Report for

EV Charging Performance Requirements

Electrical Engineering Services

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PROJECT NO. 2-21-050
6/1/2021

DESIGNING A BETTER TOMORROW

Executive Summary

This report documents methods for developing electric vehicle (EV) charging performance requirements for communities in the Greater Toronto Hamilton Area (GTHA). This report is a technical resource that complements a separate costing study prepared by AES Engineering to inform GTHA local governments that are considering implementing "EV Ready" requirements. The Clean Air Partnership (CAP), with support from The Atmospheric Fund, commissioned these studies as part of broader efforts to support GTHA local governments considering EV Ready requirements.

Canadian cities are increasingly adopting "EV Ready" parking requirements, which specify that residential parking spaces in new developments feature an adjacent electrical outlet capable of providing "Level 2" EV charging. To reduce costs, EV charging infrastructure can be designed to use EV energy management systems (EVEMS) to control EV loads. EVEMS often employ load sharing to achieve these goals, in which a single circuit is shared by multiple EVSE.

To ensure that EV drivers can receive sufficient charge from residential charging systems, cities' EV Ready requirements are recommended to reference minimum "charging performance requirements" that limit the amount of sharing allowed on a circuit. This report presents a model developed by AES Engineering to determine charging system performance requirements. These performance requirements are presented in terms of an acceptable number of charging stations on a circuit of a given electrical capacity. The model includes variation in vehicle energy requirements as well as variation in the power and timing of charging.

The parameters included in the model that affect energy required by the vehicle are:

- Daily driving distance;
- Rated efficiency of the vehicle;
- Ambient temperature and related auxiliary system use (heating/ cooling);
- The total capacity of the battery.

The parameters included in the model that affect energy delivered to the vehicle by overnight charging are the:

- Time of arrival at the parking stall;
- Available capacity of the circuit;
- Available capacity of the electric vehicle supply equipment (EVSE);
- Efficiency of the charging system.

This is a multi-timestep stochastic simulation with 15-minute timesteps. A complete simulation run consists of:

- 10 independent sets of trials using weather data from different years.
- 365 consecutive days in each trial.

- 30 stalls in each trial, with each vehicle assigned to a stall.

The daily driving distances, also known as the vehicle kilometers travelled (VKT) per day, is one of the key inputs. There are large variations in VKT between households. Nevertheless, trends exist across the GTHA which can inform performance requirements. The daily VKT in the GTHA was analyzed using data from the Transportation Tomorrow Survey (TTS) and is mapped by region and planning district in Figure 1.

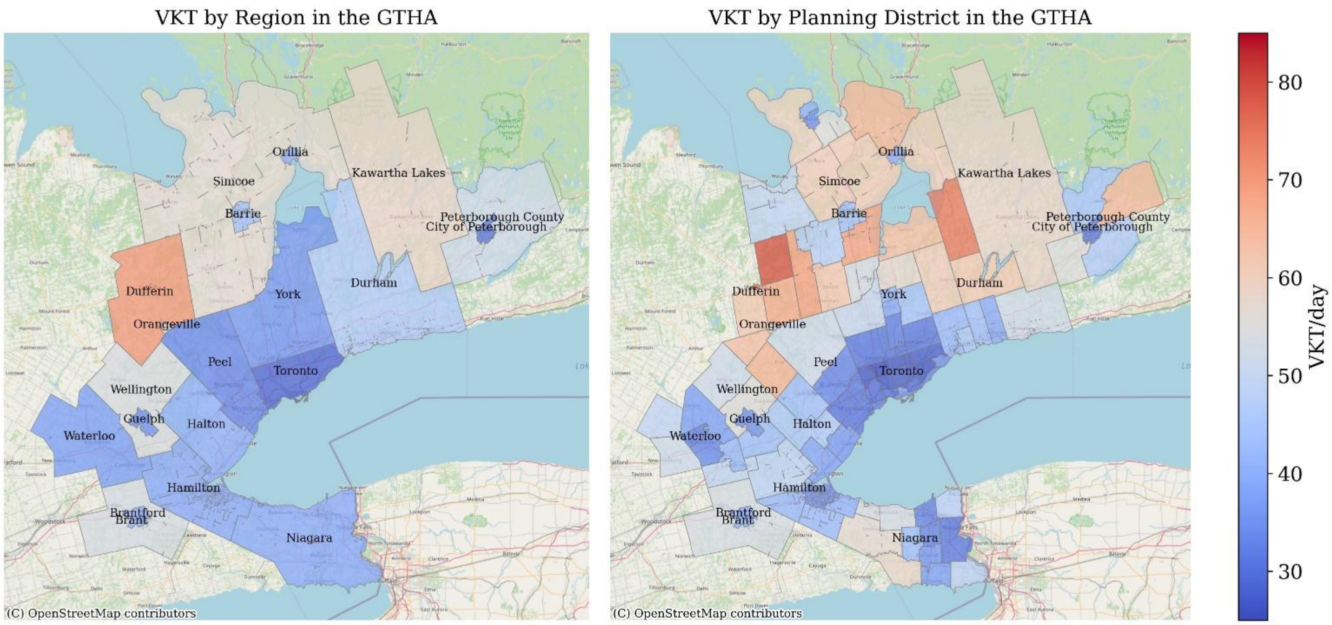

Figure 1: Map of mean VKT by region (left) and planning district (right) in the GTHA. Planning districts with less than 100 vehicles in the TTS data are not plotted.

The metrics used in this report to assess home charging reliability are how often vehicles are fully charged and how often they can complete the next day's driving on the previous night's charge. Thresholds of 10% of days when vehicles are not fully charged overnight and 1% of days when vehicles cannot complete the next day's driving are used to determine an acceptable amount of load sharing on each circuit size.

The resulting performance requirements for different mean VKT values are shown in Table 1. These performance requirements can be used in conjunction with the maps of mean VKT to establish EV Ready performance requirements for municipalities in the GTHA.

Table 1: Summary of performance requirements in terms of the amount of sharing allowed on each circuit size for different mean VKT.

	Maximum number of EVs (by Mean VKT)					
Circuit Breaker Size	45km or less	50km	55km	60km	65km	70km
20A	1					
30A	2	2	1	1	1	1
40A	4	3	3	2	2	2
50A	5	4	4	3	3	2
60A	6	5	5	4	4	3
70A	8	7	6	5	5	4
80A	9	8	7	6	6	5
100A	12	10	9	8	7	7
125A	15	14	12	11	10	9

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1. Introduction

1.1 BACKGROUND

Electric vehicle (EV) adoption is growing rapidly. Bloomberg New Energy Finance forecasts that within five years, the cost to produce EVs will be equivalent to internal combustion engine vehicles (ICEVs), and lower cost thereafter [1]. Public policy is likewise driving EV adoption, with the Government of Canada targeting the phase out of new ICEV sales by 2040 [2]. Achieving local, national and global climate targets will require the near complete electrification of transportation prior to 2050.

In this context, cities are increasingly focused on ensuring that their residents have access to convenient forms of EV charging. Over the last four years, the City of Vancouver and 12 other municipalities in British Columbia have adopted 100% "EV Ready" requirements for parking in new residential developments. These requirements specify that all residential parking spaces in new developments feature an adjacent electrical outlet capable of providing "Level 2" EV charging. This futureproofing allows apartment and townhome residents to then easily install EV Supply Equipment (EVSE) as EVs are adopted over time, avoiding the significant cost and complications that are associated with EV charging retrofits.

EV charging infrastructure can be installed with an EV energy management system (EVEMS) to control EV loads. By controlling the total load from EV charging, the upfront cost of electrical infrastructure can be reduced, as well as potentially the operating cost of electricity. EVEMS often employ load sharing to achieve these goals, in which a single circuit is shared by multiple EVSE. However, to ensure that EV drivers can receive sufficient charge from residential charging systems, many municipalities define a minimum performance requirement which effectively limits the amount of sharing allowed on a circuit.

1.2 OVERVIEW

This report summarizes a method for determining minimum electric vehicle (EV) charging performance requirements for residential buildings. Minimum EV charging performance requirements should be specified such that EV drivers can receive sufficient charge to meet daily driving needs while still allowing for the efficient use of electrical infrastructure and minimized development costs. This report considers minimum performance requirements in the form of a maximum number of EVSE on a circuit of a specified size. Minimum EV charging performance requirements depend on the daily energy needs of vehicles, the time available to charge, the charging power of each EVSE/ vehicle, and the specification of an acceptable system reliability in terms of how often vehicles are fully charged and how often they can complete the next day's driving.

2. EV Charging Performance Stochastic Model

The goal of an EV charging system in a residential building is to deliver all the energy a vehicle requires to complete daily driving needs, for the vast majority of days. This chapter develops a model for determining charging system performance requirements in terms of an acceptable number of charging stations on a circuit of a given size. This chapter first outlines the mathematical model, with accompanying text descriptions. Then, the metrics and confidence interval to quantify the charging system performance are presented. Finally, the selection of all parameters and metric thresholds is discussed.

2.1 MODEL DEFINITION

This model includes variation in vehicle energy requirements as well as variation in the power and timing of charging.

The parameters included in the model that affect energy required are:

- the distance driven prior to arrival at the parking stall;
- rated efficiency of the vehicle;
- ambient temperature and related auxiliary system use (heating/ cooling);
- the total capacity of the battery.

The parameters included in the model that affect energy delivered to the vehicle by overnight charging are:

- the time of arrival at the parking stall;
- the available capacity of the circuit;
- the available capacity of the electric vehicle supply equipment (EVSE);
- the efficiency of the charging system.

This is a multi-timestep stochastic simulation with 15-minute timesteps. A complete simulation run consists of:

- 10 independent sets of trials.
- 365 consecutive days in each trial (January 1 through December 31).
- 30 stalls in each trial, with each vehicle assigned to a stall.

When 30 is not evenly divisible by the number of stalls per circuit, the remainder is excluded from the simulation.

2.1.1 Vehicle energy requirements

The energy used by vehicle n on day d is calculated as the product of distance travelled, the vehicle efficiency, and an adjustment to efficiency based on temperature. This is capped at the battery capacity; the driver will have to charge mid-day on days when they need to drive more than their battery capacity. In this case, it is assumed they arrive home with a fully depleted battery. This can be written as:

$$\mathrm{E}_{\mathrm{n,d}}^{\mathrm{used}} = \min\left(\mathrm{d}_{\mathrm{n,d}} \cdot e_n^{\text{vehicle}} \cdot a_d^{temp}, E^{\text{battery capacity}}\right)$$

where

- $d_{n,d}$ is the distance driven (in km) prior to arrival at the parking stall of vehicle n on day d.
- e_n^{vehicle} is the rated efficiency of vehicle n.
- a_d^{temp} is an adjustment factor based on temperature on day d.
- $E^{\text{battery capacity}}$ is the capacity of the battery.

