High Power and Dynamic Wireless Charging

ORNL, INL, and NREL

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High Power and Dynamic Wireless EV Charging

Objective: Design develop and validate 200 kW high power dynamic wireless EV charging in real-world conditions

Project partners

	• Project lead: ORNL • 200 kW power dynamic EV charging system design, simulation, hardware development, vehicle integration and validation
	• Kona EV for high power dynamic wireless EV charging demonstration • Engineering support and guidance for integration of DWPT system with the vehicle
	• Site for 'electrified mile' dynamic charging demonstration (FY21) • Infrastructure and support for demonstration
	• Evaluation and guidance of making the ground side coils and power electronics roadworthy

Why Dynamic Wireless Charging of EVs?

~~Range anxiety~~ → Increased on-Board battery capacity → Increased weight and volume → Reduced energy efficiency

Dynamic Wireless Charging as a viable solution:

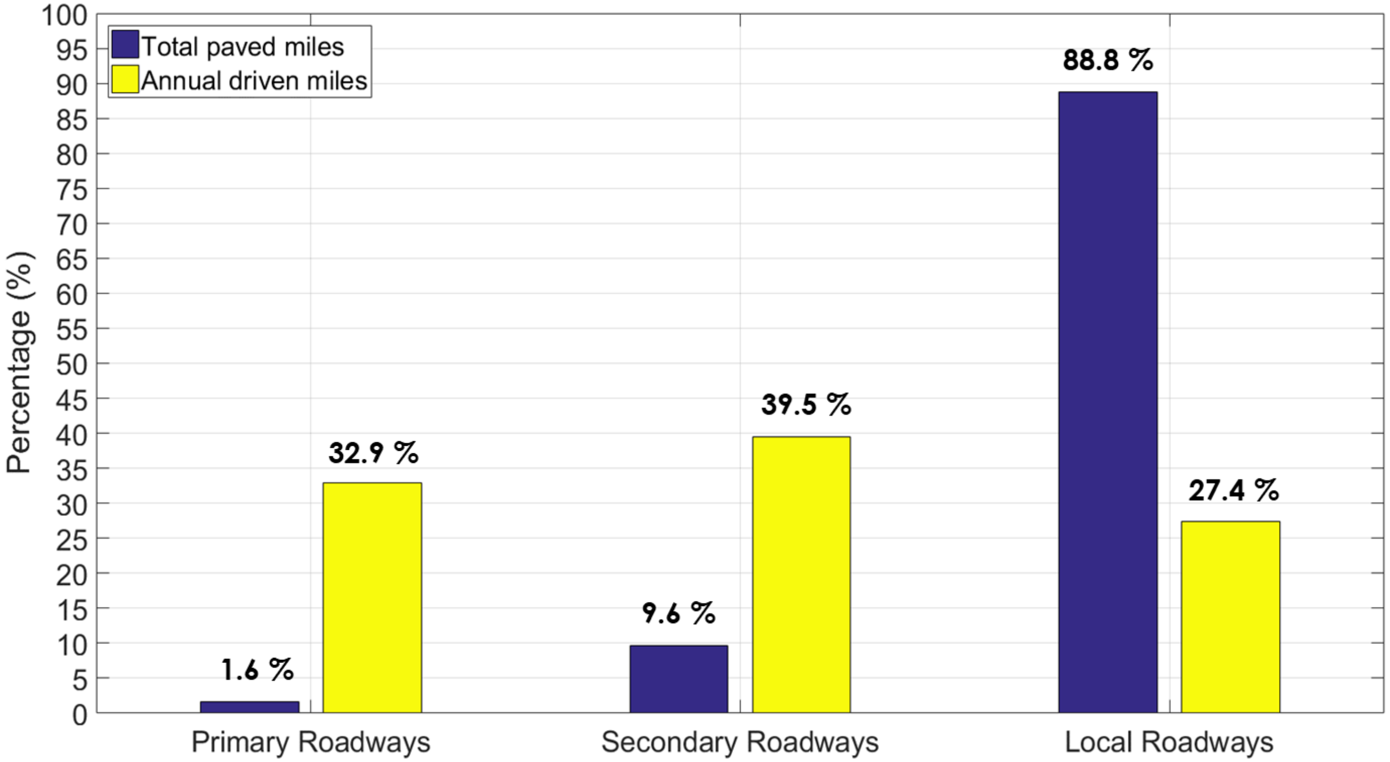
Power level for economic feasibility ?

Technical feasibility?

Types of Roadways and Applicability of Dynamic Charging

Total paved roadway miles in USA – 4.2 million

1. **Primary** – Interstate and other freeways and expressways
2. **Secondary** – Other principal arterial and minor arterial roadways
3. **Local roadways**



