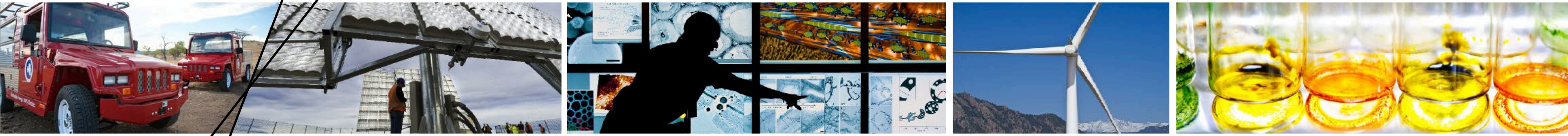
NATIONAL RENEWABLE ENERGY LABORATORY

Dynamic Wireless Power Transfer
Grid Impacts Analysis



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EPRI EV IWC Meeting
Atlanta, GA
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NREL/PR-5400-65449
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

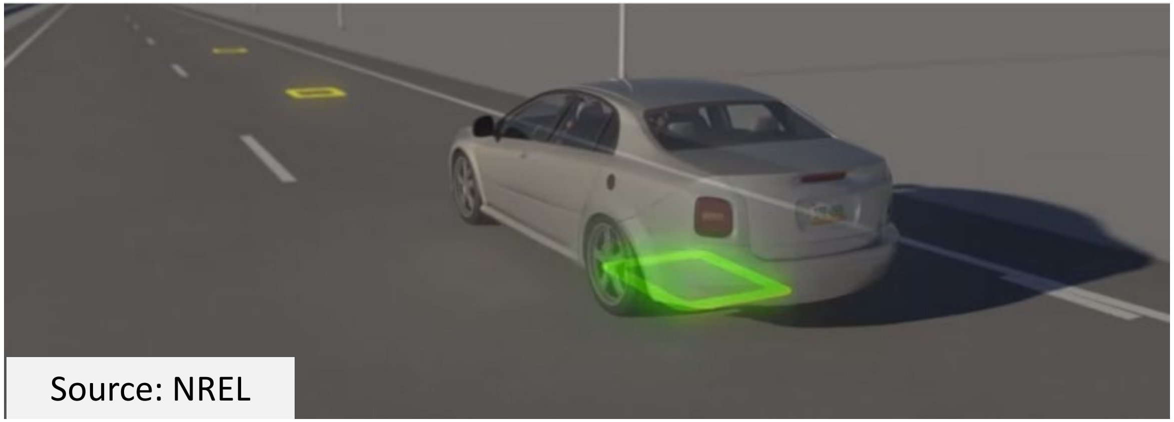
Electrified Roadways Implementation Benefits

- **Electrified Roadways Opportunity**
  - Expand vehicle utility and value
  - Integrate with renewable resources and grid operations

- **Electric Vehicles (EVs)**
  - Roadway electrification extends operable range
- **Plug-In Hybrid Electric Vehicles (PHEVs)**
  - Fully electrified operation possible even with a medium-size battery
- **Hybrid Electric Vehicles (HEVs)**
  - Fuel displacement from a more-electrified operation

Background Analyses

- Electrified roadway grid impact analysis builds on NREL's previous incremental in-motion wireless power Transfer (WPT) rollout evaluation for urban areas [1].
- Used 2010 Census Combined Statistical Area (CSA) geographic boundaries to analyze road segments and vehicle miles travelled (VMT) within region.
- Datasets from NREL's Transportation Secure Data Center [2] were paired with a specific CSA in multiple regions to investigate applications to seven CSA regions.
- Work concluded that if 1% of the road miles within a geographic region were electrified, 25% of the fuel used by the “fleet” could be displaced.
- Simulated hourly loads to show some alignment with renewables generation and potential curtailment reduction.



Source: NREL

https://www.youtube.com/watch?v=gqfih5swB8Q

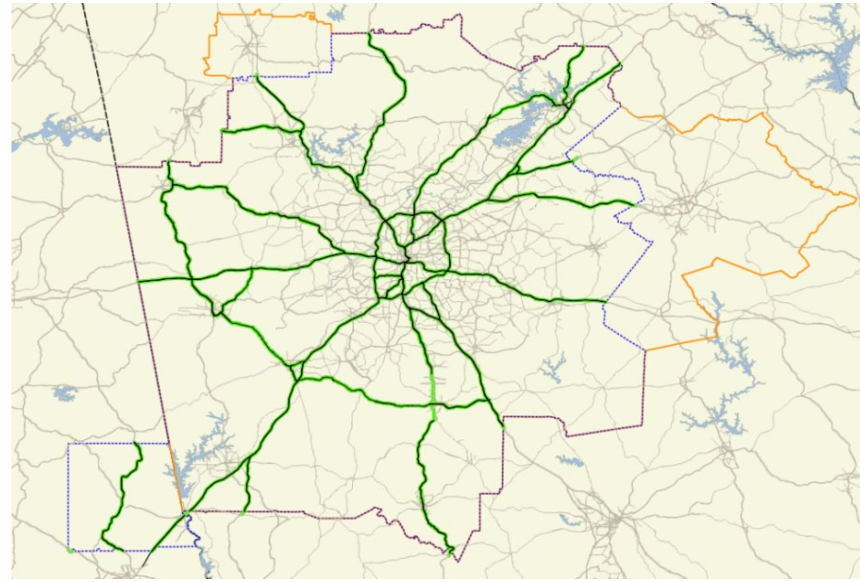
Multi-Platform Analysis Completed

- **Transit Bus Analysis**
  - Minneapolis route data used to select charge points and battery sizes
  - For same net present value as HEV solution, WPT bus achieves 50% cut in consumption from conventional