The energy in the vehicle battery when it arrives at home is the energy in the battery at the end of the previous day, minus the energy used during the current day (note that "days" start at 6am for the purpose of this simulation). This is written as:

$$E_{n,d,t_{n,d}^{arrive}}^{\text{battery, raw}} = E_{n,d-1,T}^{\text{battery}} - \mathrm{E}_{\mathrm{n,d}}^{\mathrm{used}}$$

where

- $E_{n,d,t^{\text{arrive}}}^{\text{battery, raw}}$ is the energy in the battery of vehicle n when it arrives at home on day d.
- $E_{n,d,T}^{\text{battery}}$ is the energy in the battery of vehicle n at the end of day d (when it has finished charging).
- $\mathrm{E}_{\mathrm{n,d}}^{\mathrm{used}}$ is the energy used by vehicle n on day d.

The energy in the battery cannot go below zero:

$$E_{n,d,t^{\text{arrive}}}^{\text{battery}} = max(E_{n,d,t^{\text{arrive}}}^{\text{battery, raw}}, 0)$$

However, the "raw" value of the battery energy, including values less than zero, is kept track of to determine the days when an insufficient charge is provided to allow for the next days' driving.

2.1.2 Energy Delivered to Vehicle

The battery is charged after it arrives at home until the battery is full or until it leaves the next day. Taking into account charging efficiency this is written as:

$$\mathrm{E}_{\mathrm{n,d,T}}^{battery} = \min(\mathrm{E}_{\mathrm{n,d},t_{n,d}^{arrive}}^{battery} + \sum_{t=t_{n,d}^{arrive}}^{\mathrm{T}} p_{n,d,\mathrm{t}} \cdot e^{\text{charge}} \cdot dt, E^{\text{battery capacity}})$$

where

- $E_{n,d,T}^{\text{battery}}$ is the energy in the battery of vehicle n at the end of day d (when it has finished charging).
- $t_{n,d}^{arrive}$ is the time of arrival at the parking stall of vehicle n on day d.
- $p_{n,d,t}$ is the energy delivered to vehicle n on day d in timestep t.
- e^{charge} is the efficiency of the charging equipment.
- dt is the timestep of the simulation.

Charging power is limited by the total power available on the circuit and the capacity of the EVSE. Different load sharing strategies are possible, but here we assume that the circuit power is divided equally between the vehicles that are plugged in[1]:

$$p_{n,d,t} = \min\left(\frac{P_c^{max}}{\sum_{n=1}^{N_c} z_{\mathrm{n,d,t}}}, \mathrm{P}_{\mathrm{n}}^{\mathrm{max}}\right)$$

where

- $p_{n,d,t}$ is the energy delivered to vehicle n on day d in timestep t.
- N_c is the total number of chargers on circuit c.
- P_c^{max} is the maximum charging capacity of the circuit c.
- $z_{n,d,t}$ is a binary variable indicating if vehicle n is charging at timestep t on day d.
- P_n^{max} is the maximum charging capacity of vehicle n (including the maximum capacity of the EVSE), after accounting for losses.

Whether are not a vehicle is charging depends on whether it is present and whether the battery is full:

$$z_{n,d,t} = x_{n,d,t} \cdot y_{n,d,t}$$

[1] The minimum charging current is 6 A for conductive charging systems as per SAE J1772 [12]. For circuits with large amounts of sharing, load switching (sequentially powering different charging stations), as opposed to load sharing (dividing the power equally between stations) may be required. These challenges should be considered by the EVSE and EVEMS provider but not expected to impact results for the overnight charging considered in this report.

where

- $z_{n,d,t}$ is a binary variable indicating if vehicle n is charging at timestep t on day d.
- $x_{n,d,t}$ is a binary variable indicating if vehicle n is at the charging station at timestep t on day d.

$$x_{n,d,t} = 0 \text{ for } t < t_{n,d}^{arrive}$$

$$x_{n,d,t} = 1 \text{ for } t_{n,d}^{arrive} \leq t < t_{n,d}^{depart}$$

$$x_{n,d,t} = 0 \text{ for } t \geq t_{n,d}^{depart}$$

- $y_{n,d,t}$ is a binary variable indicating if vehicle n does not have a full battery at timestep t on day d.

$$y_{n,d,t} = 1 \text{ if } E_{n,d,t}^{battery} < E^{\text{battery capacity}}$$

$$y_{n,d,t} = 0 \text{ otherwise}$$

2.2 METRICS

Each day, the energy that was not delivered to fill the battery is calculated as:

$$E_{n,d}^{\text{not full}} = E^{\text{battery capacity}} - E_{n,d,T}^{battery}$$

When the battery is not filled overnight, it does not necessarily impact the driver if the next day's driving needs can be fulfilled with the energy in the battery. To keep track of when the next day's driving is impacted, we calculate $E_{n,d,t^{\text{arrive}}}^{\text{battery, raw}}$, which is the energy in the battery without limiting it to zero as described in Section 2.1.1. Any values below zero represent days when the driving requirements are not met due to a lack of performance by the charging system, and are calculated as:

$$E_{n,d}^{\text{deficient}} = min(E_{n,d,t^{\text{arrive}}}^{\text{battery, raw}}, 0)$$

The percent of vehicle days when the battery is not fully charged and when the next day's driving cannot be completed (without mid-day charging) are the metrics of reliability for the charging system.

2.2.1 Confidence Level

Ten independent trials are run for each simulation to determine the reported metrics. A confidence interval with a 99% confidence level is also reported, where the confidence interval for each metric is calculated based on the t-statistic as:

$$\mathrm{CI} = \bar{x} \pm t^{*} \cdot \frac{s}{\sqrt{n}}$$

where:

- CI is the confidence interval
- $\bar{x}$ is the sample mean
- t^{*} is the t-statistic (3.25) for a 99% confidence interval with 9 degrees of freedom
- s is the sample standard deviation
- n is the number of samples (10)

The confidence interval provides an estimate of variability from year to year, and an estimate of the confidence of the overall result based on the number of independent trials.

2.3 PARAMETER SELECTION

The selection of values for the parameters of the model are discussed in detail in this section. This includes the three stochastic parameters:

- daily vehicle driving distances
- vehicle energy consumption rate
- arrival time

2.3.1 Vehicle Driving Distances

Daily driving distance (vehicle kilometers travelled, or VKT) ($d_{n,d}$) are calculated as the following mixed distribution:

$$\mathrm{VKT}_{n,d} = \begin{cases} 0, \text{ with probability } f^{no\ drive} \\ \overline{VKT} \cdot e^{X_{n,d}}, \text{ with probability } 1 - f^{no\ drive} \end{cases}$$

where:

- $\overline{VKT}$ is the mean vehicle kilometers travelled (VKT) per day.
- $f^{no\ drive}$ is the percent of non-driving days (10%)
- $X_{n,d}$ is a random variable from the normal distribution with mean of -0.5 and standard deviation of 1.

VKT for the GTHA were calculated from data collected in the 2016 Transportation Tomorrow Survey (TTS) [3][2]. An explanation of the calculation of VKT based on trip and household survey data is provided in Appendix A. The mean and median VKT for each region in the GTHA are summarized in Table 2, where the overall mean VKT is 37 km. Simulations were run with a range of mean VKT values. The average percent of non-driving days across the GTHA was calculated at 20% but due to high uncertainty in the calculation assumptions, we use a more conservative value of 10%.

A comparison of the actual distribution of VKT in regions across the GTHA compared to the modelled distribution is provided in Appendix B, with an example for Toronto shown in Figure 2. The different distributions were shown to have a relatively small impact on the results. In contrast, considering the differences in mean VKT within a region can have a large impact on results. Figure 3 shows a map of the mean VKT of each region on the left and of each planning district on the right. In some areas, such as Simcoe and Peterborough counties, the maps clearly show a wide range of VKTs in planning districts across the region. VKT also varies at a higher geographic granularity (e.g. traffic analysis zones, individual buildings etc.), but considering this high granularity is less practical at a regional or municipal planning level. Higher resolution maps are provided in Appendix C for reference.

Table 2: Mean and median of VKT of regions in the GTHA.

Region	Mean	Median
Toronto	29	20
Durham	46	32
York	36	26
Peel	34	24
Halton	40	29
Hamilton	39	23
Niagara	39	23
Waterloo	37	20
Guelph	35	16
Wellington	54	42

Region	Mean	Median
Orangeville	57	47
Barrie	44	17
Simcoe	56	37
Kawartha Lakes	58	39
City of Peterborough	31	11
Peterborough County	52	34
Orillia	40	10
Dufferin	70	61
Brantford	40	16
Brant	53	35

[2] The TTS data only includes weekdays. Some literature indicates that the mean driving distances on weekends versus weekdays is lower, however information on the distribution shape is limited [4] [5]. It is logical that weekend driving would include a higher number of long-distance trips, even if the overall mean is lower. Due to a lack of data, weekend driving is not considered separately but is acknowledged as a limitation of this report.

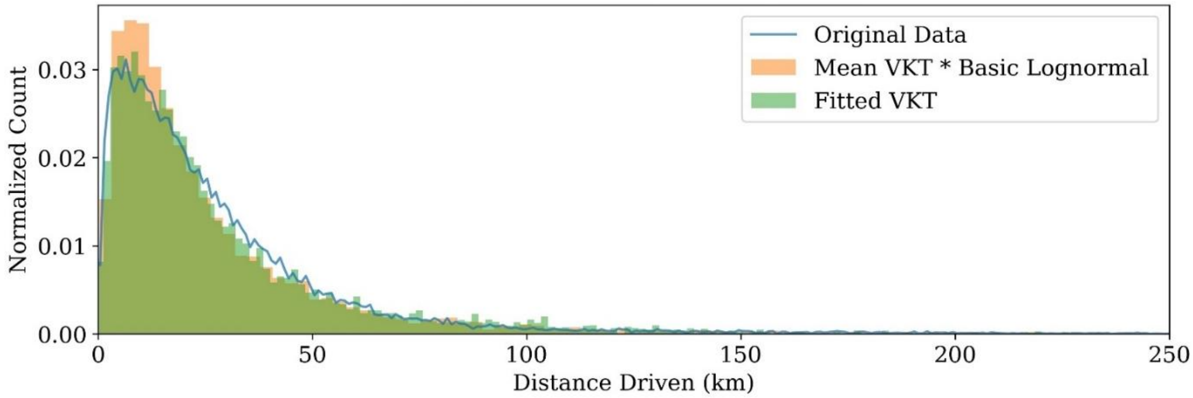

Figure 2: Example of the modelled distribution (orange) compared to the actual data (blue) and a fitted lognormal distribution (green) for Toronto.

