Analyzing Potential Grid Impacts from Future In-Motion Roadway Wireless Power Transfer Scenarios

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Analyzing Potential Grid Impacts from Future In-Motion Roadway Wireless Power Transfer Scenarios

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Summary

This work examines the grid impact of in-motion roadway wireless power transfer through the examination of the electrification of high-capacity roadways inside a metropolitan area. The work uses data from a regional travel study and the Federal Highway Administration's Highway Performance Monitoring System to estimate the electrified roadway's hourly power use throughout a week. The data are then combined with hourly grid load estimates for the same metropolitan area to determine the overlay of traditional grid load with additional load from a future electrified roadway.

Keywords: wireless charging, dynamic charging, vehicle to grid, infrastructure

1 Introduction

The electrified roadway grid impact analysis builds on the National Renewable Energy Laboratory's (NREL's) incremental in-motion wireless power transfer (WPT) rollout evaluation for urban areas [1]. That evaluation defined urban areas using the 2010 Census Combined Statistical Area (CSA) geographic boundaries to create delineations for analyzing roads and travel distances within an analysis region and excluding travel outside that region. Datasets from NREL's Transportation Secure Data Center [2] were then paired with a specific CSA in several regions to investigate seven CSA regions. The following work details the approach used to conduct grid analysis on the Atlanta, Georgia, CSA, which leverages and builds upon the work in [1].

2 Approach

2.1 Regional Travel Study: Hourly Travel

The Transportation Secure Data Center data for the Atlanta CSA comes from the Atlanta Regional Commission: 2011 Regional Travel Survey. In this survey, vehicle global positioning system travel data were collected for a one-week period on a total of 1,422 vehicles from a 727-household subset of the study. The data were collected over the study period such that all vehicles were recorded for a full week, but not all vehicles were recorded in the same week. In this grid analysis, the travel data from all 1,422 vehicles are combined to provide an hourly travel distribution on the selected high-capacity roadways [3]. It is assumed that even though the recorded travel occurs on different weeks during the study, the combination of all vehicles provides a representative sample of a "typical" travel week. While six other CSAs were studied in the previous analysis, only the data from the Atlanta CSA are considered for the grid impacts analysis for two reasons: first, the collection of vehicle travel data took place over a consistent week period, and second, the initial survey was confined to households that reside in a single CSA. The hourly distribution of vehicle miles travelled (VMT) on the roadways selected for electrification by the initial analysis is included in Fig. 1; these roadways are indicated in green in Fig. 2.

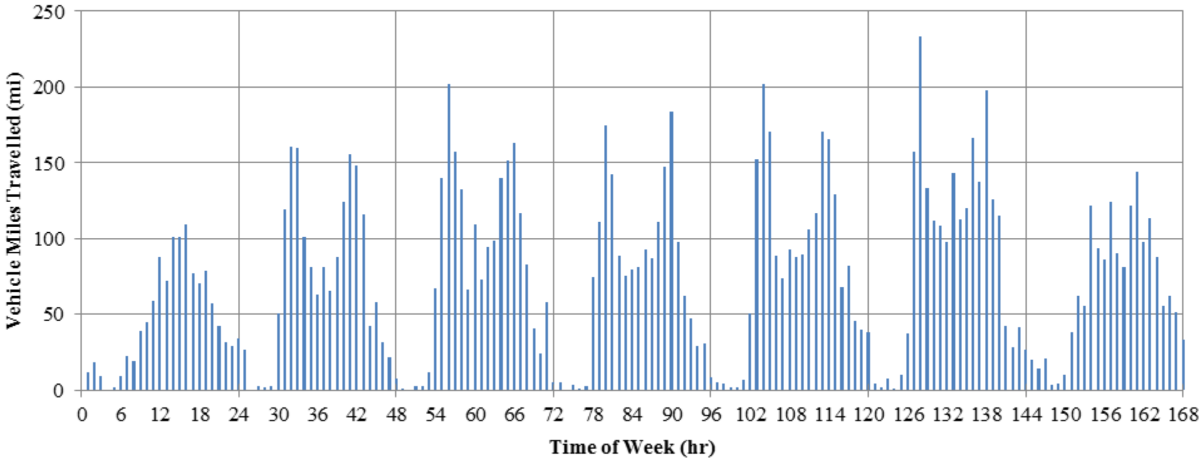

Figure 1: Hourly distribution of VMT on selected roadways for a "typical" week of travel

2.2 Highway Performance Monitoring System: Total Roadway Travel

The travel survey data provide a distribution of travel miles at an hourly resolution throughout the week. To determine the hourly power use of the selected roadways, these segments were geospatially matched to the Federal Highway Administration's Highway Performance Monitoring System (HPMS) 2013 dataset. Fig. 2 illustrates the results of this geospatial match with the road segments from the initial study shown in green and the newly selected HPMS segments shown in black. Note that the 2010 CSA boundary is identified with a dashed blue line and that the updated 2013 CSA boundary is defined in orange. The 2010 boundary is used in this work to better match the boundaries of the travel survey. The authors believe that the minor road and boundary changes between the different base map vintages do not meaningfully impact the high-level conclusions that can be drawn from this analysis.