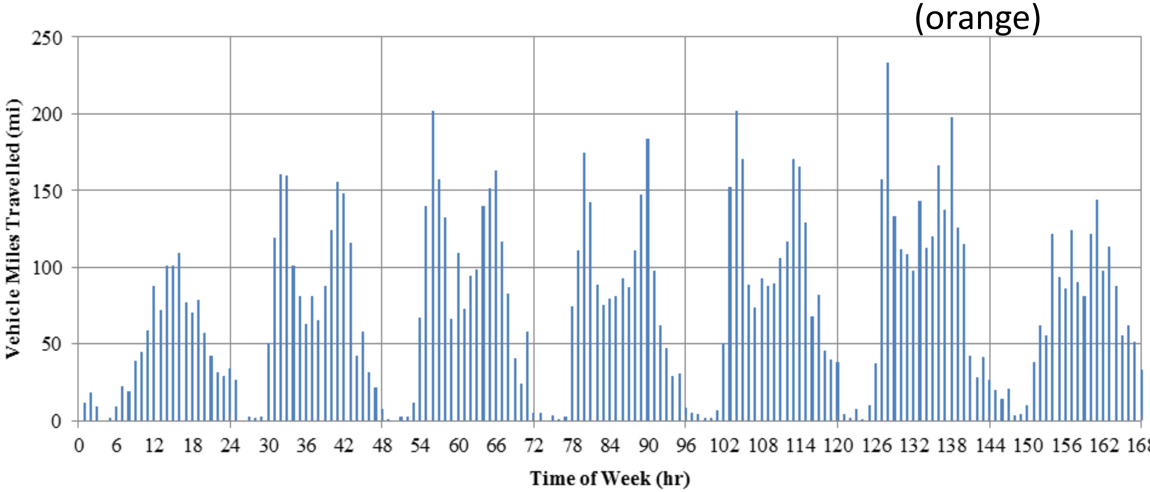
- **Heavy Truck Simulations**
  - Target moderate- to high-grade roadway segments
  - 100-kW WPT on 1.5% or greater grade allows engine downsizing and 9% fuel savings
- **Light-Duty Vehicles**
  - Target urban areas and highly utilized roads show 1% of roadway cuts consumption by 25%

ARC: 2011 Regional Travel Survey

- Down select of Atlanta CSA from the previous analysis – consistent full-week data for vehicles in the study
- Focus on most used roadways in the incremental in-motion WPT rollout provides scenario for initial deployment
- Roadway segments (green network on the map) and the ARC travel data generate weekly time distribution for vehicle miles travelled (graph below)



Previous analysis roadway (green) to selected roadway from 2013 HPMS (black) with the 2010 Census CSA Boundary (blue dashed) and 2013 CSA boundary (orange)

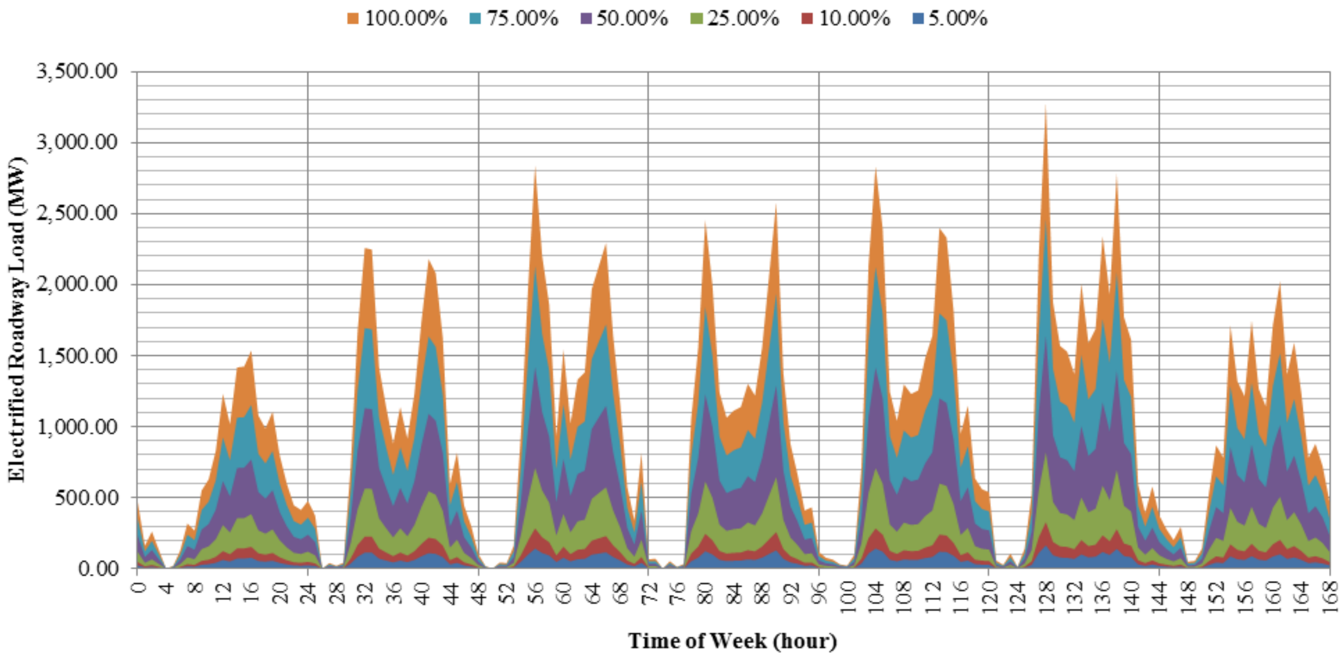


Hourly distribution of VMT on selected roadways for a "typical" week of travel

ARC - Atlanta Regional Commission [3]
HPMS – Highway Performance Monitoring System