Types of roadways in the USA

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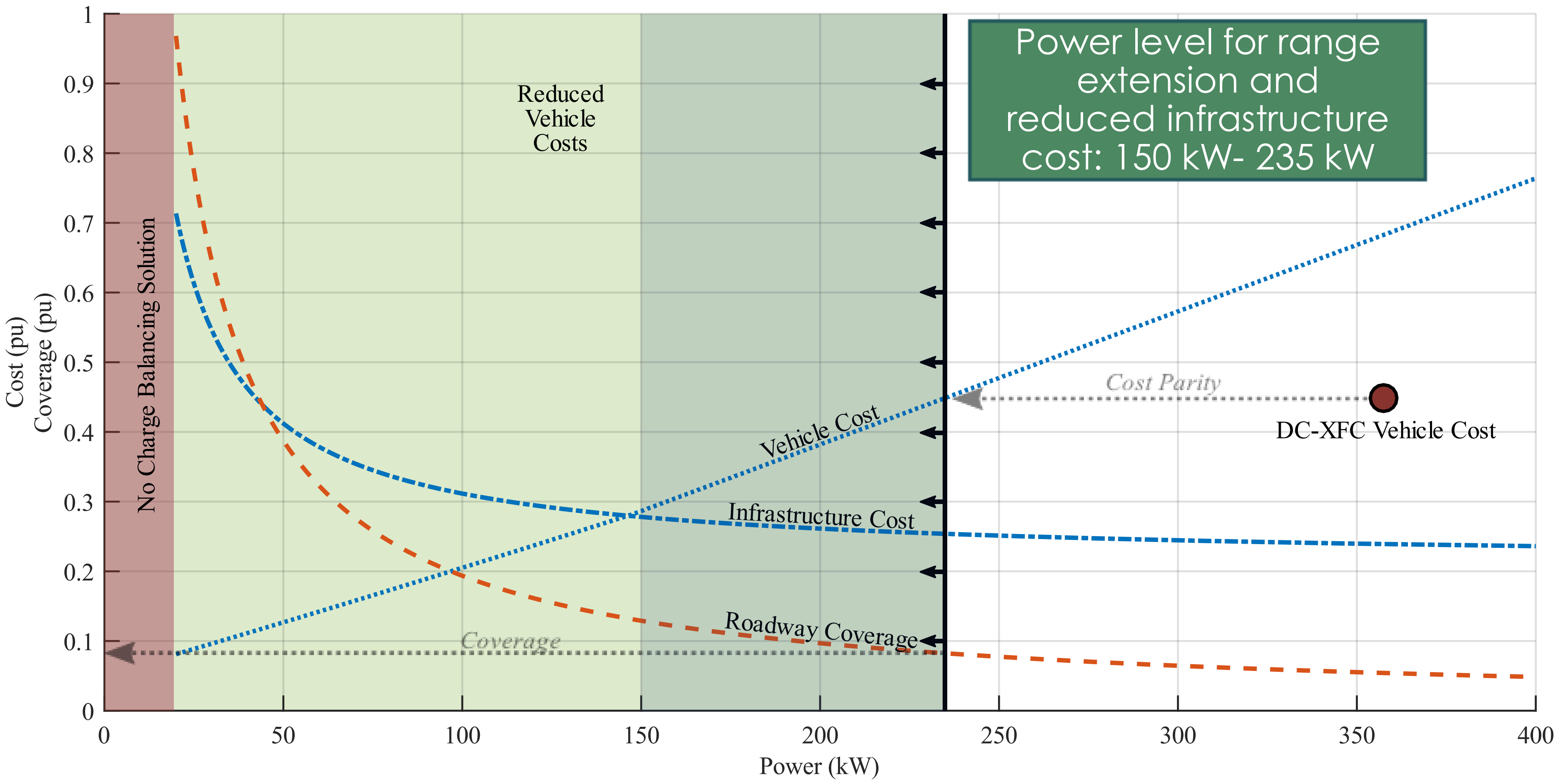
[1] Office of Highway Policy Information. (2014). Public road length- 2014: Miles by type of surface and ownership/functional system national summary.

High Level Cost and Feasibility Study Results

LD Vehicle Assumptions	
Average Speed	65MPH
Minimum Battery Capacity	37kWh
DC-XFC Battery Capacity	112kWh, 4C ΔSOC=80%

Minimum Coverage DWPT Solution	
Power	235kW
Battery Capacity	59kWh*
C-Rate	4.0
Roadway Coverage	8.2%
Electrified Miles	5,500 Miles

*Battery charge rate limited to 4C



Total paved miles – 4.2 Million

- 1.6 % of total paved miles or 67,200 miles – primary roadways
- 8.2 % of primary roadways or 5,500 miles – electrified roadway

Project Target → 200 kW+ Dynamic Wireless EV Charging

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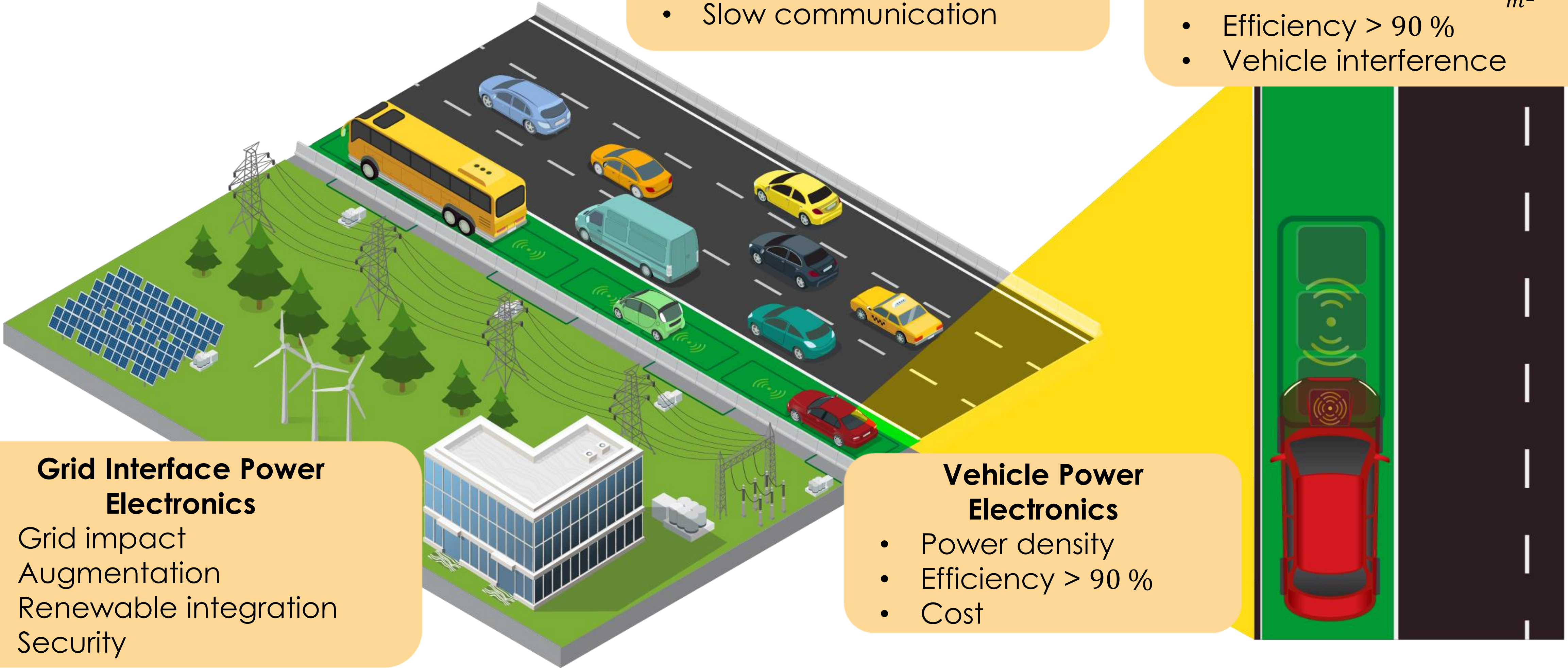
Challenges for High Power and Dynamic Wireless Charging