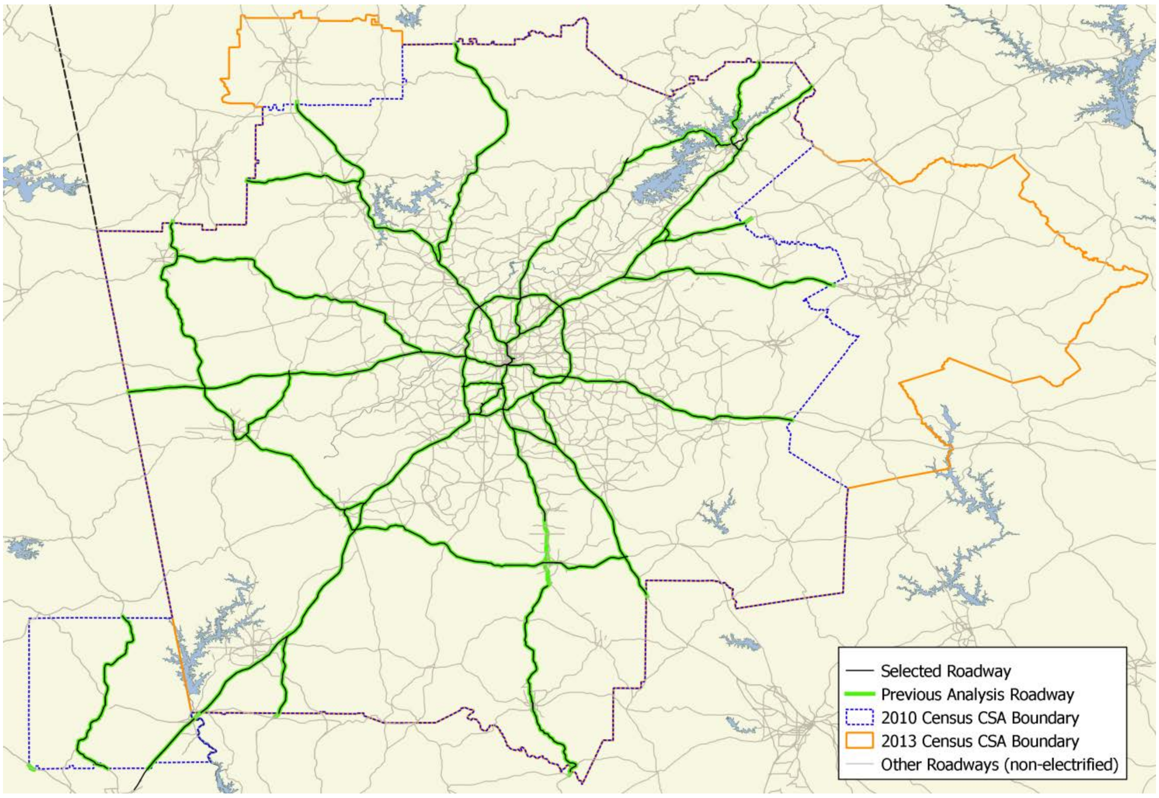

Figure 2: Comparison of previous analysis roadway (green) to selected roadway from 2013 HPMS (black) with the 2010 Census CSA boundary (blue dashed) and 2013 CSA boundary (orange)

The HPMS dataset defines the annual average daily traffic flow, the length and functional class (FC) of each roadway, and many other road segment attributes. Daily VMT for any given segment can be calculated from the product of the segment length and the annual average daily traffic that traverses the segment. This calculation yields an estimated daily VMT of 59.3 million miles for the selected roadways, which include HPMS-defined FC 1, 2, and 3 segments (shown in black solid line in Fig. 2). As a check, this same calculation was applied to travel on all Interstate highways (FC 1 roads) across the entire state of Georgia, which yielded a daily VMT estimate of 82.3 million miles. This result is not far off from that suggested by the published annual VMT statistics for urban and rural interstate travel in Georgia [4].

This HPMS-derived estimation of VMT includes all traffic on the roadways selected for electrification. The Federal Highway Administration also reports annual vehicle travel disaggregated by roadway type and vehicle type [5]. For this light-duty–focused analysis, the disaggregation was combined with the HPMS dataset to remove VMT attributed to heavy-duty vehicles. In [5], the distribution is defined by three categories: "interstate system," "other arterials," and "other." Each of these is further disaggregated into rural and urban sub-categories. To align these with the seven HPMS functional class categories (which also receive either a Census Urban Area Code or a rural area designation), NREL assumed the "interstate system" is defined as FC 1, the "other arterials" are FC 2 through FC 4, and the "other" roads are FC 5 through FC 7. Note that the removal of heavy-duty VMT is not meant to suggest that an electrified roadway system should or could only be designed separately for light-duty or heavy-duty vehicles. This analysis simply focuses on light-duty vehicles and leverages the light-duty Transportation Secure Data Center dataset to estimate hourly VMT distribution throughout a week. The addition of heavy-duty VMT to the WPT system would impact the shape and scale of the hourly VMT distribution as has been indicated in [6].