Electrified Roadway Load Forecasting

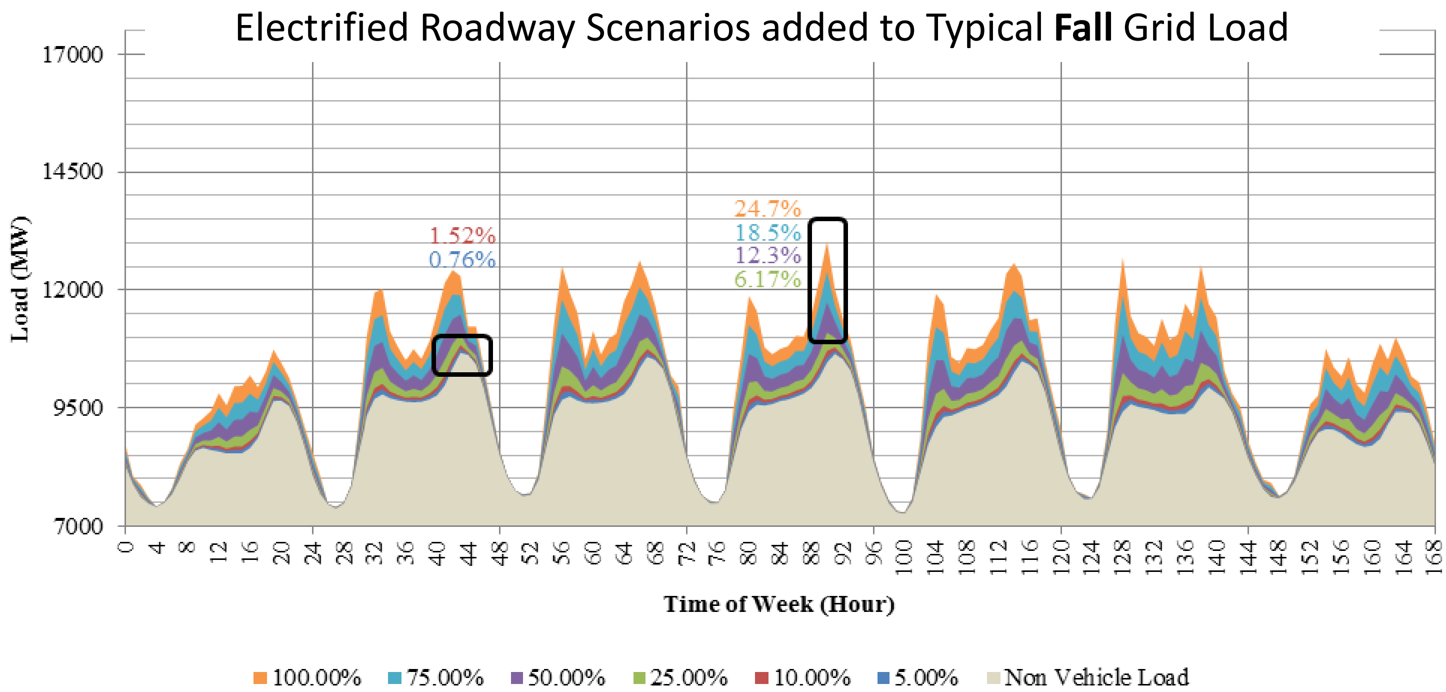
- The Federal Highway Administration's HPMS 2013 data set was used on the road segments highlighted in black on the map to produce daily VMT for the proposed electrified roadways
- The grid power used by these roads for various levels of total VMT is shown in the graph below using the weekly distribution from the ARC 2011 study
- Grid power has been calculated to <u>484 Whr</u> per VMT based on the 2014 RAV4 EV (similar 26 mpg as the production-weighted MY2014 car and truck EPA fuel economy) Representative of fleet consumption



Electrified roadway grid load for a "typical" week on the designated roads as a percent of total HPMS defined VMT

Seasonal Load Scenarios – Fall

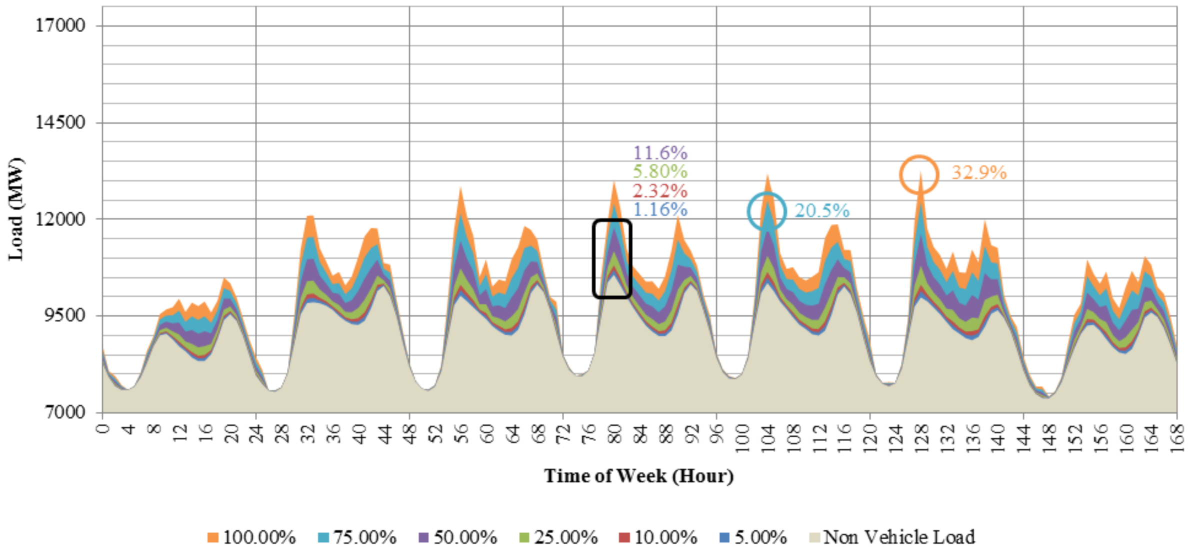
- Atlanta region grid load determined from the power consumed within the 2013 Atlanta CSA (orange line on map) taken from NREL 2013 Eastern Renewable Generation Integration Study (ERGIS) [4]
- The grid load for the four seasons has been determined by averaging the hourly load throughout a week for each hour within the season
- Graphs show hourly load growth with electrified roadway load over the baseline at from each fractional VMT scenario (colored text indicates the percent)