Control and Communication
- Optimal control strategy
- Power oscillations
- Slow communication

WPT Coupler
- Embedding in roadway
- Power density > $400\,\frac{kW}{m^2}$
- Efficiency > $90\,\%$
- Vehicle interference

Grid Interface Power Electronics
- Grid impact
- Augmentation
- Renewable integration
- Security

Vehicle Power Electronics
- Power density
- Efficiency > $90\,\%$
- Cost

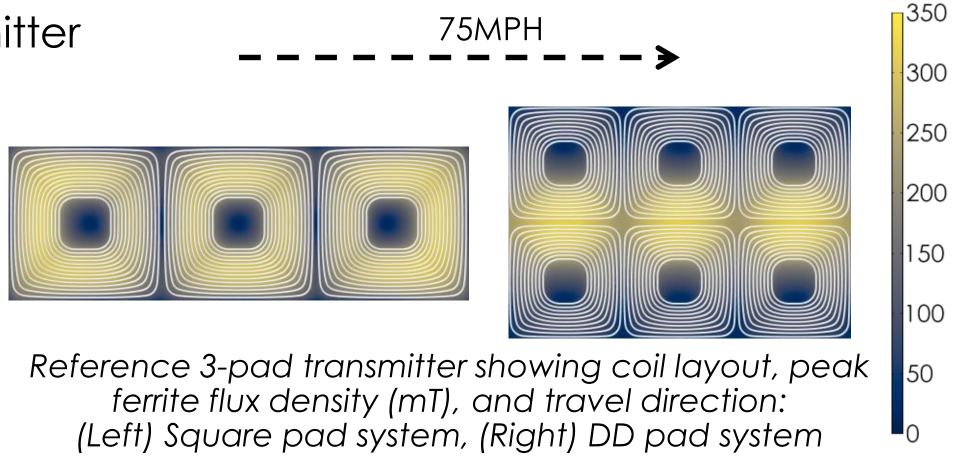
WPT Coupler Design: Geometry Selection

Analyzed Power Transfer Profile of Multi-Transmitter System

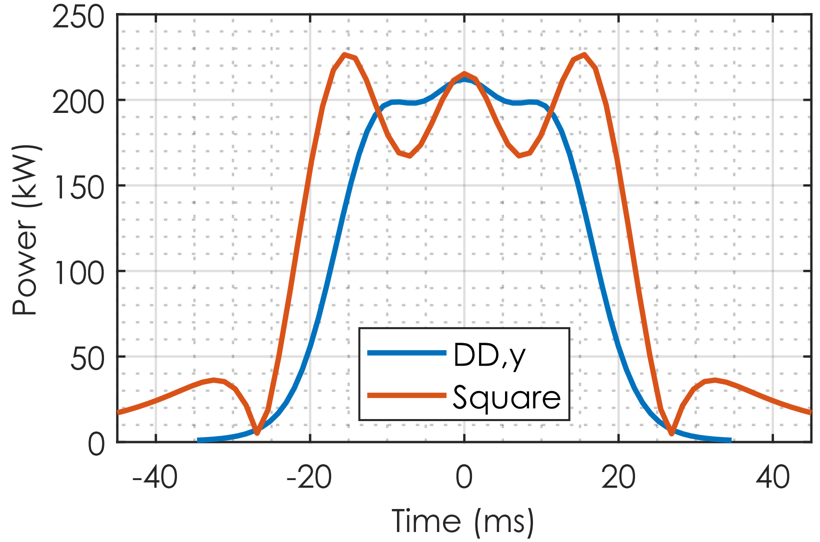
Issue: Square coils have degraded performance in multiple transmitter systems

- Lower effective power due to magnetic coupling interference
- High power ripple
- Control issues (series tuning)

Receiver	Square	DD
Length	52.2cm	78.7cm
Width	52.2cm	38.7cm
Mass	10.2kg	14.5kg
Effective Power	211kW	208kW
Specific Power	20.7kW/kg	14.3kW/kg
Power Ripple	48kW	14kW
Ripple Frequency	17.5Hz	13.0Hz
Simulated Energy Transfer Efficiency	87.9	89.7



Reference 3-pad transmitter showing coil layout, peak ferrite flux density (mT), and travel direction: (Left) Square pad system, (Right) DD pad system



Reference pad power profiles assuming a vehicle velocity of 75MPH (33.5m/s)