2.3 Electrified Roadway Load

Total energy demand for the electrified roadway is calculated by multiplying the VMT results from the previous discussion by the energy consumption of individual vehicles on the roadway. NREL applied the following assumptions for calculating individual vehicle energy demands: 1) vehicles consume only the energy needed to traverse the distance of the electrified roadways (i.e., charge-neutral travel); 2) energy use per mile travelled is based on U.S. Environmental Protection Agency (EPA) combined city/highway consumption; and 3) the energy use is based on a vehicle representative of the average energy efficiency of the national light-duty fleet. Hourly power consumption, represented as an average power over the hour period, is calculated based on the temporal VMT distribution from the Atlanta Regional Commission survey's global positioning system-instrumented vehicles and scaled to match the HPMS total average daily VMT.

Average energy efficiency of the national light-duty fleet is determined to be 24.3 mpg (4.12 gal/100 mi) by combining the production-weighted car and truck EPA fuel economy estimates and fleet proportions for 2014—i.e., 27.9 mpg (3.58 gal/100 mi) and 61.3% for cars, and 20.1 mpg (4.98 gal/100 mi) and 38.7% for trucks [7]. The 2014 Toyota RAV4 is used as a representative vehicle to compare fuel economy of a conventional vehicle to that of a similar electrified vehicle. The conventional 2014 RAV4 has an EPA city/highway combined fuel economy of 26 mpg (3.8 gal/100 mi) for the front-wheel drive automatic and 25 mpg (4.0 gal/100 mi) for the all-wheel drive automatic. The 44 kWh/100 mi (or 440 Wh/mi) EPA rating for the electric version of the RAV4 may therefore provide a reasonable basis from which to estimate the average per-mile efficiency of vehicles using the electrified roadway [8]. The EPA energy consumption is determined based on SAE J1634, which includes the conductive charging system efficiency. Given that electrified roadway charging is likely to have a lower efficiency than conductive charging, the estimated grid load is adjusted to 484 Wh per vehicle-mile based on [9] and [10]. Fig. 3 provides the resulting hourly power use of the selected roadways for various assumed percentages of total light-duty VMT that are replaced by WPT-enabled vehicles.

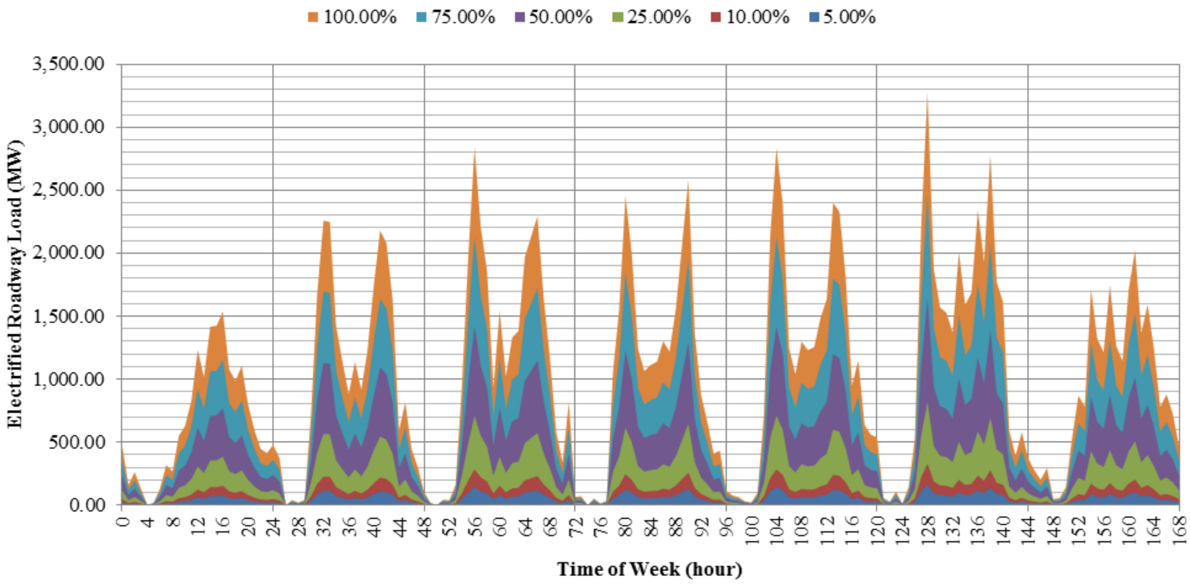

Figure 3: Electrified roadway grid load for a "typical" week on the designated roads

2.4 Grid Load Modeling Approach

Grid load information for the Eastern Interconnect areas in this study was taken from the *Eastern Renewable Generation Integration Study* (ERGIS) developed by NREL [11]. For the ERGIS, historical hourly load data from 2006 were obtained and scaled to reach projected 2026 load levels, which required several steps. The 2006 hourly load profiles for each region were created by summing Ventyx Velocity Suite 2006 hourly profiles for the Ventyx transmission zones within each of the ERGIS sub-regions [12].