Vehicles : Grid
5% = 0.76%
10% = 1.52%
25% = 6.17%
…

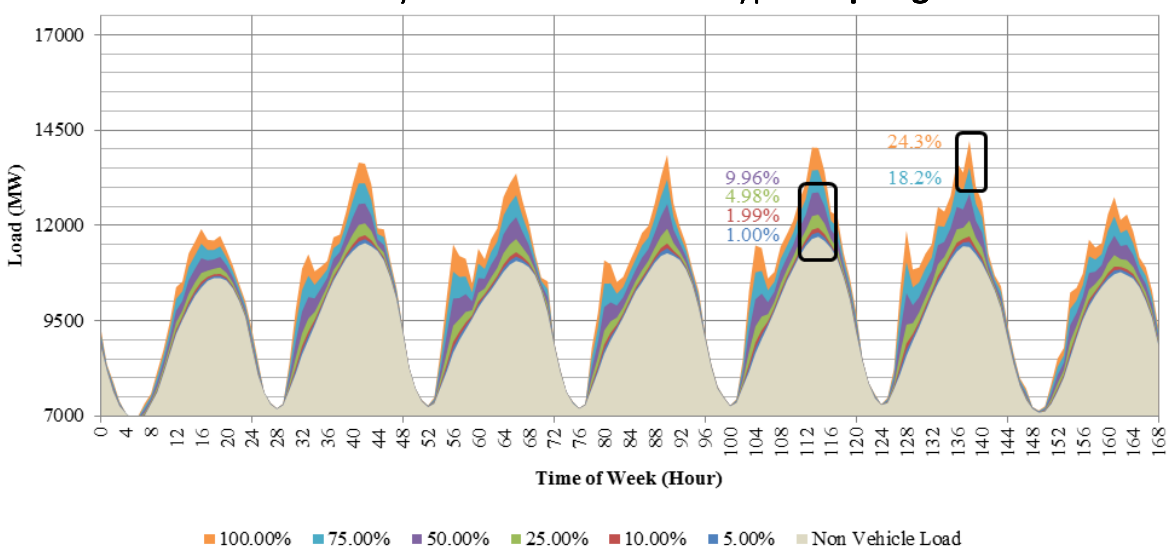
Seasonal Load – Winter & Spring

Electrified Roadway Scenarios added to Typical **Winter** Grid Load



Vehicles : Grid
5% = 1.16%
10% = 2.32%
25% = 5.80%
…

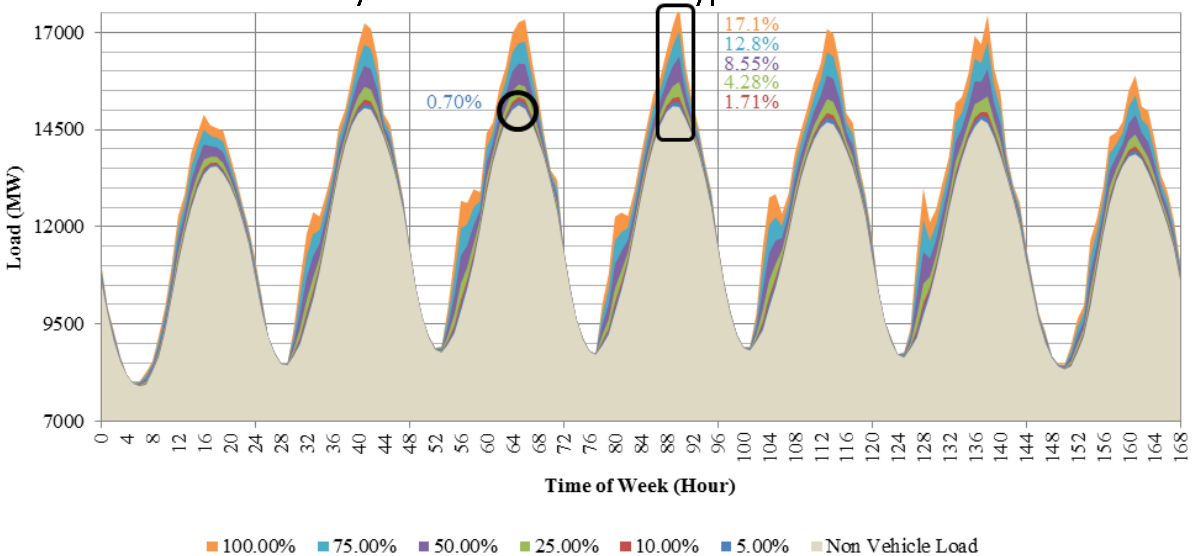
Electrified Roadway Scenarios added to Typical **Spring** Grid Load



