC
- For LDVs, 8-12% coverage with 200-250 kW DWPT can provide charge sustaining operation at highway driving speeds (70 mph)
- Grouping LDVs and HDVs together can help minimize the infrastructure and energy loss requirements of the system by decreasing the energy losses over the operating lifetime of the DWPT system.

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

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Questions and Discussion

FOR MORE INFORMATION
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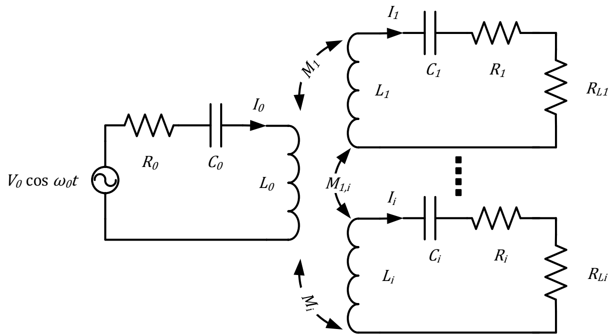
Technical Back-Up Slides

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

TECHNICAL BACKUP SLIDE 1

System design with single transmitter and multiple receivers



$$V_0 = I_0(R_0 + \sum_{i=1}^{N} \frac{(\omega M_i)^2}{R_i + R_{Li}})$$

$$P_0 = V_0 I_0 = I_0^2(R_0 + \sum_{i=1}^{N} \frac{(\omega M_i)^2}{R_i + R_{Li}})$$

$$P_i = I_0^2 \frac{(\omega M_i)^2 R_{Li}}{(R_i + R_{Li})^2}$$

Objective function of energy infrastructure requirements for the automated highway concept with multiple CAVs

$$\begin{aligned} \underset{\mathbf{x}}{\text{minimize}} \quad & f(\mathbf{x}) = M_{inv}(\mathbf{x}) + M_{road}(\mathbf{x}) + M_{Litz}(\mathbf{x}) + M_E(\mathbf{x}) \\ \text{subject to} \quad & P_{LDV}(v) - P_i(\mathbf{x})\beta_{road} \leq 0 \\ & 0.5P_{HDV}(v) - P_i(\mathbf{x})\beta_{road} \leq 0 \\ & P_0(\mathbf{x}) - P_{sys} \leq 0 \\ & n_{LDV} l_{LDV} + n_{HDV} l_{HDV} - 0.5 l_{sys} \leq 0 \end{aligned}$$

$$M_{inv}(\mathbf{x}) = W_{inv} \frac{P_{sys}\beta_{road}}{l_{sys}}$$

$$M_{road}(\mathbf{x}) = W_{road}\beta_{road}$$

$$M_{Litz}(\mathbf{x}) = W_{Litz} \frac{N_t \beta_{road}}{l_{sys}}(2l_{sys} + 2w_{sys})$$

$$M_E(\mathbf{x}) = W_E \frac{(AADT \times 365)Y_{LT}}{n_{LDV} + n_{HDV}} \times \frac{\beta_{road}(P_0(\mathbf{x}) - \sum P_i(\mathbf{x}))}{v}$$

TECHNICAL BACKUP SLIDE 2

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

70 mph Results for DWPT Integrated Automated Highway with multiple CAVs