The first scale factor was calculated using 2006 to 2011 state retail load data [13]. For this process, the increase or decrease in load from 2006 to 2011 was found for each state in the U.S. Eastern Interconnect. The second scale factor was calculated using Energy Information Agency Annual Energy Outlook projected growth in retail electricity sales for each of the National Energy Modeling System Electricity Market Module (EMM) regions [14]. Scale factors for 2011 to 2026 were calculated as the projected 2026 load divided by the 2011 load for each EMM region.

To combine the two sets of scale factors, the state scale factors had to be aggregated to the EMM regions. This was done by mapping the states to the EMM regions and then calculating a load-weighted scale factor for each region. The two sets of scale factors were then compounded to get an aggregate for the entire 2006–2026 period for each EMM region. Hourly load information for the Atlanta region was then determined by identifying the load from nodes within the Atlanta 2013 CSA geospatial boundary identified by the solid-orange line in Fig. 2.

3 Results

3.1 Seasonal Variation

Grid load information for the transmission nodes within the Atlanta 2013 CSA is averaged on an hourly level for each season to develop a seasonally averaged "typical" week of grid load. The electrified roadway load for the "typical" week is then added to each seasonal week to determine the combined load. The results are shown for each season in Fig. 4 through Fig. 7. These figures identify six cases for a range of the total light-duty VMT, which are considered in order to understand the electrified vehicle rollout on the entire electrified roadway network. The numbers in colored text on each figure indicate the percent load growth over the baseline at the new seasonal average load peak resulting from each fractional VMT electrification scenario.