Vehicles : Grid
5% = 1%
10% = 2%
25% = 5%
…

Seasonal Load – Summer & Highest Week

Electrified Roadway Scenarios added to Typical **Summer** Grid Load



Vehicles : Grid

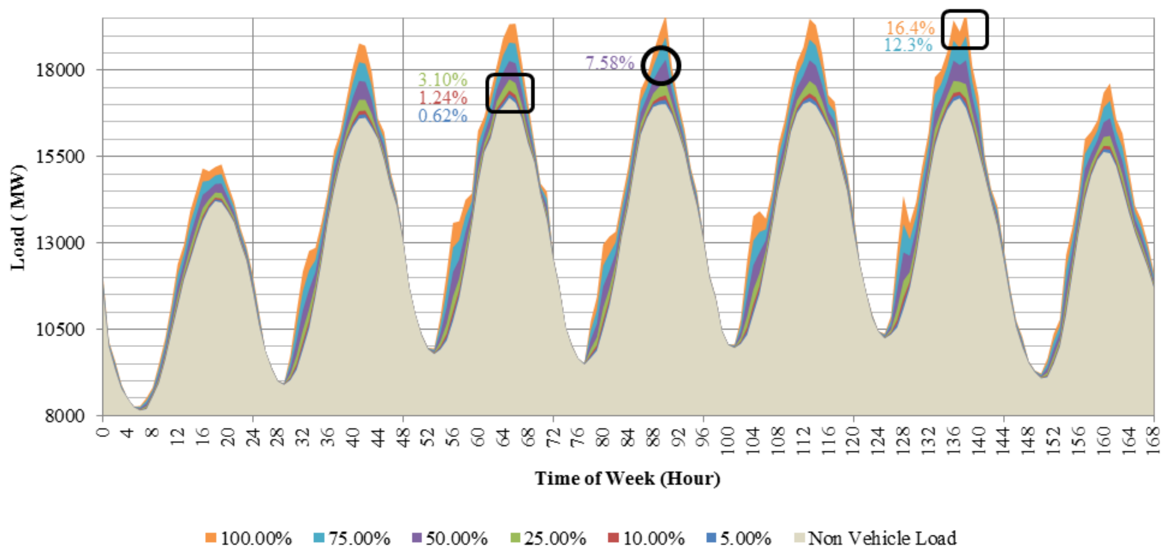
5% = 0.70%

10% = 1.17%

25% = 4.28%

…

Electrified Roadway Scenarios added to **Highest Week** Grid Load



Vehicles : Grid

5% = 0.62%

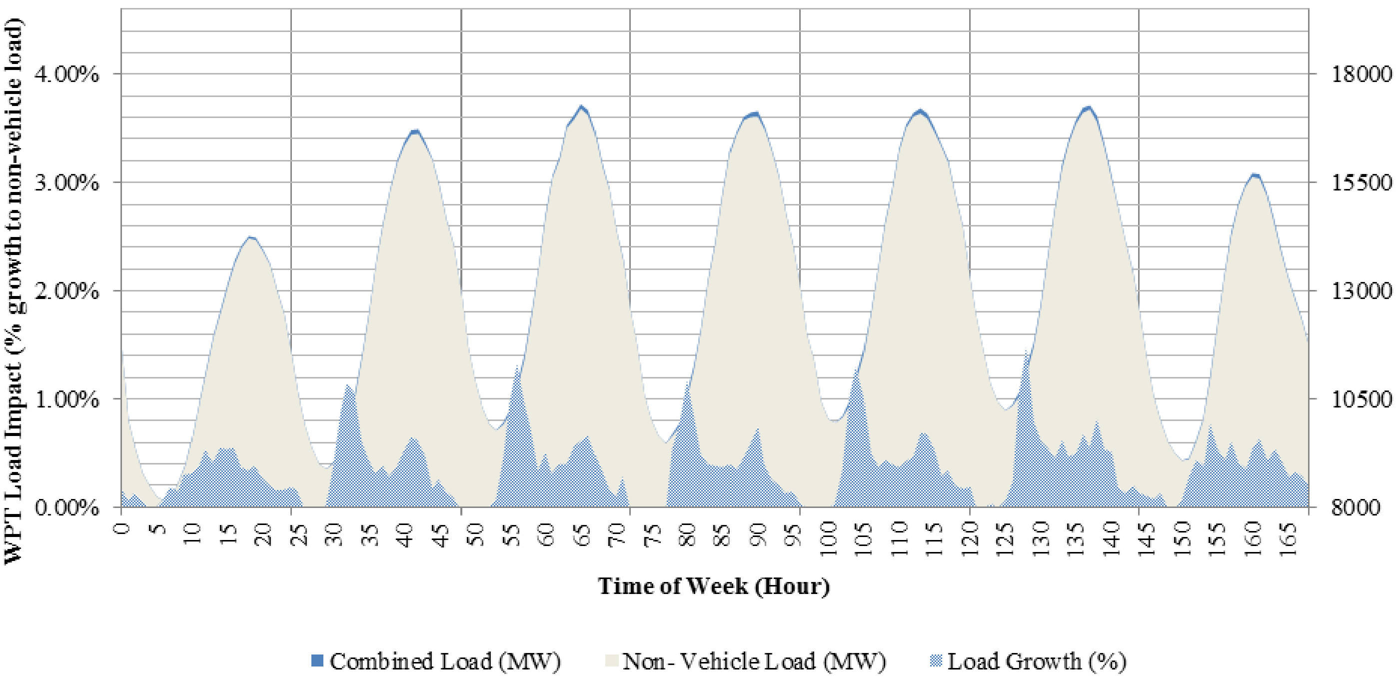
10% = 1.24%

25% = 3.10%

…

Result Discussion

- The findings indicate that electrifying 5% of all VMT on high-capacity roads in the Atlanta area could increase peak hour grid demand by a little over 100 MW, which is a little less than a 1% load increase
- 5% electrification of VMT is the lowest roadway electrification case examined in the preceding grid analysis
    - Represents an aggressive penetration of WPT-enabled vehicles
    - HEVs have been commercial for over 15 years, but still account for less than 3% of new car sales [6]



Absolute and incremental percentage load impacts from the 5% of light-duty VMT electrified roadway scenario added to the baseline highest yearly grid load week

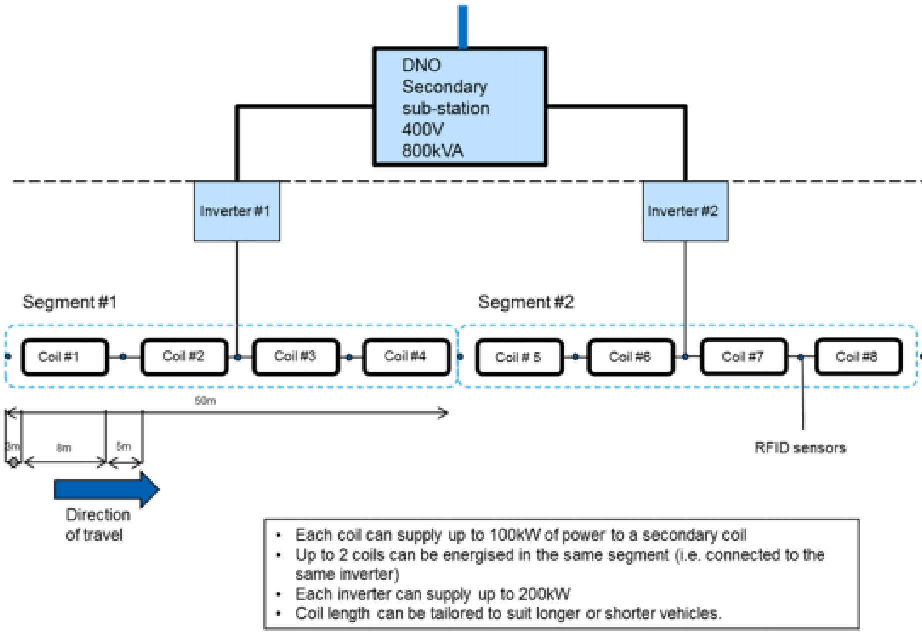
Results

- **Not included here**
  - Stationary charging of the vehicles along with electrified roadway power
  - Differences in powertrain implementations' ability to utilize roadway
    - All EVs: fully functional
    - HEVs/PHEVs: should have large enough e-drive system to maintain highway speeds
  - System layout and its impacts on power delivery and quality
  - Integration of both light-duty and heavy-duty utilization profiles