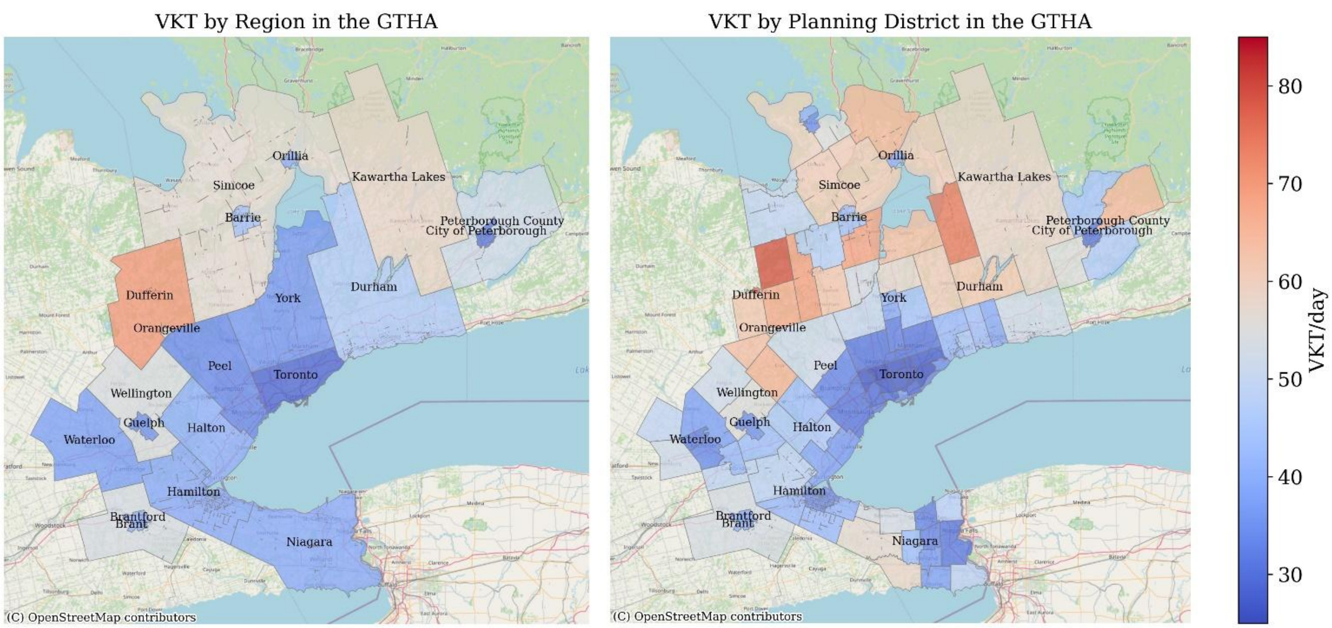

Figure 3: Map of mean VKT by region (left) and planning district (right) in the GTHA. Planning districts with less than 100 vehicles in the TTS data are not plotted.

2.3.2 Energy Consumption

In this model, energy consumption ($E_{n,d}$) is dependent on vehicle type and temperature. The population of vehicles is assigned a type based on the percentage of different vehicle types in Canada as shown in Table 3 [4]. Average energy consumption (e_n) is calculated for each vehicle class based on combined (highway/ city) efficiency ratings from the Environmental Protection Agency (EPA) [5][3].

Energy consumption of vehicles is then adjusted each day based on historical temperature data. Daily mean temperatures from Environment Canada for the Toronto Pearson International Airport weather station (plotted in Figure 4) are used for all municipalities in the GTHA [6]. Each simulation trial is run with a different year of weather data, starting with 2020 and working backwards. Energy consumption is adjusted using a curve fit to the average (50th percentile) adjustment to EV driving range at different temperatures, as reported by GeoTab and shown in Figure 5.

Table 3: Percentage of different vehicle types in Canada. Based on data from [4] and [5].

Vehicle Type	Percent of Vehicle Population	Energy Consumption (kWh/ 100 km)
Multi-purpose vehicles	47.79%	22
Passenger cars	25.75%	19
Pick-up trucks	20.80%	36
Vans	5.56%	29

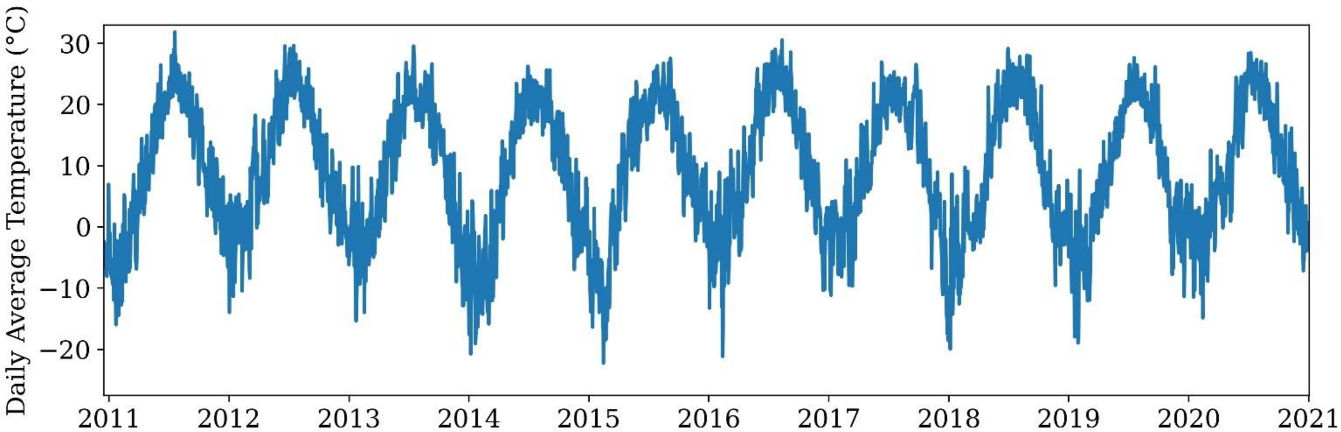

Figure 4: Daily average temperature in Toronto from 2011 to 2021. Data from [6].

[3] There are currently no electric pick-up trucks or vans reported by the EPA. Truck efficiencies are based on advertised efficiencies of two production-intent electric trucks [16] [15]. Van efficiencies are taken as half-way between truck and SUV efficiencies.

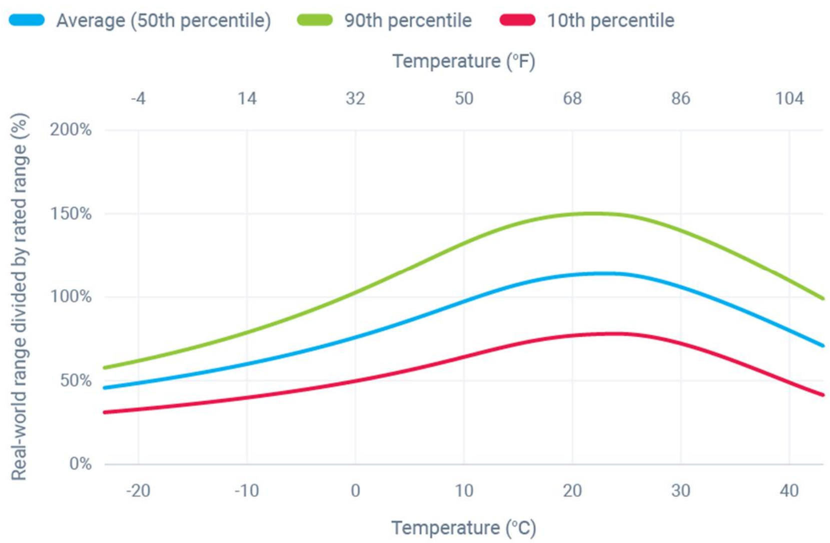

Figure 5: Real-world range compared to rated range of EVs. Reproduced from [7].

2.3.3 Arrival Time at Charging Station

The arrival time of vehicles ($t_{n,d}^{arrive}$) at the charging station is modelled as a normal distribution with a mean of 6:00 pm and standard deviation of 1 hour.

2.3.4 Other Parameters

VARIABLE	DESCRIPTION	VALUE
$E^{battery\ capacity}$	BATTERY CAPACITY	90 kWh
P_n^{max}	MAX VEHICLE CHARGING POWER	6.6 kW
e^{charge}	CHARGING EFFICIENCY	85%
$t_{n,d}^{depart}$	DEPARTURE TIME	6:00 am

2.3.5 Metric Thresholds

To determine performance requirements as an acceptable amount of sharing per circuit, thresholds for each metric are used. These thresholds should be defined based on what society and policy makers deem to be an acceptable reliability of the charging system. As defined in Section 2.2, we consider the percent of vehicle days when the battery is not fully charged and when the next day's driving cannot be completed (without mid-day charging). Proposed limits, which were used to produce the results in this report, are shown in Table 4.

Table 4: Metric thresholds.

VARIABLE	DESCRIPTION	VALUE
Percent of days with $E_{n,d}^{\text{not full}} > 0$	PERCENT OF VEHICLE DAYS WITH BATTERY NOT FULLY CHARGED	10%
Percent of days with $E_{n,d}^{\text{deficient}} > 0$	PERCENT OF VEHICLE DAYS WHEN NEXT DAY'S DRIVING CANNOT BE COMPLETED	1%

3. Results of Stochastic Model

This section presents results of the stochastic model, including example results with 4-way sharing on a 40A circuit for a mean VKT of 40km, a summary of results different mean VKT values, and a sensitivity analysis of key input parameters.

3.1 EXAMPLE RESULTS FOR A SINGLE REGION

This section presents example results for a mean VKT of 40km to provide an intuitive understanding of the allowable sharing on each circuit size prior to presenting results for a range of mean VKTs in Section 3.2. Table 2 summarizes the allowable sharing on each circuit size using the metric thresholds presents in Section 2.3.5. It is notable that the amount of sharing is always limited by the percent of days without full charge, as opposed to the percent of days where the next day's driving cannot be completed. In addition, there is considerable variability from year to year, as shown by the large confidence intervals ("CI") relative to the average values. However, conservative metric thresholds have been used which should assure adequate performance of the charging system even at the upper end of the confidence interval.

Table 5: Simulation results for 40 VKT.