DD Coil selected based on efficiency and reduced ripple

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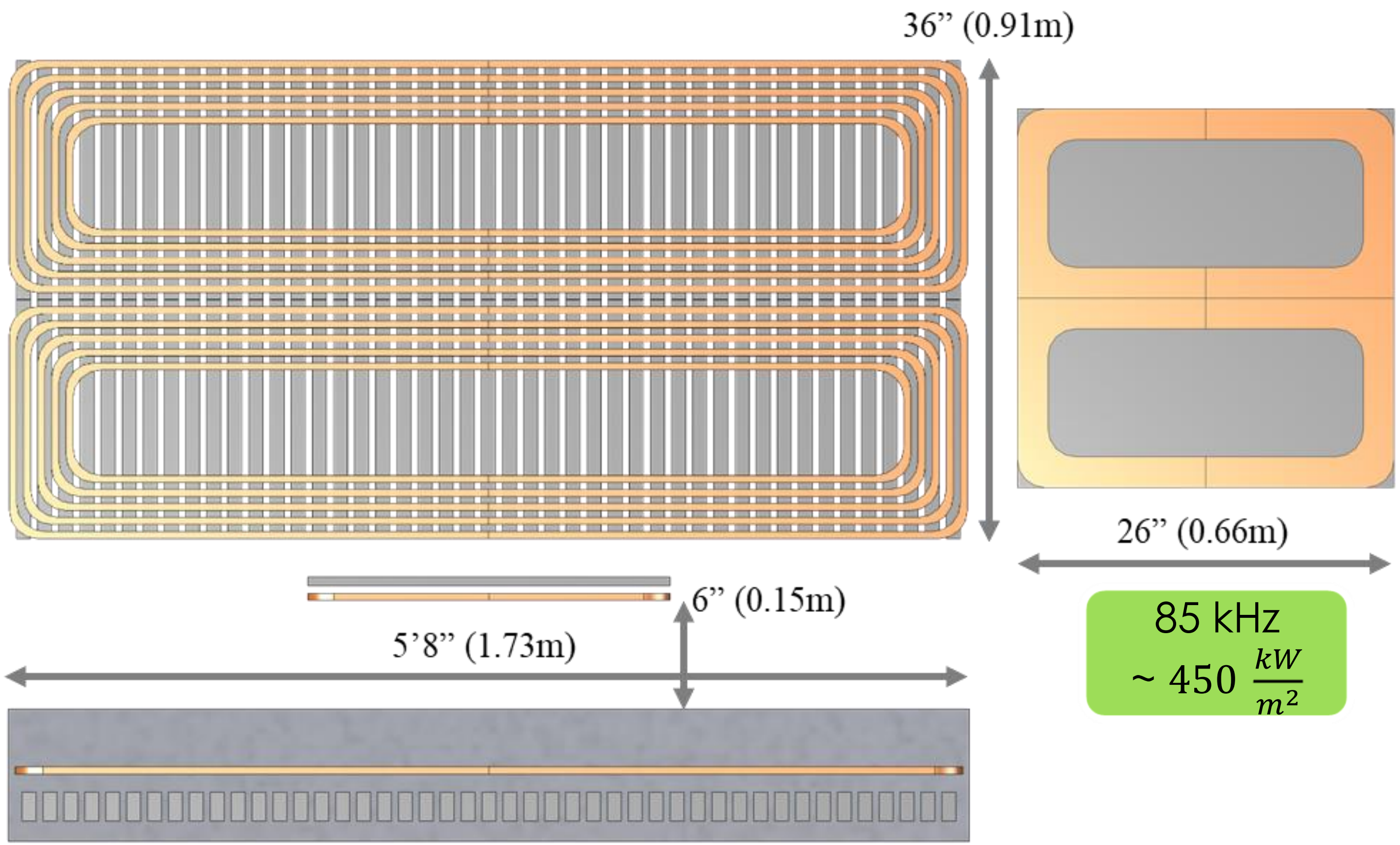
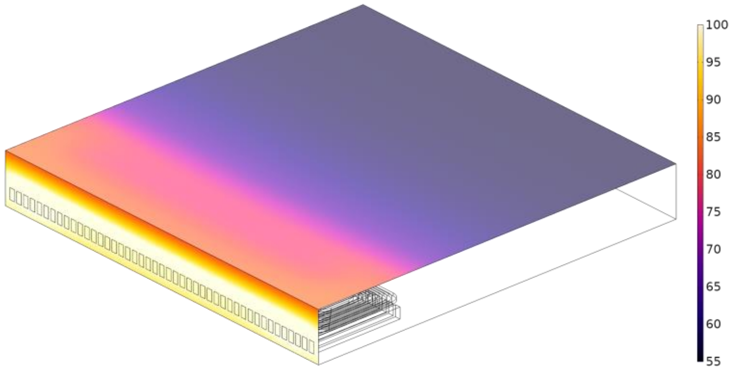
WPT Coupler: Design Considering Roadway Parameters

Goal: Ensure feasibility of construction and operation of roadway embedded DWPT system

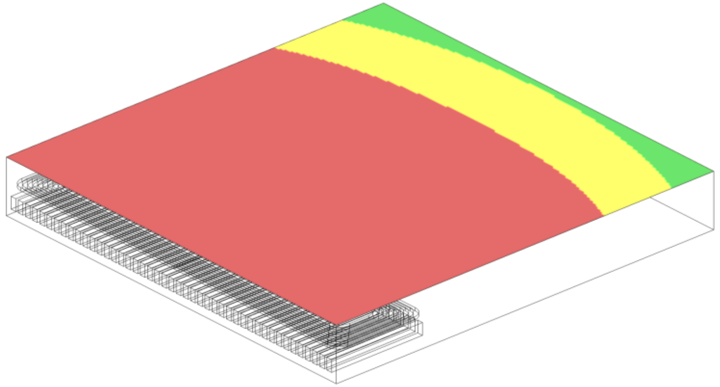
Challenge: Thermal, mechanical, and field emissions constraints limit the ability of embedded transmitters to push power across a large magnetic airgap