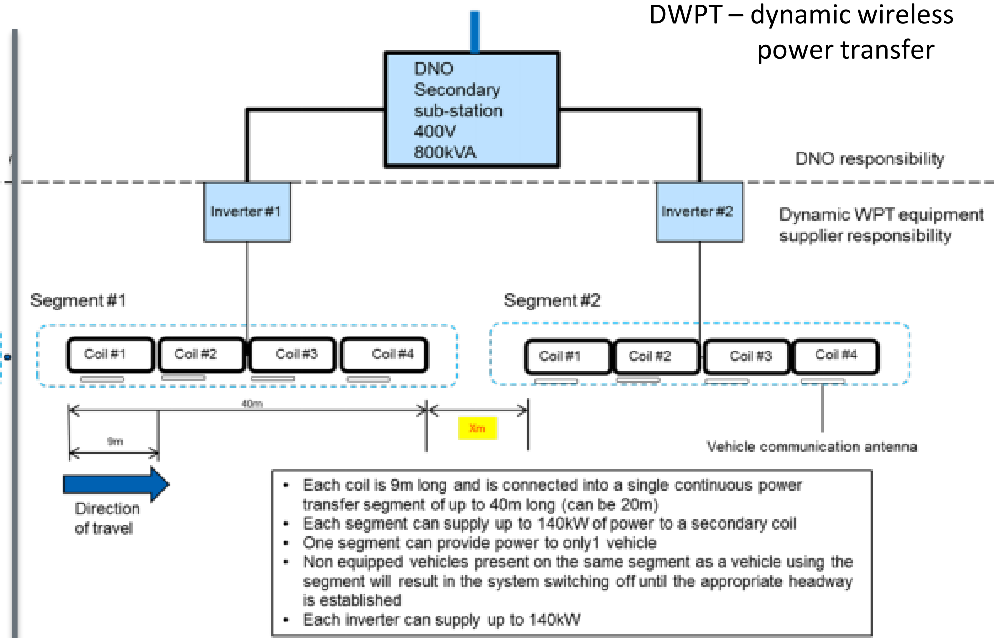
- **Future analysis and testing should consider other WPT implementation challenges**
  - Fall and winter midday trough accentuated with electrified roadway loads
  - Infrastructure and load profile differences depending on the class of vehicle (light, medium, heavy-duty) and powertrain to be served (EV, PHEV, HEV)
  - The ability to charge batteries rather than just meeting the instantaneous driving load
  - Data presents "hourly" average power and its impact
    - Analysis by Highways England in [7] has shown that sub-hour maximum power flow is influenced by the design and layout of the WPT system

Highways England Report – System Layouts

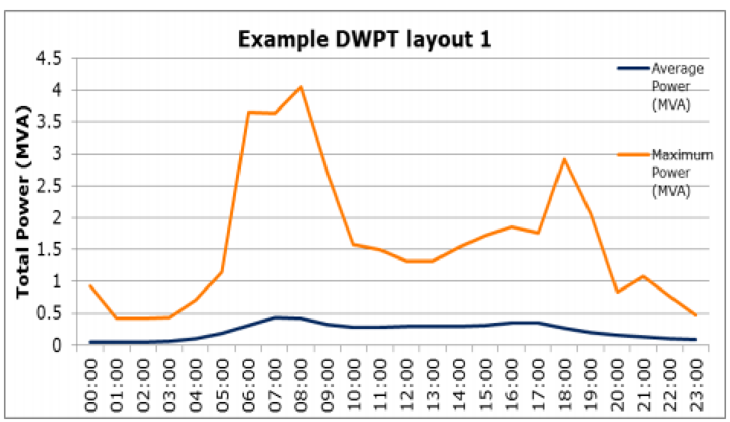
DWPT – dynamic wireless power transfer



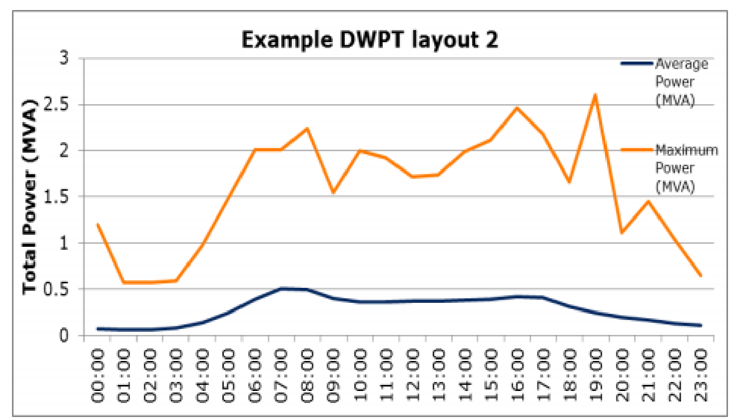
Example DWPT System- Layout 1 [7]



Example DWPT System- Layout 2 [7]



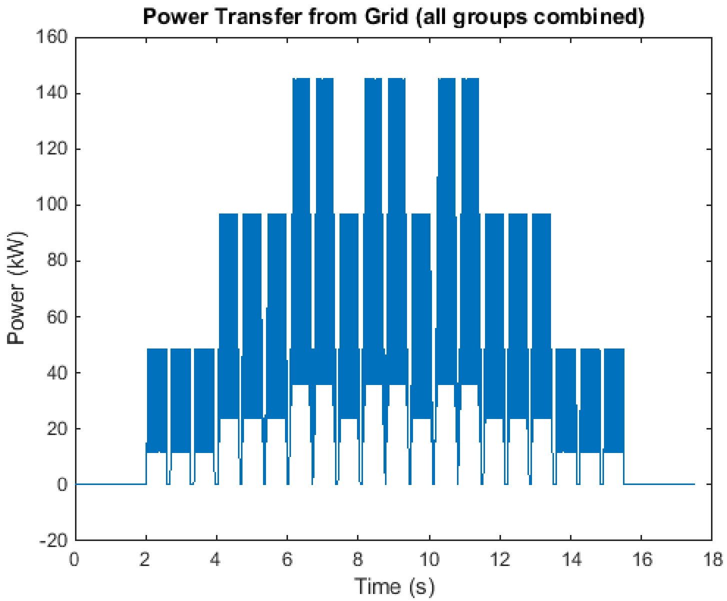
Power demand per mile of motorway for 30% light vehicle and 50% heavy vehicle penetration at 55 mph, DWPT system layout 1 [7]

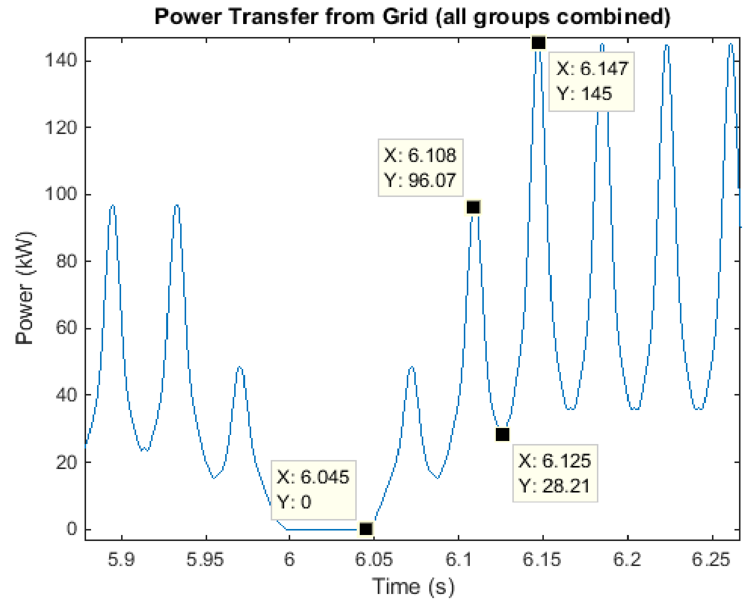


Power demand per mile of motorway for 30% light vehicle and 50% heavy vehicle penetration at 55 mph, DWPT system layout 2 [7]