Circuit Breaker Size (A)	Number of Way Sharing	Days without Full Charge		Days when Next Day's Driving Cannot be Completed		Charge Completion Time	
		Average	CI	Average	CI	Average	CI (min)
20	1	7.2%	1.0%	0.17%	0.04%	9:03 PM	7
30	3	9.1%	1.9%	0.31%	0.11%	9:25 PM	10
40	4	6.2%	1.4%	0.23%	0.12%	9:11 PM	8
50	6	8.4%	2.4%	0.31%	0.14%	9:31 PM	10
60	7	6.9%	1.8%	0.26%	0.17%	9:23 PM	10
70	9	8.3%	2.5%	0.32%	0.19%	9:33 PM	10
80	10	6.6%	2.7%	0.28%	0.19%	9:25 PM	10
100	14	9.7%	3.5%	0.48%	0.34%	9:41 PM	10
125	17	8.4%	3.3%	0.37%	0.29%	9:39 PM	12

Figure 6 and Figure 7 show the average power per circuit and the average percent of total system power used at each timestep. Figure 8 shows a histogram of the time charging is complete. This demonstrates how the majority of charging is completed well before midnight, with a small percentage continuing until morning.

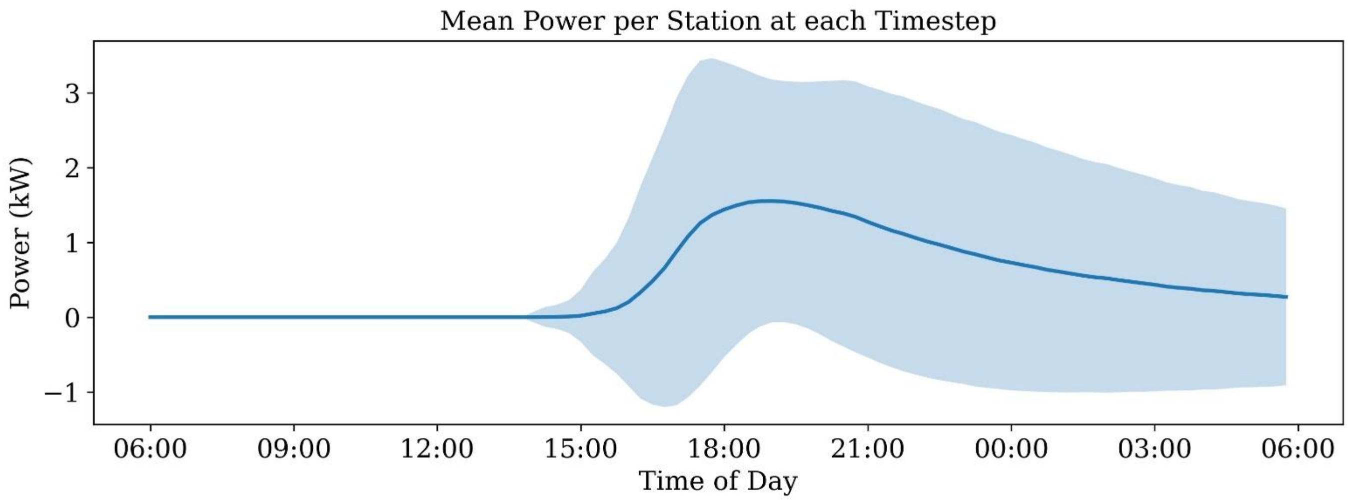

Figure 6: Mean power per circuit at each timestep in the simulation, with +/- 1 standard deviation shown in shading, for an example simulation of 4-way sharing on a 40A circuit for 40 VKT.

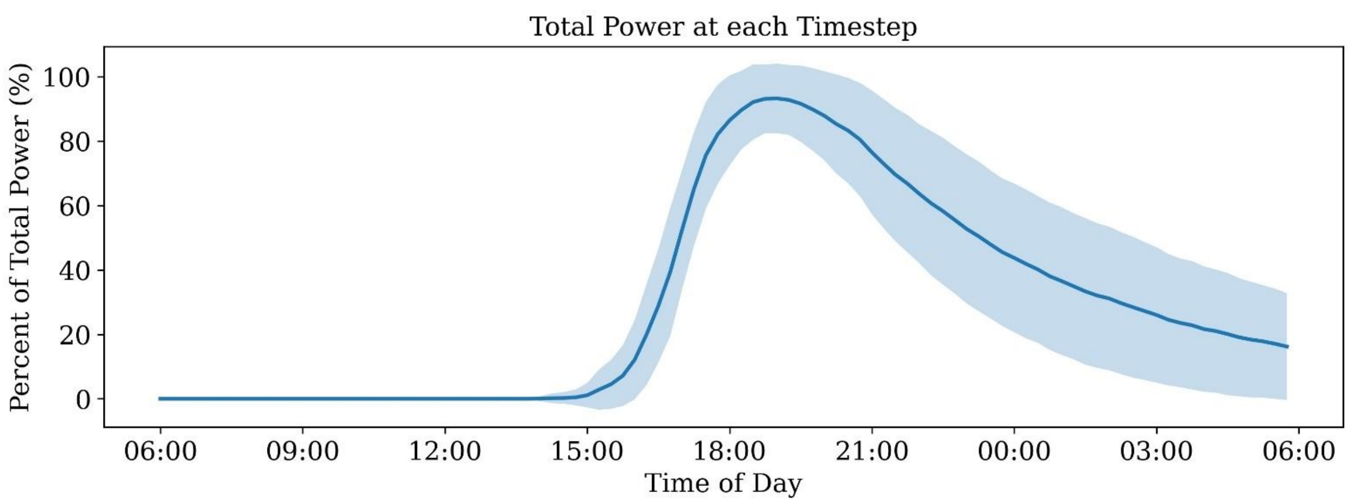

Figure 7: Mean percent of total available power used at each timestep in the simulation, with +/- 1 standard deviation shown in shading, for an example simulation of 4-way sharing on a 40A circuit for 40 VKT.

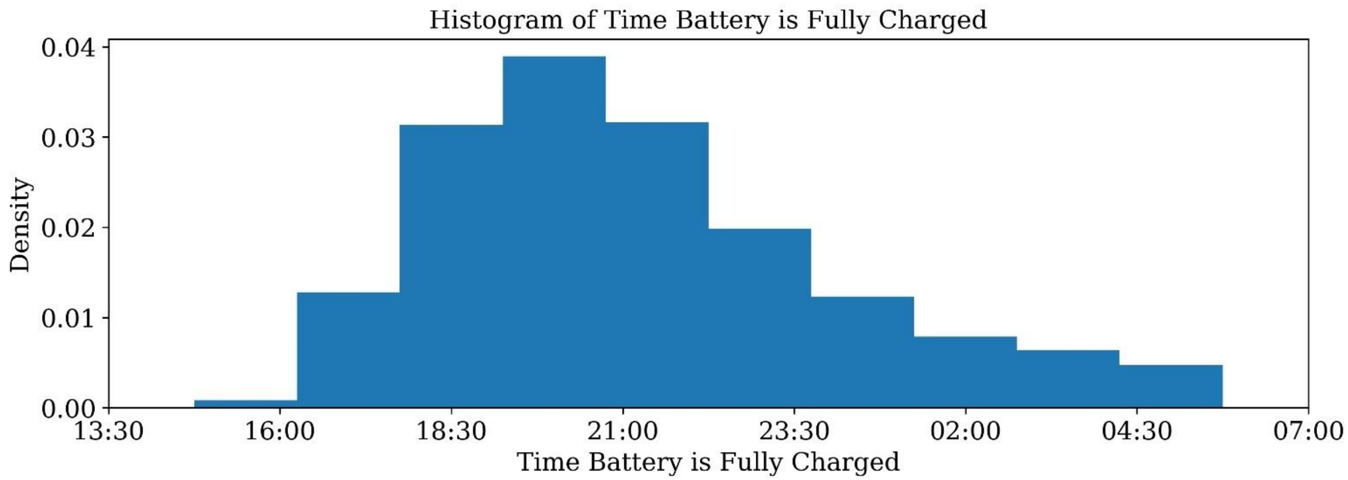

Figure 8: Histogram of time that batteries are fully charged for an example simulation of 4-way sharing on a 40A circuit for 40 VKT.

Figure 9 shows an example of the percent of vehicles that are not fully charged overnight on each day of a simulated year. For this simulation, the overall percentage of vehicle days without a full charge is 5.4%. However, there are days in the winter with more than 25% of vehicles that do not receive a full charge overnight. When looking at the equivalent plot for days where vehicles cannot fulfill the next day's driving needs (Figure 10), we see that even when the battery is not fully charged, vehicles almost always have the enough energy for their driving needs.

This is also demonstrated by Figure 11. Figure 11 shows a few weeks in March when, for this example vehicle, the battery is sometimes not fully charged overnight. The amount of energy in the battery is shown in blue, where 90kWh is a fully charged battery and 0kWh is a fully depleted battery. The charging power is shown in green. Note that the battery energy used for driving is depicted at the beginning of each day, even though in reality it is depleted throughout the day. On March 21, a larger amount of energy is used (approximately 60kWh). The battery is not fully charged that night, but can still be driven the next day and is recharged fully the following night.

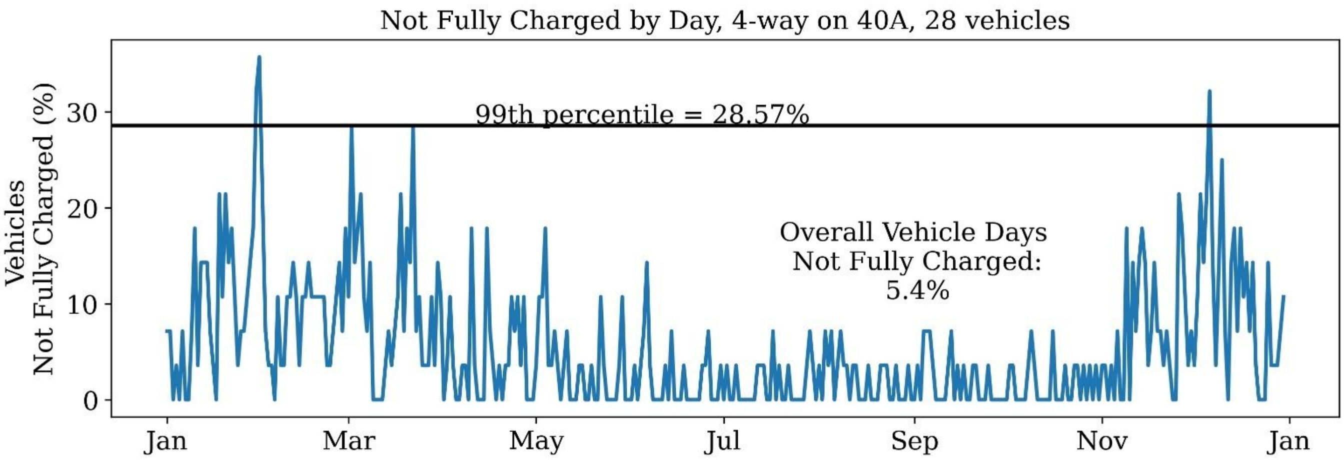

Figure 9: Percent of vehicles that are not fully charged throughout a year of simulations.