Views of the ground coupler (top left) and vehicle coupler (top right); Side view of the ground coupler showing the surrounding concrete and vehicle coupler ground clearance



Thermal analysis of DWPT system embedded in concrete with ambient temperature of 55C

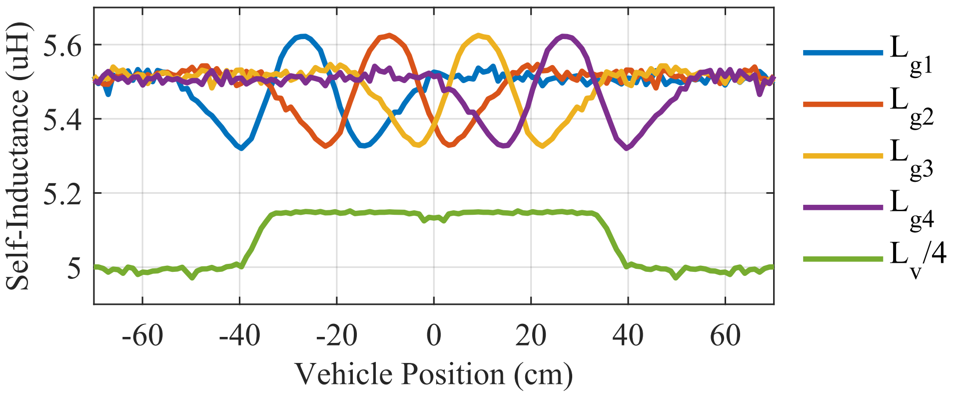


Electromagnetic field emission on the roadway; Green less than 15 μT rms, Yellow – between 15 μT rms and 27 μT rms; Red greater than 27 μT rms

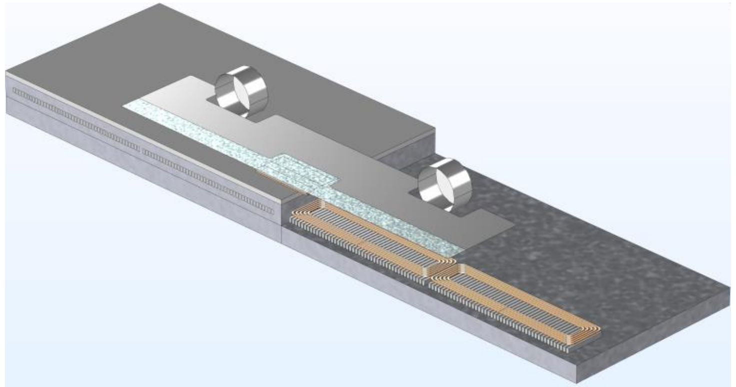
WPT Coupler: Design Considering Vehicle Body Effect

Goal: Develop accurate DWPT system models

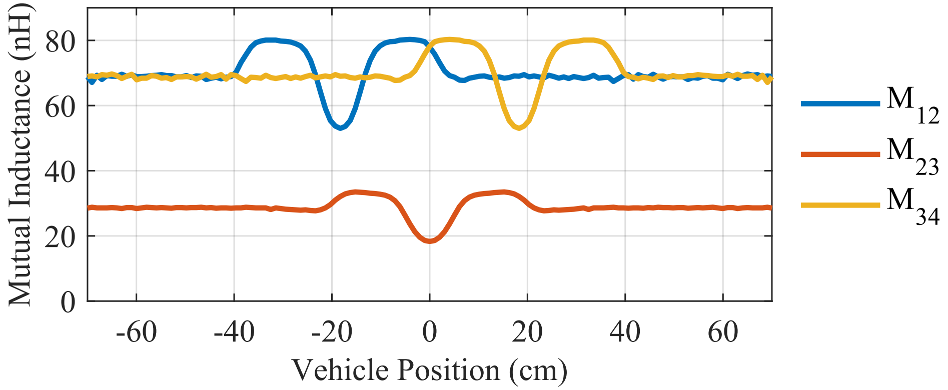
Challenge: Self-inductances, mutual inductances, and parasitic resistances depend on vehicle position



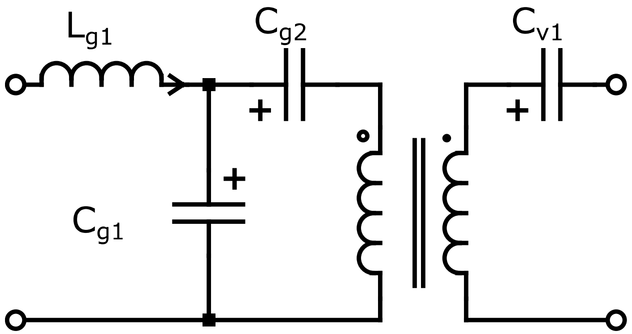
Transmitter self-inductance depends on vehicle position



FEA model used to investigate transmitter coupling, vehicle position dependent system parameters, and vehicle body losses



Mutual coupling between the transmitters also depends on vehicle position



Dead Time	0ns	600ns
L_{g1}	1.992μH	2.356μH
C_{g1}	2.004μF	2.146μF
C_{g2}	1.034μF	0.917μF
C_{v1}	174.5nF	177.9nF