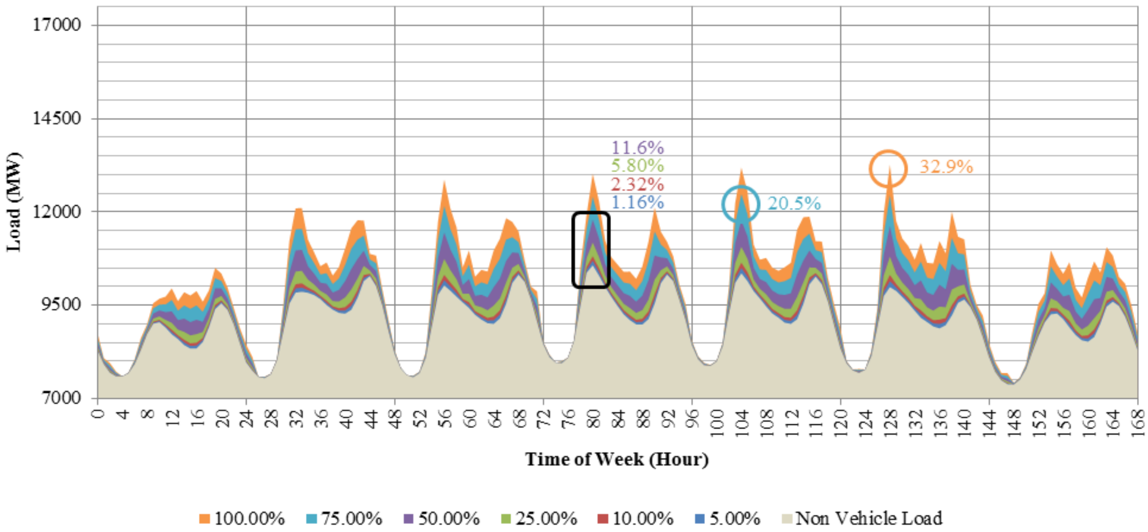

Figure 4: Electrified roadway scenarios added to typical winter grid load

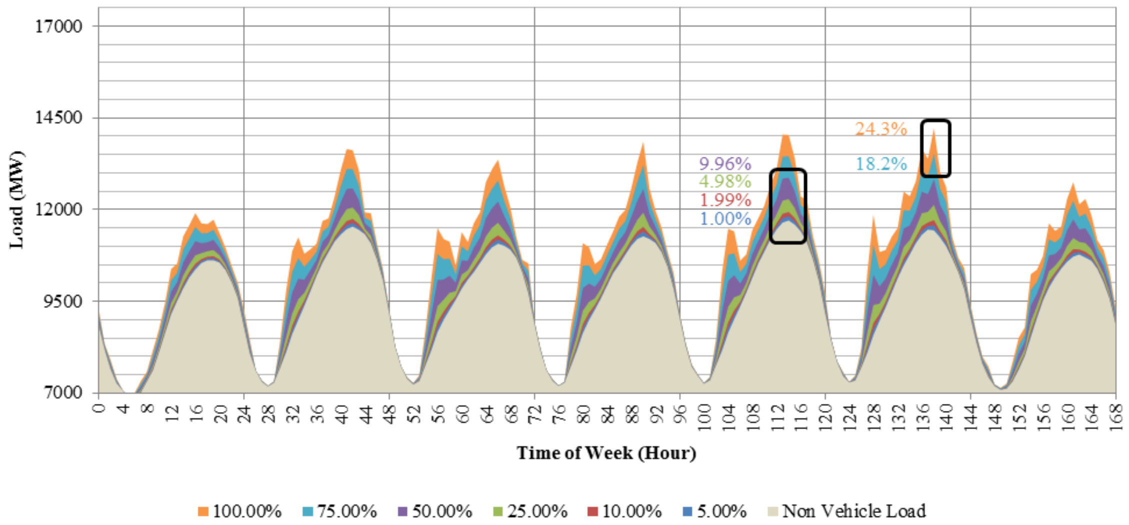

Figure 5: Electrified roadway scenarios added to typical spring grid load

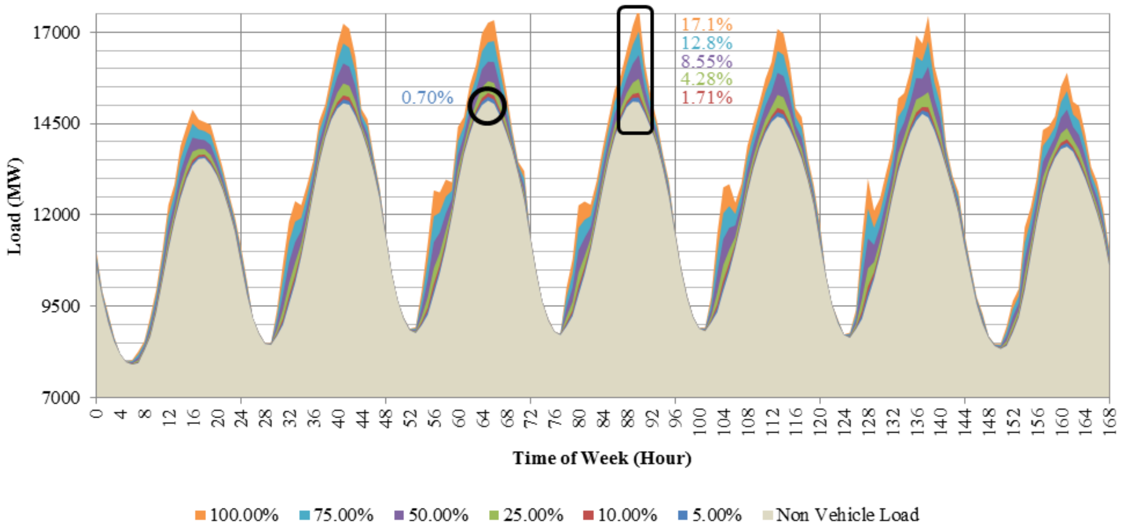

Figure 6: Electrified roadway scenarios added to typical summer grid load

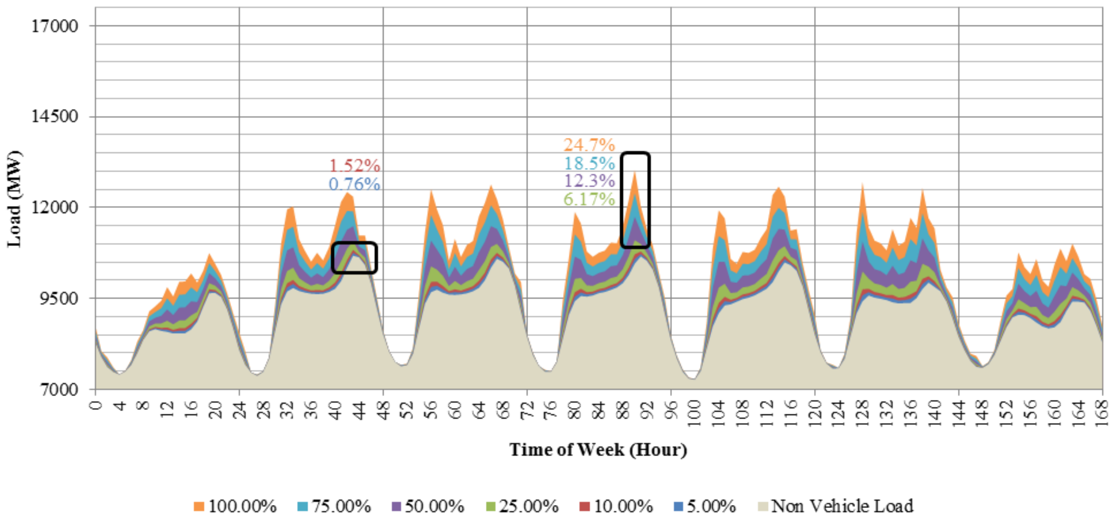

Figure 7: Electrified roadway scenarios added to typical fall grid load

The seasonal average results show that the electrification of 5% of light-duty VMT would result in a load growth between 0.70% and 1.16% for the peak load hour in the weekly average for each season. Similarly, the load growth for the electrification of 100% of light-duty VMT would result in an increase between 17.1% and 32.9%. The magnitude of this load growth at the peak hour for the summer seasonal average load is between 107 MW and 2.60 GW for electrification of 5% and 100% light-duty VMT, respectively.

These results show that the effect this load growth would have on power generation requirements will vary by season as the overlap of grid peak load from non-vehicle load and peak travel periods change throughout the year. It should be noted that the seasonal impact of traffic flow could not be accounted for in this study given the available data for the Atlanta region. Further, additional vehicle load from daytime and nighttime static charging of battery electric vehicles that may likely utilize these roads and be incentivized from its deployment have not been included in the total grid load. The illustrated scenarios instead reflect a case where the electrified vehicles utilize fuel for their remaining daily travel off the electrified roadway (such as would be the case for WPT-enabled hybrid electric vehicles).