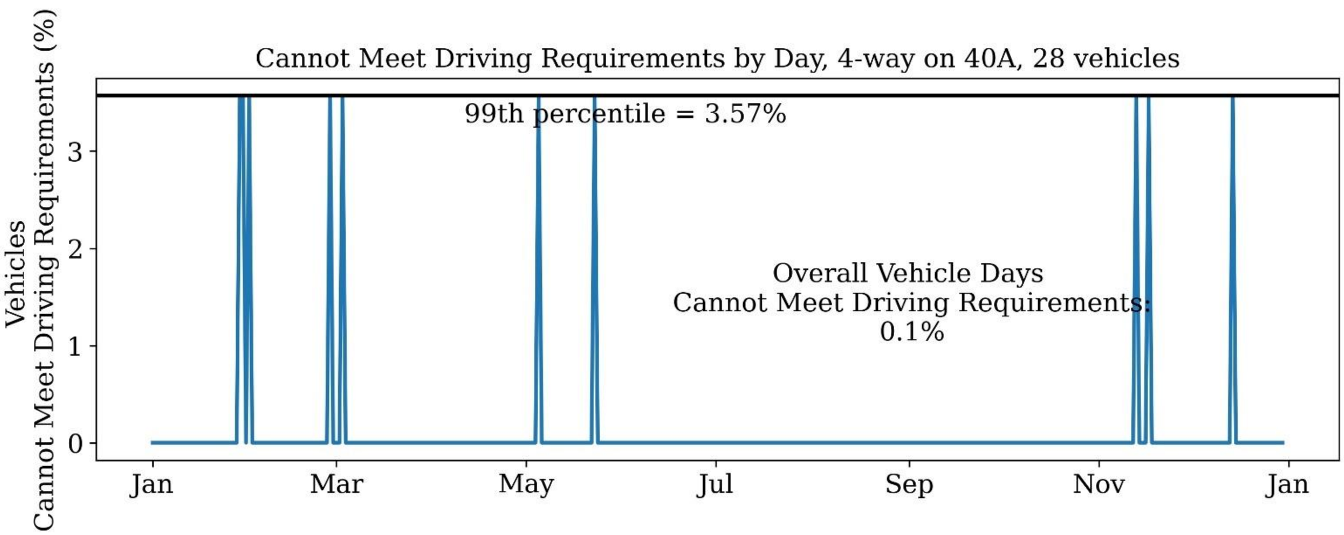

Figure 10: Percent of vehicles that cannot complete the next day's driving throughout a year of simulations.

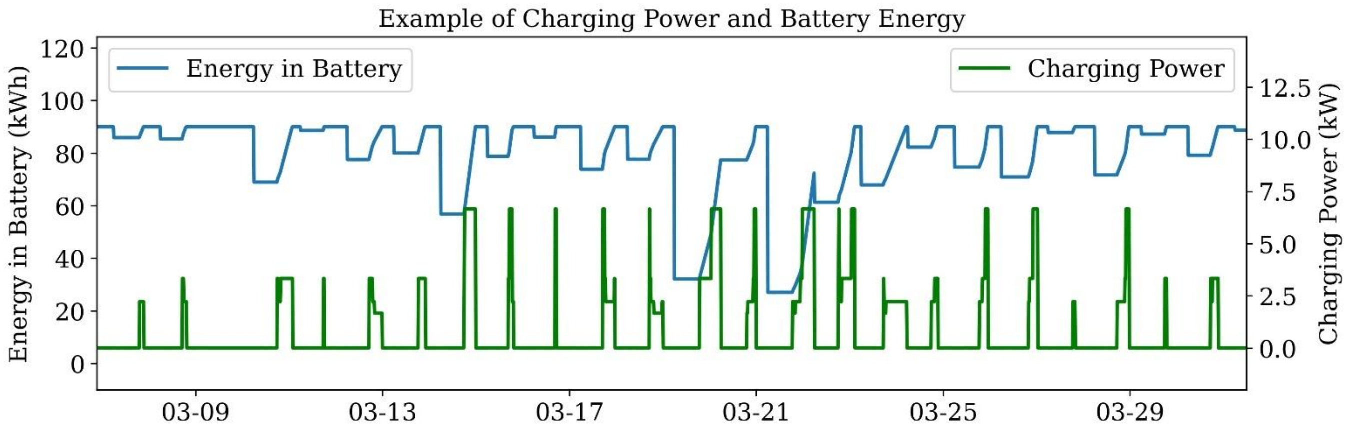

Figure 11: Charging power and energy in the battery of an example vehicle for a few simulated weeks in March 2019.

3.2 SUMMARY OF RESULTS FOR DIFFERENT VKT

The results for different mean VKT values are shown in Table 6. These tables can be applied regions or planning districts in the GTHA by referring to Table 2 and the maps in Figure 3 and Appendix C. Notwithstanding the levels of sharing that are theoretically possible at lower mean VKT values, AES does not recommend that local governments adopt performance requirements that allow for more sharing than those summarized the values in the 45 mean VKT. This is because in the future cities may feature fewer vehicles, which travel further on average.

Table 6: Summary of performance requirements for different mean VKT.

	Mean VKT								
Circuit Breaker Size (A)	30	35	40	45	50	55	60	65	70
20	2	1	1	1					
30	4	3	3	2	2	1	1	1	1
40	6	5	4	4	3	3	2	2	2
50	8	7	6	5	4	4	3	3	2
60	10	9	7	6	5	5	4	4	3
70	13	10	9	8	7	6	5	5	4
80	15	12	10	9	8	7	6	6	5
100	18	15	14	12	10	9	8	7	7
125	24	20	17	15	14	12	11	10	9

3.3 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to determine the impact of some of the input variables on the percent of vehicle days when the battery was not fully charged and when the next day's driving could not be completed. This analysis is shown for 2-way sharing on a 40A circuit in Figure 12 and Figure 13. A sensitivity analysis of the permitted amount of sharing on 40A and 80A circuits is shown in Figure 14 and Figure 15 respectively, based on the thresholds presented in Section 2.3.5. The baseline test case is shown by a black vertical line in each figure. The baseline test case uses the values shown in Table 7. In all charts, if two tests have the same output value, only the larger value is labelled.

Table 7: Baseline values for sensitivity analysis.

VARIABLE	DESCRIPTION	BASELINE	TEST VALUES
$\overline{VKT}$	MEAN VKT (km)	50	30, 40, 50, 60, 70
	NON-DRIVING DAYS (%)	20	0, 10, 20, 30, 40
$\overline{t^{arrive}}$	MEAN ARRIVAL HOUR	18 (6PM)	16, 17, 18, 19, 20
$\text{std}(t^{arrive})$	STANDARD DEVIATION OF ARRIVAL HOUR	1	0, 0.5, 1, 1.5, 2
	COMPOSITION OF VEHICLE TYPES	See Table 3	All Cars, All Trucks

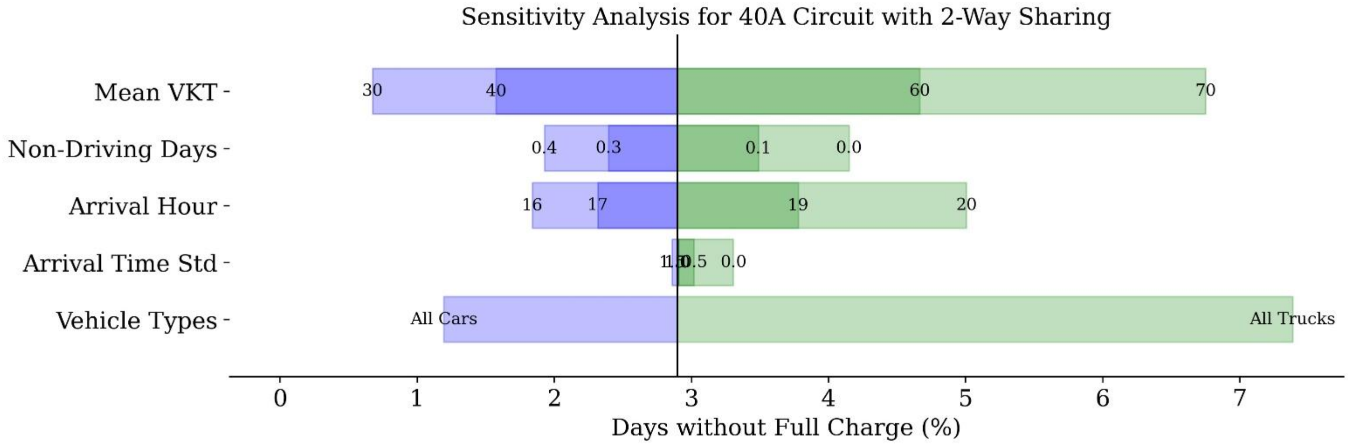

Figure 12: Sensitivity analysis of days without full charge for 40A circuit with 2-way sharing.

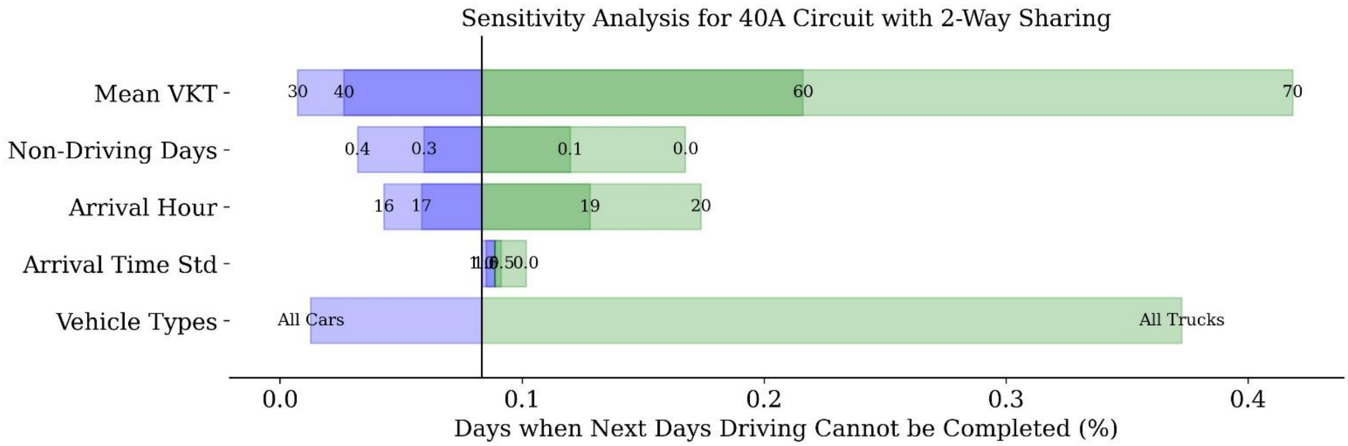

Figure 13: Sensitivity analysis of days when next day's driving cannot be completed for 40A circuit with 2-way sharing.