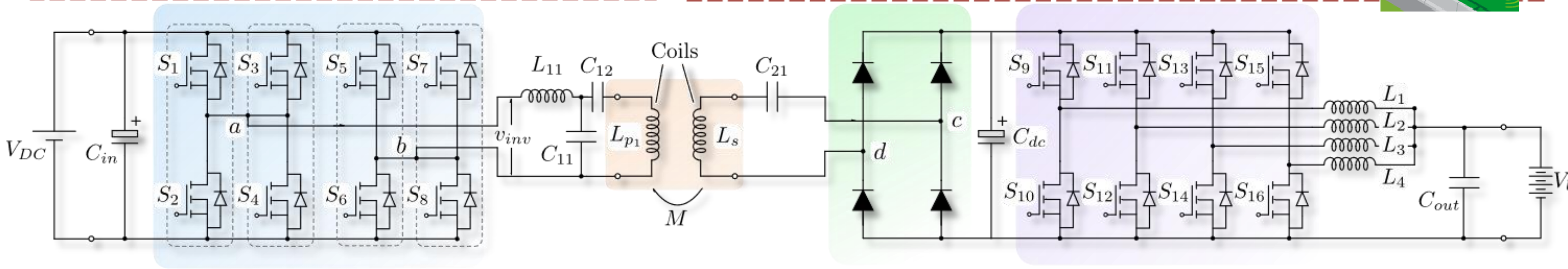
Comparison of tuning parameters for wide load-range, vehicle position independent ZVS for the ideal case (0ns dead-time) and 600ns dead-time

Architecture: To enable Optimized 200 kW+ DWPT System

Goal: Performance, power density, and optimal control

Ground Side

Vehicle Side Moving up to 75 mph



Proposed architecture for 200 kW dynamic wireless EV charging

Primary Side HF inverter
- Input: 680 V – 800 V DC
- Frequency: 85 kHz

Increases power density of
- Power electronics
- Filters
- couplers

Primary Side LCC tuning
Secondary Side Series Tuning
DD Coil architecture

Optimized for
- Controllability
- Minimal power oscillations

Secondary Side DC-DC converter
- 70 kHz
- Four phases in parallel

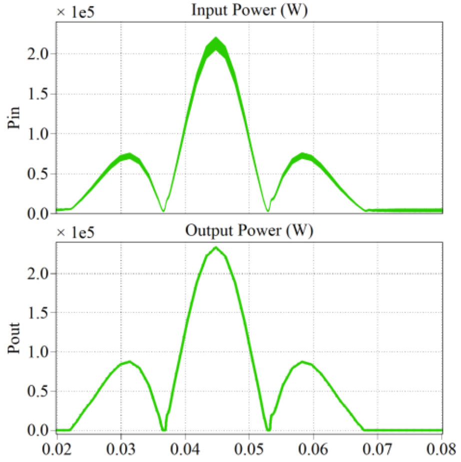
Optimized for
- Power density
- Fast dynamic response

Control: Architecture to Minimize Impact on EV Battery and Utility

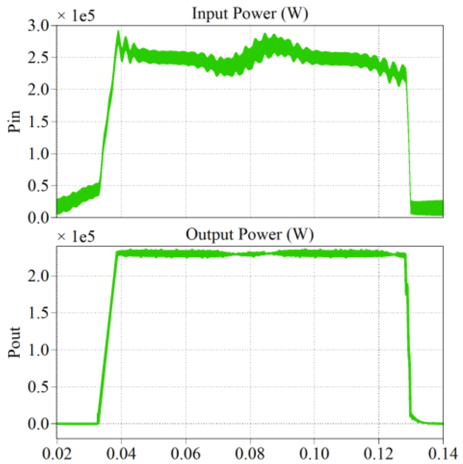
Goal: Provide accurate and wide range EV charging voltage and current control with minimal impact to utility
Issue: High power DWPT leads to pulse-like load profile, which can affect the utility grid stability and EV battery charging process

Control System Architecture

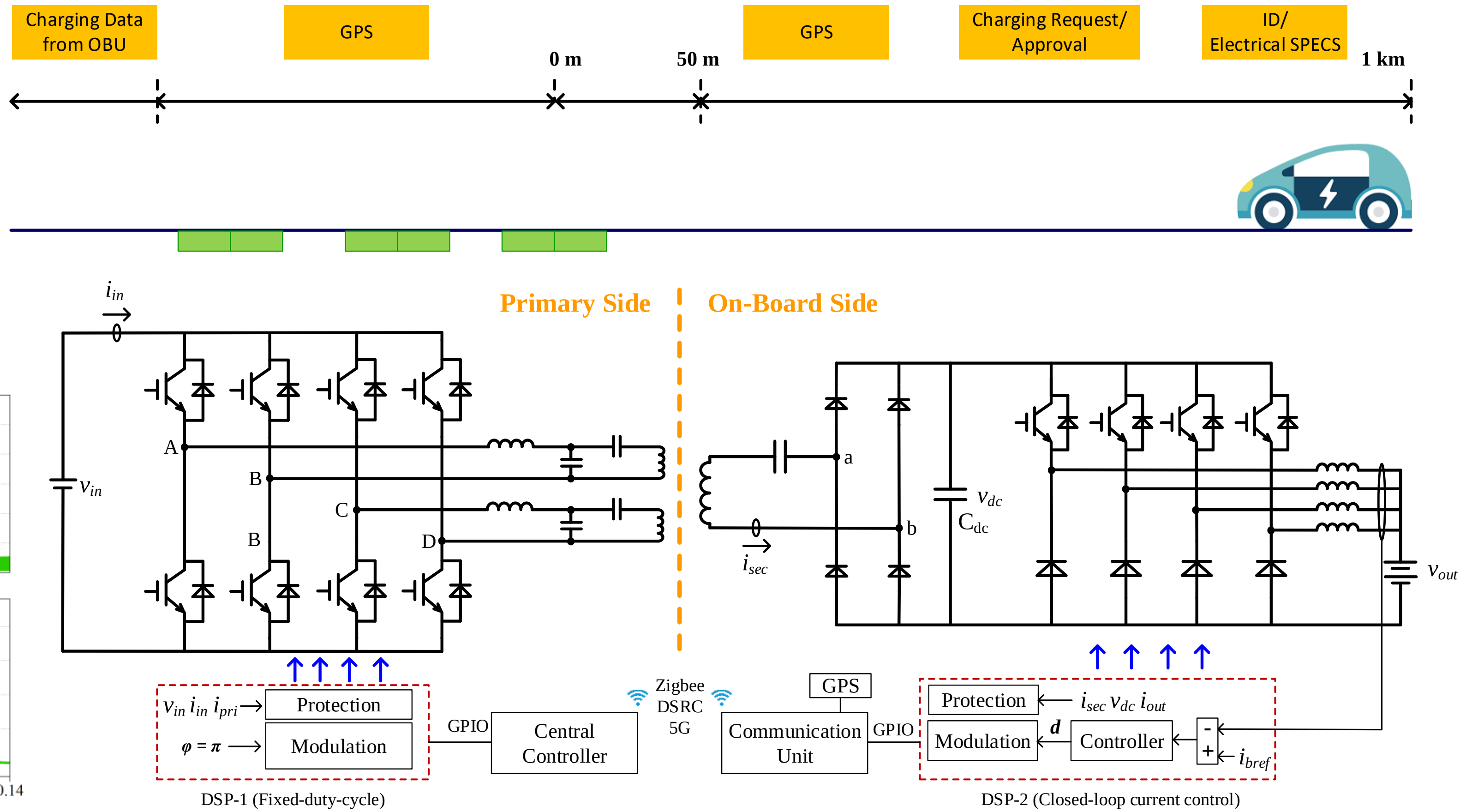
- Central controller: Charging sequence management
- Primary and on-board controller: Accurate and fast control loop
- Communication range and latency consideration