Load growth experienced for the 5% VMT electrification case in all seasonal average weeks is not enough to move the peak hour of weekly power from the hour in which it occurs for the non-vehicle load alone. For the higher-percent VMT electrification cases in which the traffic load was significant enough to move the hour in which the weekly peak load occurs, the new peak hours occur at either 08:00 or 18:00, corresponding to either the morning or early evening traffic peaks. This overlap exacerbates the midday trough in load that is seen in both the fall and winter seasonal average weeks where the morning and afternoon peaks in travel overlap with similar peaks in grid load. In the spring and summer, the main overlap occurs with the early evening peak in both grid load and travel.

3.2 Highest Yearly Load

The peak hour of non-vehicle grid load for the Atlanta CSA occurs at 17:00 on Tuesday (or hour 65 for the week) of week 31 in July/August for the ERGIS 2026 dataset. This week also contains the second, third, and fourth highest hourly loads, which occur at hours 137, 136, and 113, respectively, and is the highest week for total energy consumption throughout the year. Fig. 8 shows the result of adding the "typical" week travel profile load to this highest load of the year week.

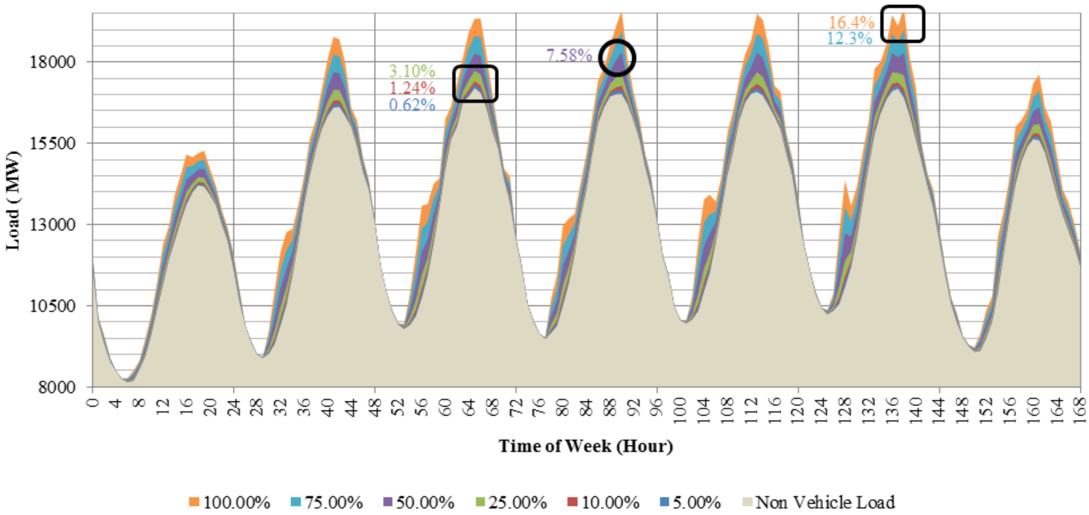

Figure 8: Electrified roadway scenarios added to the highest yearly grid load week. The numbers in colored text indicate the percent load growth over the baseline at the new seasonal average load peak resulting from each fractional VMT electrification scenario.