Simulated Power Flows Impacted by Speeds and Headway

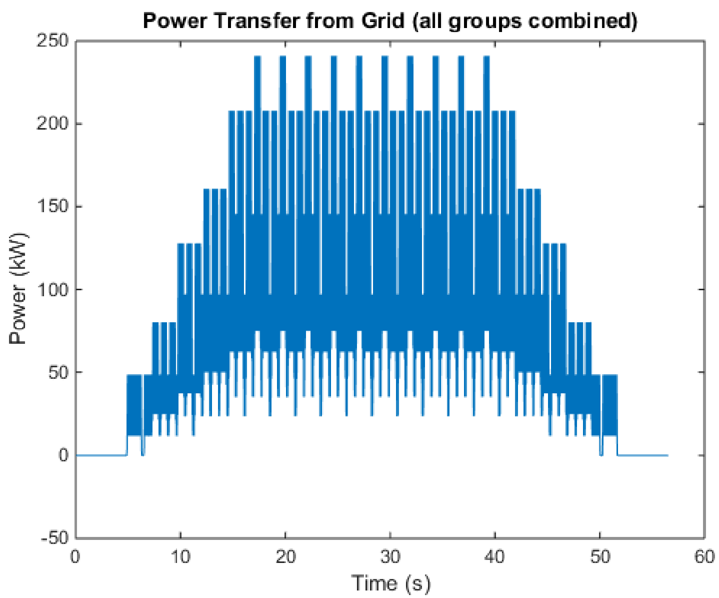
100 kph, 50 kW, 55-m headway

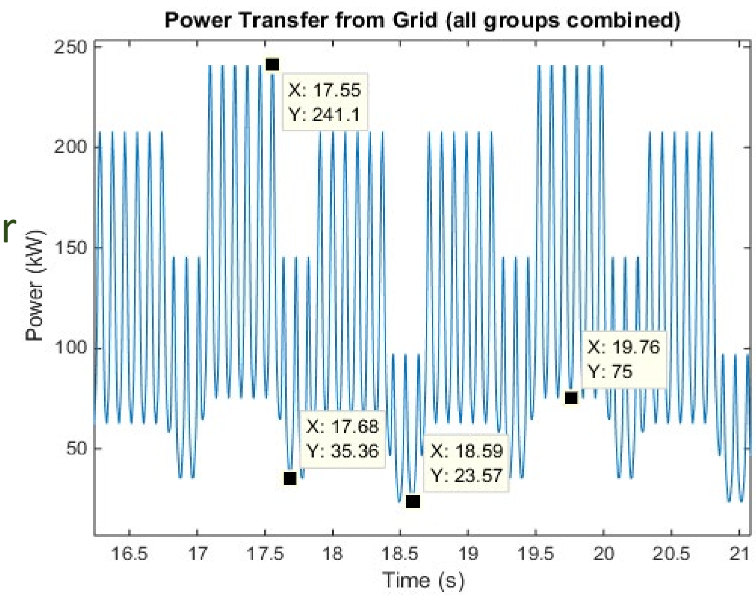




Dynamics of 0-150 kW in 0.1s

40 kph, 50 kW, 27-m headway





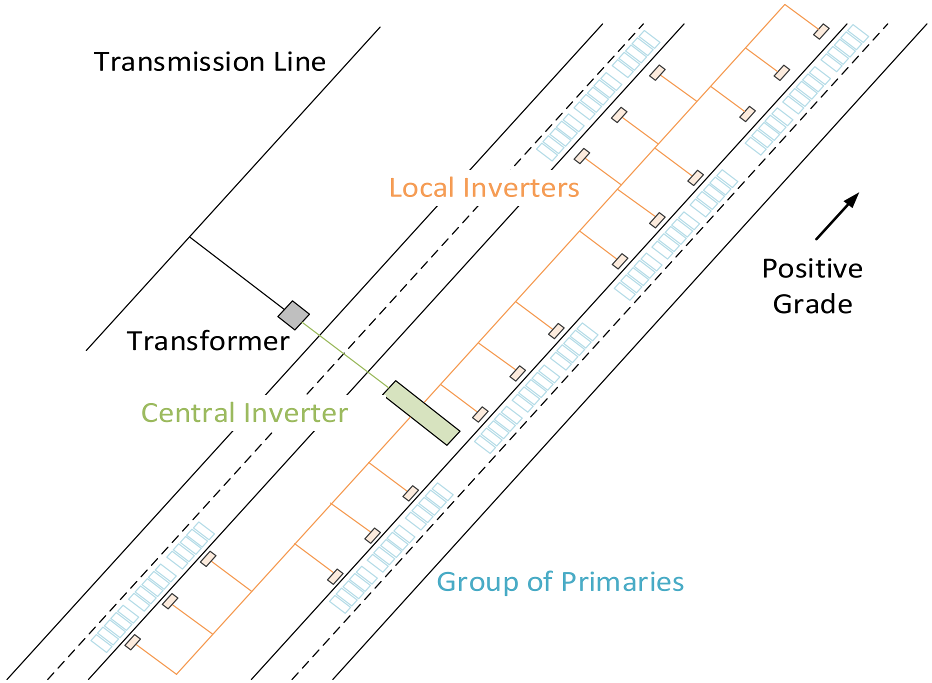
Even higher at lower speeds

Discussion – Roadway WPT Scenarios

Many WPT mechanization concepts for dynamic power transfer, one example is shown in the image below