Conventional Architecture



Proposed Architecture



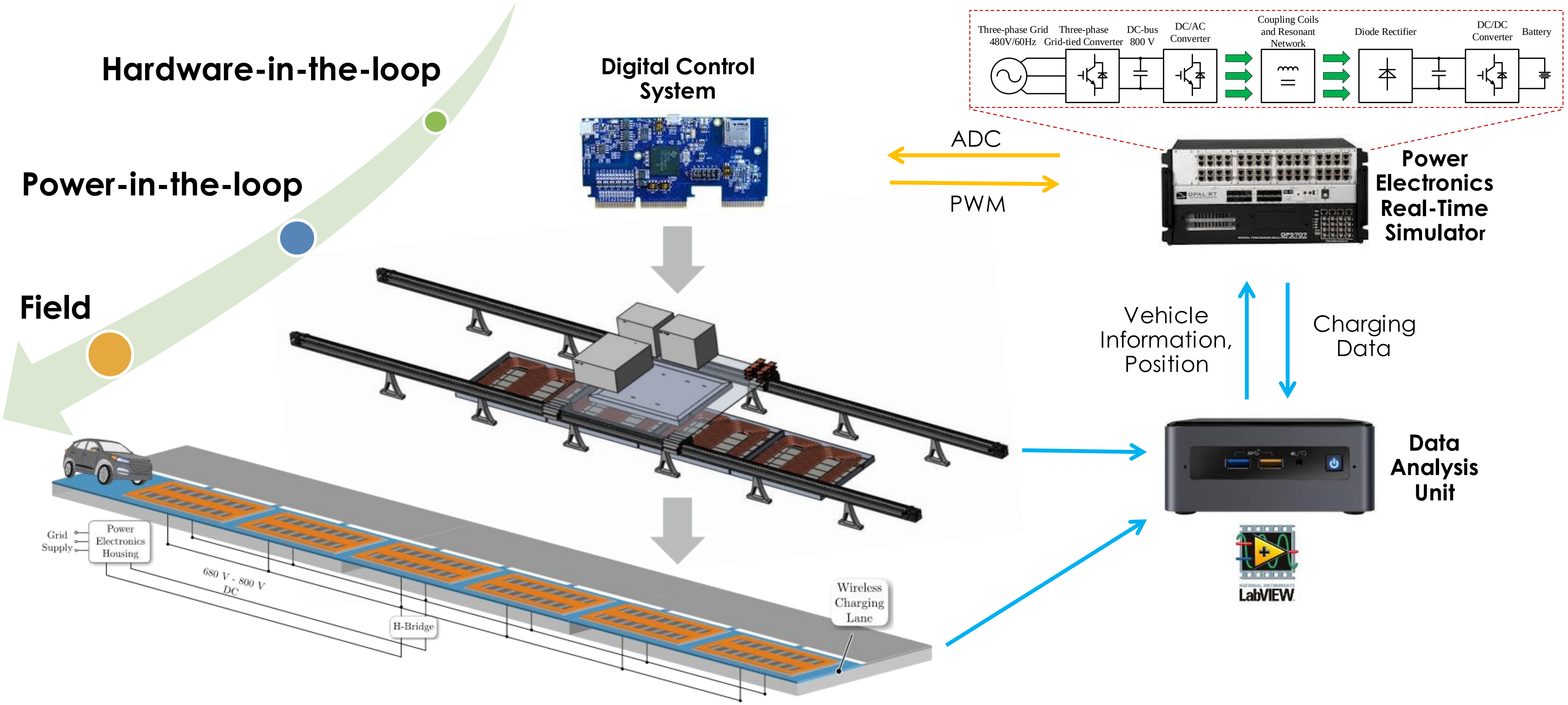
Proposed optimized dual side control architecture with primary side LCC and secondary side series tuning

Control: Proof of Concept Validation

Goal: To develop and validate dynamic models necessary to develop optimal power control strategy to realize 200 kW dynamic charging

Challenges:
- **Short power transfer window (~5 ms)**
- **High power transfer rate (200 kW)**

ORNL Dynamic Inducive Charging Emulator
- 8 m/s or ~ 18 mph → 60 feet long
- SOA Data acquisition system
- Integration with Opal RT or Smart charge management



Sequence of steps for proof of concept validation

Power Density of Power Electronics and Couplers

Goal: To enable high frequency high power density operation
Challenge: High frequency and high current operation require optimized layout and components with minimal parasitic inductances