The highest yearly load results show that the electrification of 5% of light-duty VMT would result in a load growth of 0.62% for the peak load hour in the week; similarly, the load growth for the electrification of 100% of light-duty VMT would result in an increase of 16.4%. The magnitude of this load growth at the peak hour is between 107 MW and 2.78 GW for electrification of 5% and 100% of light-duty VMT, respectively.

These results are consistent with the peak hour trend seen in the summer seasonal average in which the new peak hour of load for the 50%, 75%, and 100% electrification of VMT cases occur in the early evenings at 18:00 when there is an overlap in evening peak traffic and non-vehicle grid load. For the 5%, 10%, and 25% of VMT electrification cases, the hour of peak grid load does not change in the highest yearly load week scenario. This is consistent for the 5% of VMT case in the summer seasonal average week scenario, but a change from that scenario for the 10% and 25% cases due to the greater amounts of load growth required to shift the peak hour in the highest load week relative to the average summer week scenario.

4 Analysis

The impact to the grid from electrified roadways is dependent on the adoption rate of these vehicles and the precipitating VMT that become electrified. While 5% electrification of VMT is the lowest roadway electrification case examined in the preceding grid analysis, it should be noted that this assumption represents an aggressive penetration of WPT-enabled vehicles. Considering the historic example of hybrid electric vehicles, which have now been commercially available for over 15 years, recent data show them still accounting for less than 3% of new car sales [15]. In addition to the considerations of a technology's maturation rate and the pace at which it gains market share in new vehicle sales, the relative proportion it achieves in the entire fleet depends on the scrappage rate for legacy vehicles, which is predicted to be 6.56% for the light-duty fleet for 2020 to 2050 [16]. The difference between the baseline (non-vehicle load) and the 5% VMT electrification cases therefore represents a tremendous jump in vehicle technology adoption. The following discussion gives context for the corresponding increase in grid demand.

Fig. 9 further illustrates the load growth for the 5% VMT electrification case relative to the highest load week of the year. The maximum percentage load increase for the week is slightly over 1% and corresponds to the weekday morning traffic peak. However, the overall peak load still occurs during the evening traffic peak, at which point the roadway electrification load adds less than 0.7% to the overall peak.

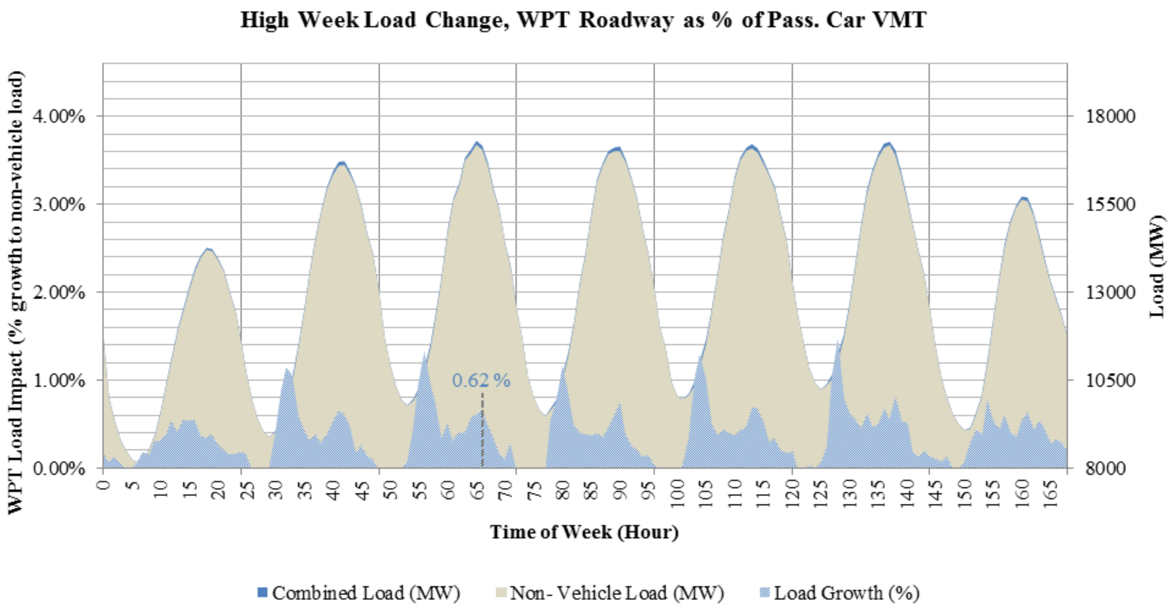

Figure 9: Absolute and incremental percentage load impacts from the 5% of light-duty VMT electrified roadway scenario added to the baseline highest yearly grid load week

The additional 0.62% of grid load from the electrified roadway at the peak hour can be compared to the historical level of grid load growth shown in Fig. 10. This figure provides the annual load growth as calculated from both a linear fit and a polynomial fit to historical summer non-coincidental peak load for all interconnects of the grid. The long-term linear fit indicates annual growth rates between 1.6% and 2.5%, which exceed the peak load growth that would be required to support the 5% VMT electrification scenario. What is more, the 7.7% single-year growth rate (from 2004 to 2005) shown in Fig. 10 exceeds the increased grid demand requirement from Fig. 8 for the 50% VMT electrification case. The amount of load growth that electrified roadways present for peak hour energy consumption does not appear to be a significant challenge to generation capacity given the long period of time that it will likely take for vehicles capable of using this infrastructure to achieve substantial penetration levels into the vehicle fleet.