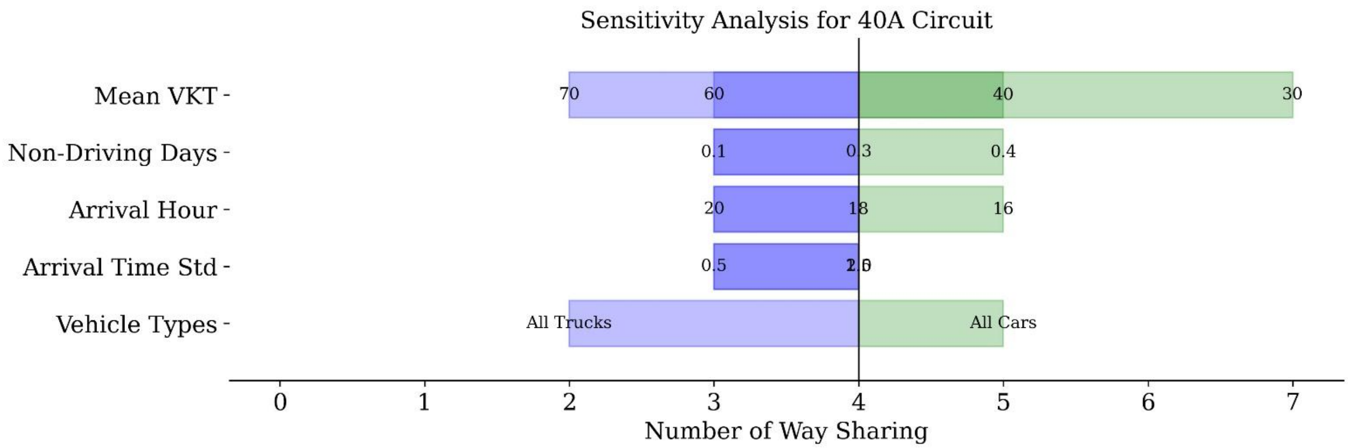

Figure 14: Sensitivity analysis of maximum sharing on a 40A circuit with specified metric thresholds.

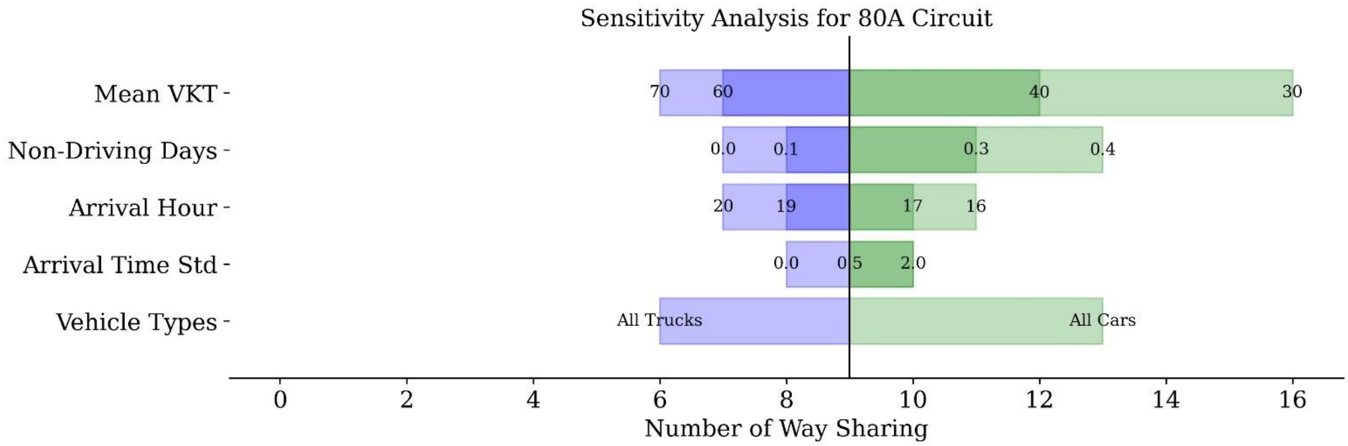

Figure 15: Sensitivity analysis of maximum sharing on an 80A circuit with specified metric thresholds.

4. Conclusion

This report has outlined a method for determining performance requirements for residential EV charging systems for the GTHA and presented results in terms of the mean daily distances driven (vehicle kilometers travelled or VKT). This report also presented maps of the mean VKT for regions and planning districts across the GTHA. The performance requirements can be used in conjunction with the maps of mean VKT to establish EV Ready performance requirements for municipalities in the GTHA.

Policy makers should recognize the differences in mean VKT within a region when establishing minimum performance requirements; performance requirements that are set based on the mean VKT across a region may result in the over-building of infrastructure in some areas and insufficient charging performance in other areas. There are multiple solutions to this potential problem. One solution is to set charging performance requirements to meet the needs of areas with higher daily driving distances at the expense of increased development costs. An optional reduction in charging performance requirements could be allowed if a developer provides proof of lower expected daily driving distances.

Another solution is to set charging performance requirements based on the mean VKT of the municipality or region, with special zones highlighted that require higher charging performance.

Municipalities can also consider how to the overall charging "ecosystem", which will include workplace, public Level 2, and DC fasting charging stations, can supplement home-based charging. However, charging at home is expected to be the most convenient for EV drivers and provides maximum flexibility to reduce EV charging loads, so depending too heavily on other locations for charging should be approached with caution.

APPENDIX A: CALCULATION OF VEHICLE KILOMETERS TRAVELLED (VKT)

The following method was used to estimate vehicle kilometers travelled (VKT) per day for the GTHA using Transportation Tomorrow Survey (TTS) data [3].

1. Remove erroneous or missing data:
    a. Remove households and corresponding trips with an unknown number of vehicles (n_vehicles = 99).
    b. Remove trips and corresponding households with unknown trip length (trip_m = 999999).
2. Get trip length (trip_m) for trips where primary travel mode of trip (mode_prime) is auto driver (D).
3. For each household, determine the number of vehicles (n_vehicle). For each household, determine the number of people with auto driver trips (referred to a n_autodriver).
4. Where the number of vehicles is greater than the number of people in the household with licenses (n_licence), adjust the number of vehicles to equal the number of licenses[4].
5. Approximate VKT (per vehicle, per day) by apportioning trip distances to each vehicle with the following logic:
    a. If number of vehicles is 0 (n_vehicle = 0), exclude those trips.
    b. If number of people with auto driver trips is 0 (n_autodriver = 0), assign VKT of 0 to all household vehicles.
    c. If there is one vehicle in the household (n_vehicle = 1) and the number of people with auto driver trips is greater than or equal to 1 (n_autodriver >=1), assign all auto driver trips to the single vehicle.
    d. If there is more than one vehicle in the household (n_vehicle > 1) and there is the same or fewer number of people with auto driver trips, assign each person's trips to a different vehicle. Assign additional vehicles VKT of 0.
    e. If number of vehicles is greater than 1 (n_vehicle > 1) and there are a greater number of people with auto driver trips than number of vehicles, assign each vehicle the average household VKT for that day (sum of trip distances divided by number of people with auto driver trips in the household).

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[4] This is the case in approximately 8% of households. Without this adjustment there are, for example, many households with 3 vehicles and 2 people with licenses. Assuming both people drove on the survey day, the third vehicle would be assigned a VKT of 0. With the adjustment, the third vehicle is ignored. This adjustment only affects the number of vehicles with VKT of 0.

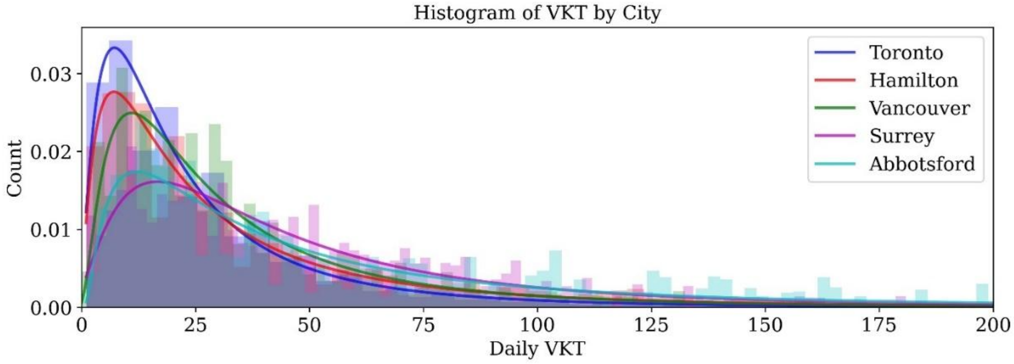

Figure 16: Plot of VKT data from municipalities in the GTHA and BC Lower Mainland. It is unclear whether the fatter tails in the Lower Mainland are due to differences in calculation of VKT or differences in driving patterns.

APPENDIX B: DRIVING DISTANCE DISTRIBUTION COMPARISON

As described in Section 2.3.1, the daily driving distances in this report are assumed to follow a lognormal distribution multiplied by the mean vehicle kilometers travelled (VKT), where the underlying normal distribution has a mean of -0.5 and standard deviation of 1. This appendix compares the assumed distribution with actual distributions of VKT for the GTHA. An explanation of the calculation of VKT based on trip and household survey data from the 2016 Transportation Tomorrow Survey (TTS) is provided in Appendix A [3].

The density distributions of VKT of regions in the GTHA are shown in Figure 17. Each region is fit with a lognormal curve. Figure 18 to Figure 22 compare the original distributions of VKT (blue line) to those modelled as mean VKT multiplied by a basic lognormal distribution (orange histogram) and those fit with a lognormal distribution directly (green histogram). It is not surprising that the fitted lognormal fits the data better since that is exactly the goal. For some cities, the mean VKT multiplied by a basic lognormal describes the distribution reasonably well (Waterloo), while others it describes less well (Toronto).

A sensitivity analysis was performed to determine the impact of the distribution shape on the percent of vehicle days when the battery was not fully charged and when the next day's driving could not be completed. This analysis is shown for 4-way sharing on a 40A circuit in Figure 23 and Figure 24. A sensitivity analysis of the permitted amount of sharing on 40A and 80A circuits is shown in Figure 25 and Figure 26 respectively, based on the thresholds presented in Section 2.3.5. The differences in these distribution shapes have varying impact depending on the region but a difference of no more than one vehicle per circuit.