Switching transition energy loss is function of v(t), i(t), and (dt)

→ Faster Turn-on and Turn-off transition improves efficiency

Fast current transitions lead to voltage overshoot

$$V_{overshoot} = L\frac{di}{dt}$$

- Minimize L (parasitic inductance)
- Analyze and place high performance decoupling capacitors
- Optimize layout and hardware design

CAS325M12HM2
1200 V, 325 A SiC Module

B58033I9505M001
5 µF,1300 V Capacitor

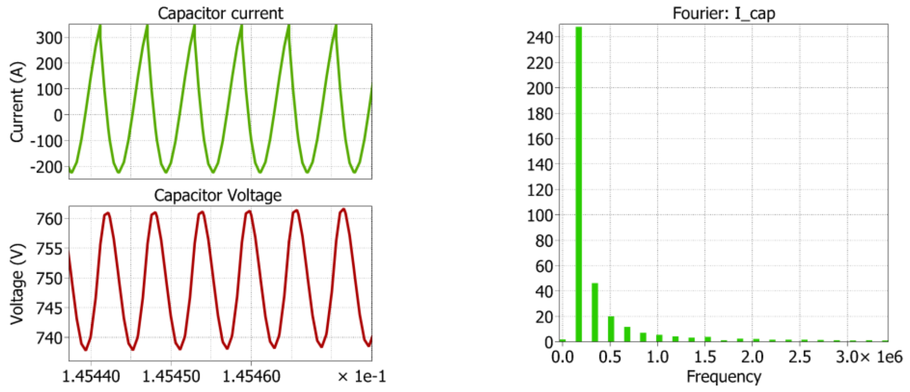
Components with low parasitic inductance are required

Low ESL (4 nH) CeraLink capacitor

Low ESL (5 nH)1200 V 325 A Wolfspeed SiC module

Summary of evaluation of power semiconductor modules for 200+ kW 85 kHz operation

	CAB450M12XM3		CAB400M12XM3		CAS325M12HM2	
Modules in parallel	1	2	1	2	1	2
Total Loss (kW)	4.144	3.879	2.571	2.025	2.299	**1.821**
Inverter Efficiency	0.983	0.984	0.989	0.991	0.990	**0.992**



Simulated capacitor current, voltage, and capacitor current harmonics for 250 kW operation

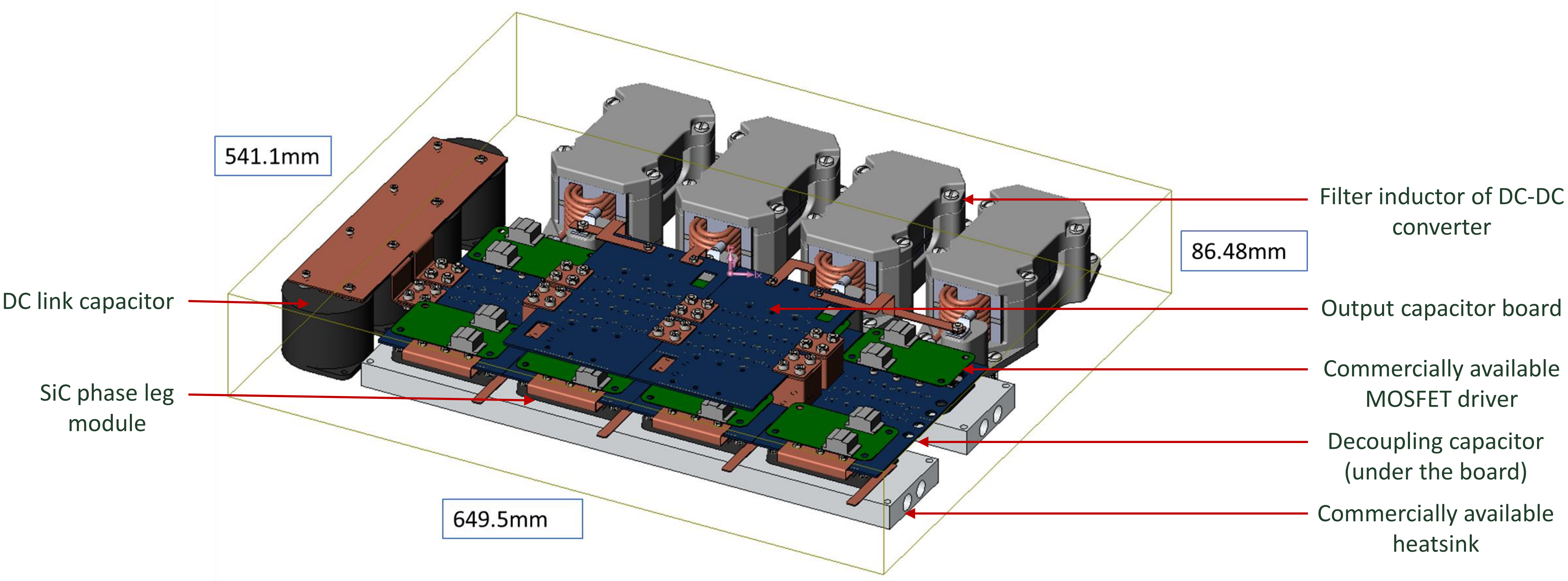
Power Electronics: 200 kW DWPT System Vehicle Side Unit

Optimized secondary side power electronics

- Integrated package for 200+ kW rectifier and DC-DC converter
- Optimized high frequency (70 kHz) 4 phase buck DC-Dc converter
- Nano-crystalline based power dense magnetics
- 649.5 mm x 541 mm x 86.48 mm

4 phase Buck DC-DC converter

- Optimized overall mass and volume
- Improved light load efficiency by load shedding
- 4 times smaller filter capacitor and inductors
- Improved dynamic response



Optimized secondary side HF rectifier and DC-DC converter

Thank You,
Questions?