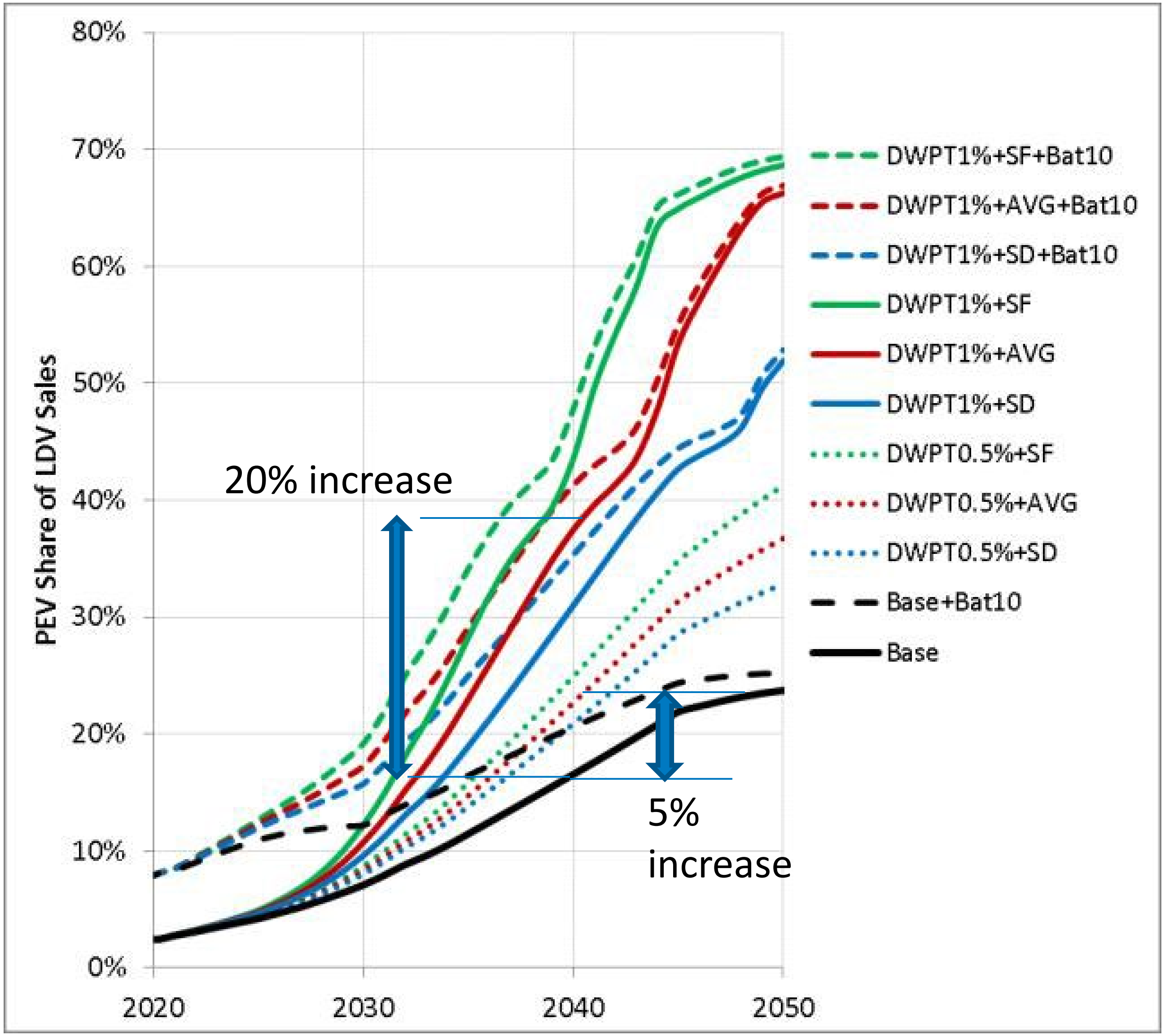
Many open questions as to what should be the design criteria for such systems

- How should the spacing of primaries along the roadway be optimized for power delivery to various load sizes?
- What is the minimum power level that secondary receivers on light-duty and heavy-duty vehicles need to provide the infrastructure flexibility?
- How does traffic impact peak power required by the grid and what limitation should be placed on transients?
- Would the use of integrated energy storage with the daily / weekly traffic patterns become a valuable grid device?



A roadway WPT system based on [8];
buffering infrastructure limits impact on power systems

Potential Impacts to Vehicle Adoption



- **ORNL analyzed several regions for vehicle preferences**
- **Roadway WPT vehicle capabilities add 5-20% to 20yr adoption potential [9]**

SF=San Francisco
SD=San Diego
AVG=Average SF/SD
Bat10=10% lower cost

Testing and Demonstration Activities

- **Multi-unit testing for grid integration**
  - Three 3-kW units on a distribution grid with varied DC sources and level 2 AC chargers
- **NREL campus shuttle application**
  - 1.5-mi loop; 60–75 circuits per day; 2–3 charging locations
- **Future opportunities**
  - Target airport shuttles with fixed routes
  - Medium-duty delivery routes

References

1) Burton, E.; Wang, L.; Gonder, J.; Brooker, A.; Konan, A. "Fuel Savings Potential from Future In-Motion Wireless Power Transfer." *Proceedings of the 3rd Conference on Electric Roads and Vehicles (CERV)*, February 2015, Park City, UT. www.nrel.gov/docs/fy15osti/63758.pdf
2) Transportation Secure Data Center, www.nrel.gov/tsdc (2015). National Renewable Energy Laboratory. Accessed 9/22/2015.
3) Atlanta Regional Travel Commission, *Regional Travel Survey: Final Report*, November 2011.
4) Eastern Renewable Generation Integration Study, http://www.nrel.gov/electricity/transmission/eastern_renewable.html . National Renewable Energy Laboratory. Accessed on 11/3/2015.
5) U.S. Energy Information Agency. "Annual Energy Review, Table 8.12A." Accessed on September 2015. http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0812a
6) Cobb, J. Jan. 6, 2015. "2014 December 2014 Dashboard." HybridCars. Accessed on 09/01/2015. http://www.hybridcars.com/december-2014-dashboard/
7) Highways England. "Feasibility Study: Powering Electric Vehicles on England's Major Roads." 07/28/2015. http://www.highways.gov.uk/knowledge/publications/1902/
8) Chen, Liang; Nagendra, G.R.; Boys, J.T.; Covic, G.A. "Double-Coupled Systems for IPT Roadway Applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics* vol. 3, no.1, pp. 37, 49, March 2015.
9) Zhenhong Lin; Jan-Mou Li; Jing Dong. "Dynamic Wireless Power Transfer: Potential Impact on Plug-in Electric Vehicle Adoption." SAE 2014-01-1965.