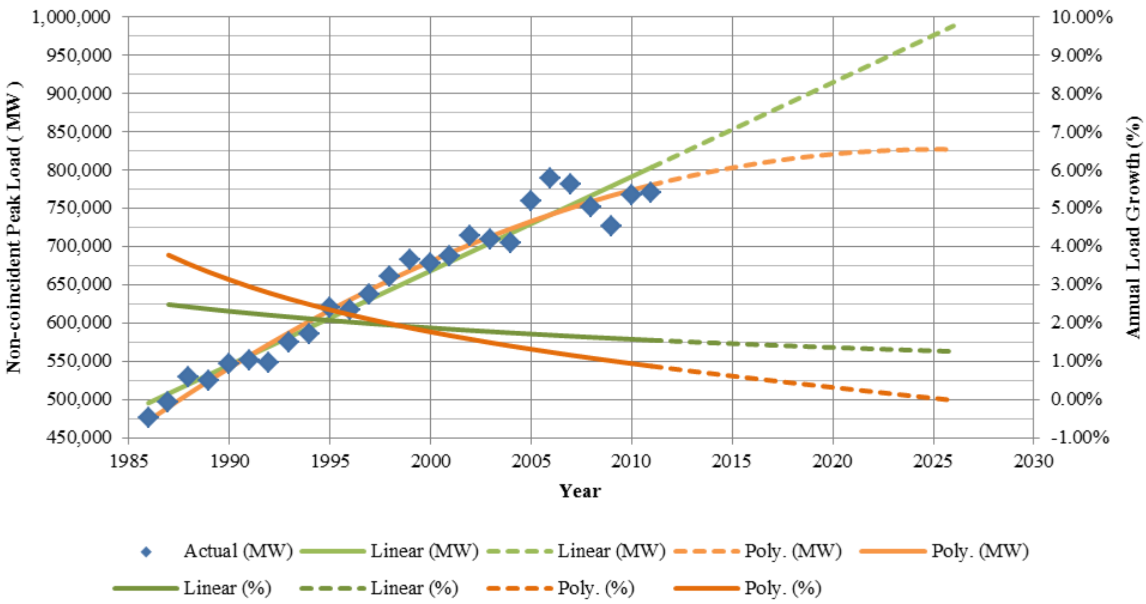

Figure 10: Historical non-coincident peak load with linear and polynomial fits and non-coincident peak load for the summer period for all interconnects on the grid from 1986 until 2011. [17]

5 Conclusions

The grid impact analysis presented builds on NREL's previous assessment of incremental electrified roadway rollout in an urban area. The analysis considered different fractional penetration levels of WPT-capable vehicles on electrified high-capacity roadways around the Atlanta area. The analysis assumed per-vehicle electric demands comparable to those that would be expected by a representative average vehicle in the light-duty fleet. Future work could consider a sensitivity evaluation around the per-vehicle consumption value; however, such an evaluation should show little difference to the range of penetration rates that is considered here. The findings indicate that electrifying 5% of all VMT on high-capacity roads in the Atlanta area could increase peak grid demand by a little over 100 MW, which is a little less than a 1% load increase. Higher levels of VMT electrification obviously lead to higher levels of load growth, with a full 100% VMT electrification resulting in roughly 16% growth in grid load. Under the cases considered, the load growth during peak traffic periods does often coincide with existing periods of peak grid load.

Future analysis could further determine to what degree this might present additional challenges to grid regulation based on the additional increase in grid load from road and vehicle electrification that would occur at other times of the day. In particular, the exacerbation of the midday trough in load shown for the fall and winter seasonal average weeks could present additional challenges if considered in conjunction with higher penetrations of solar generation on the grid. Further effects to regulation would need to be understood based on the sub-hourly changes in vehicle flow, which may provide additional variability in the total grid load. Study of these sub-hourly changes would be needed to determine if energy storage or other controlling mechanisms would be needed to mitigate these effects on the regulation of the grid. When considering the overall magnitude of the load increases, however, the analysis suggests that the increase in demand due to roadway electrification for light-duty VMT would be small when compared with historic rates of load growth on the grid. For instance, while it would be expected to take many years to incrementally increase VMT electrification by 5% (leading to increased grid load on the order of 0.6%), historic trends show that grid load has commonly increased by over 2% in a single year.

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