As discussed in Section 2.3.1, it is also important to consider the differences within a region. A thorough analysis of the distribution shape of planning districts compared to regions was not performed, however, Figure 27 to Figure 31 give an idea of how these distributions vary. There is not enough data available for individual traffic analysis zones to analyze the distributions at the granularity.

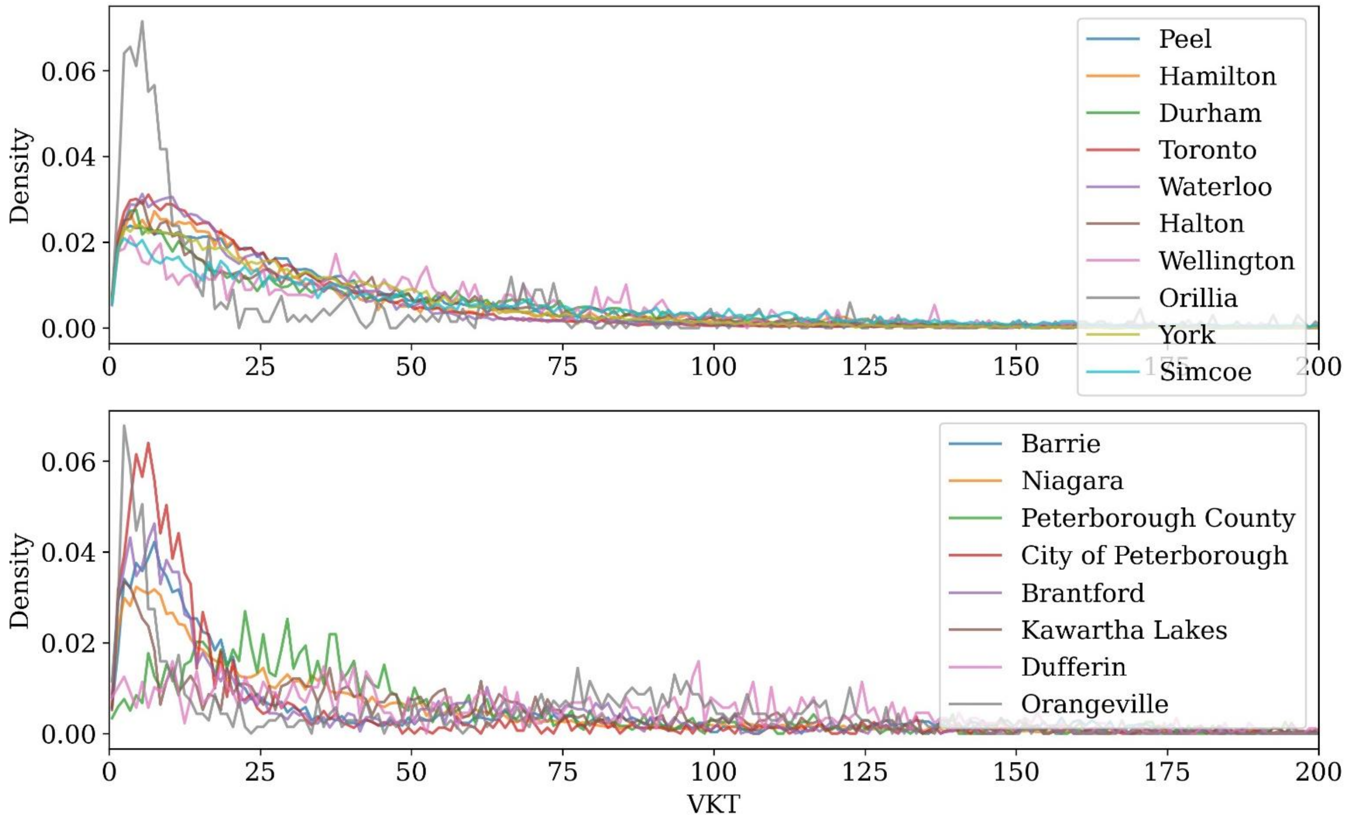

Figure 17: VKT distributions of regions in the GTHA (divided into two plots for better readability).

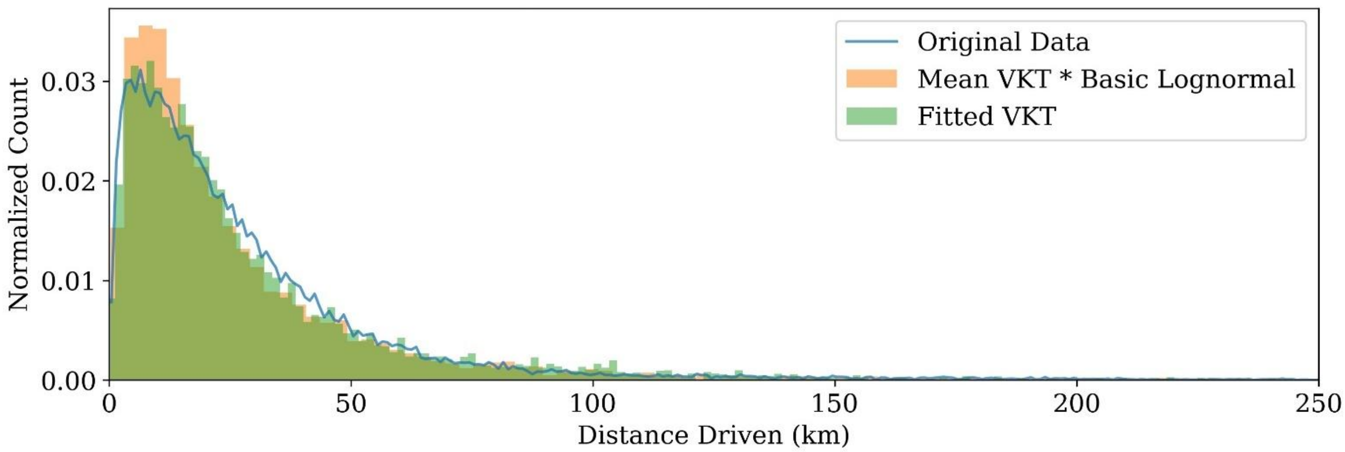

Figure 18: Original data (blue) compared to mean VKT multiplied by a basic lognormal (orange) and fitted lognormal (green) for Toronto region.

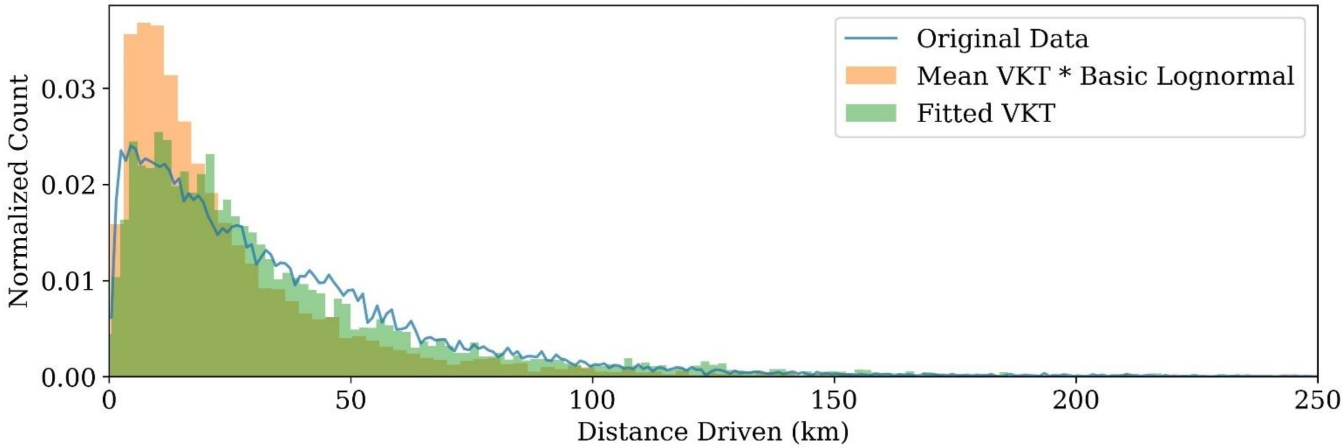

Figure 19: Original data (blue) compared to mean VKT multiplied by a basic lognormal (orange) and fitted lognormal (green) for York region.

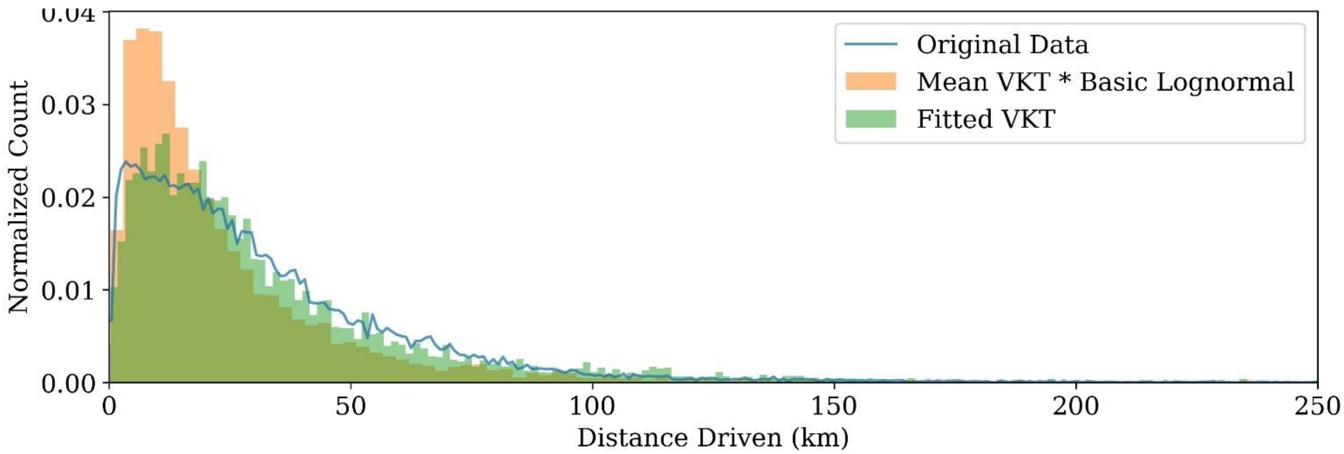

Figure 20: Original data (blue) compared to mean VKT multiplied by a basic lognormal (orange) and fitted lognormal (green) for Peel region.

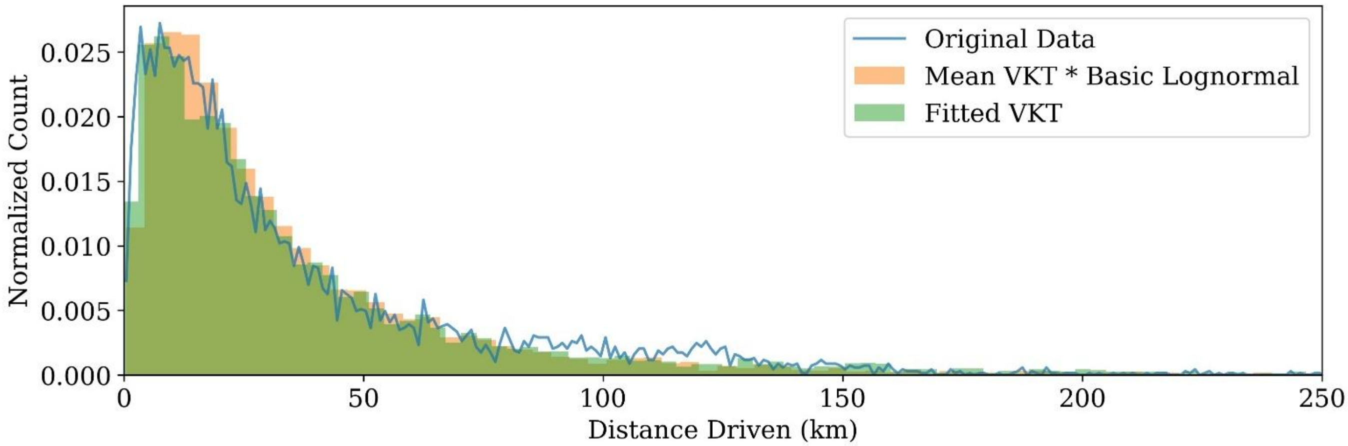

Figure 21: Original data (blue) compared to mean VKT multiplied by a basic lognormal (orange) and fitted lognormal (green) for Hamilton region.

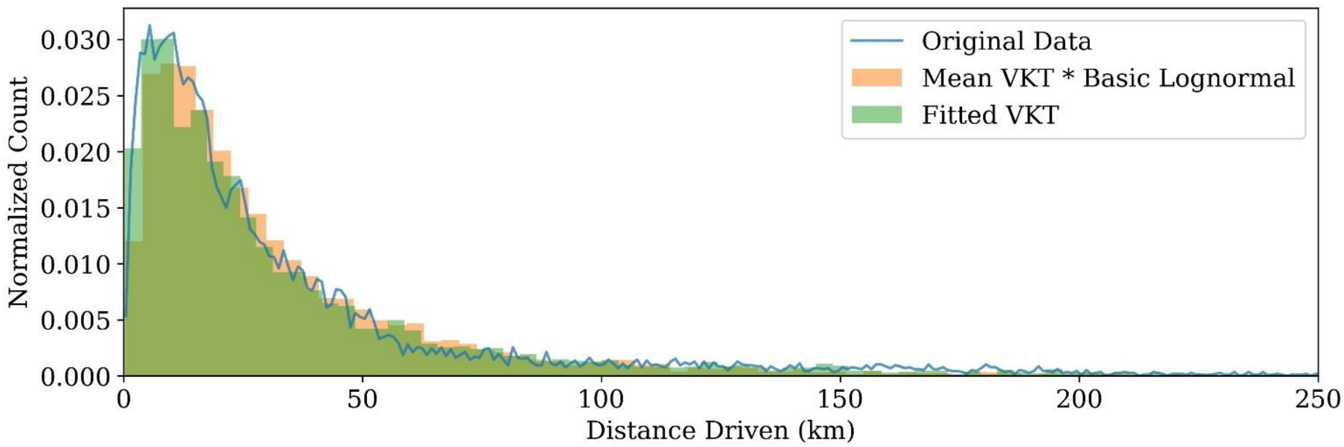

Figure 22: Original data (blue) compared to mean VKT multiplied by a basic lognormal (orange) and fitted lognormal (green) for Waterloo region.

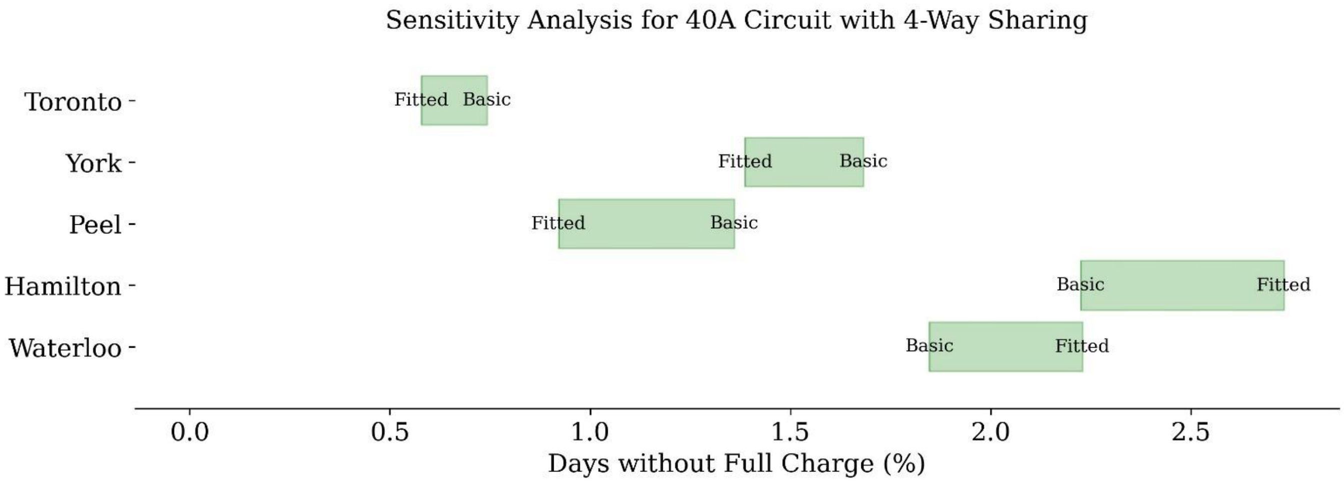

Figure 23: Sensitivity analysis of days when battery is not fully charged for 40A circuit with 4-way sharing.

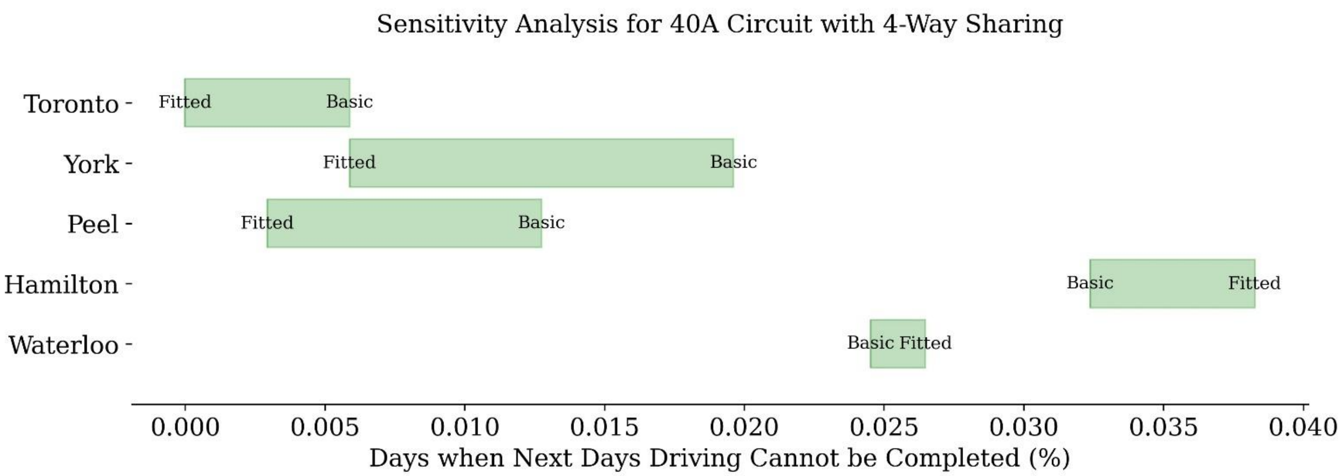

Figure 24: Sensitivity analysis of days when next day's driving cannot be completed for 40A circuit with 4-way sharing.

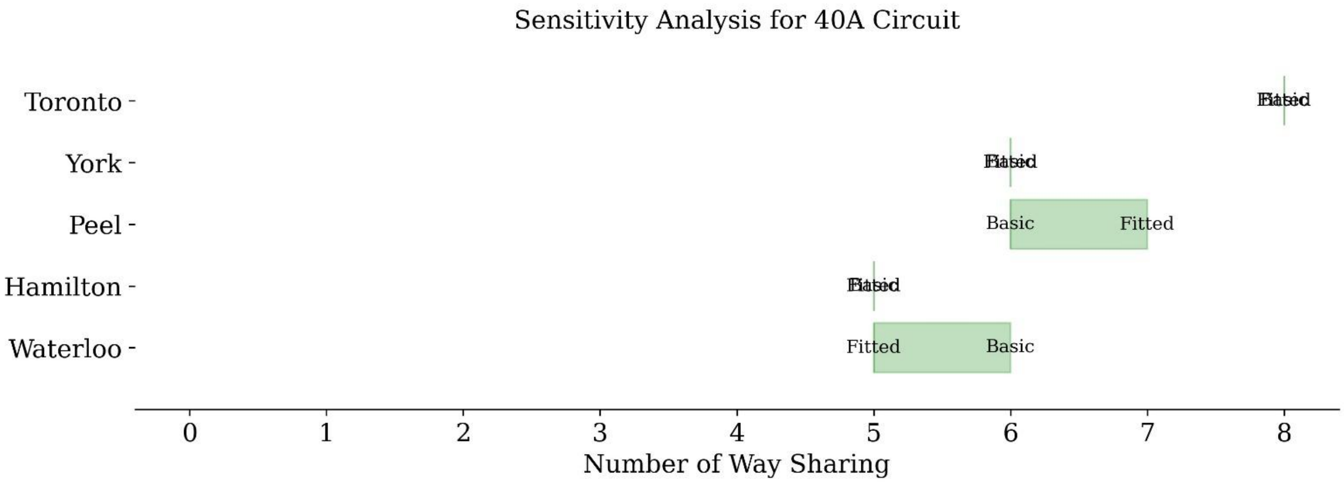

Figure 25: Sensitivity analysis of maximum sharing on a 40A circuit with specified metric thresholds.

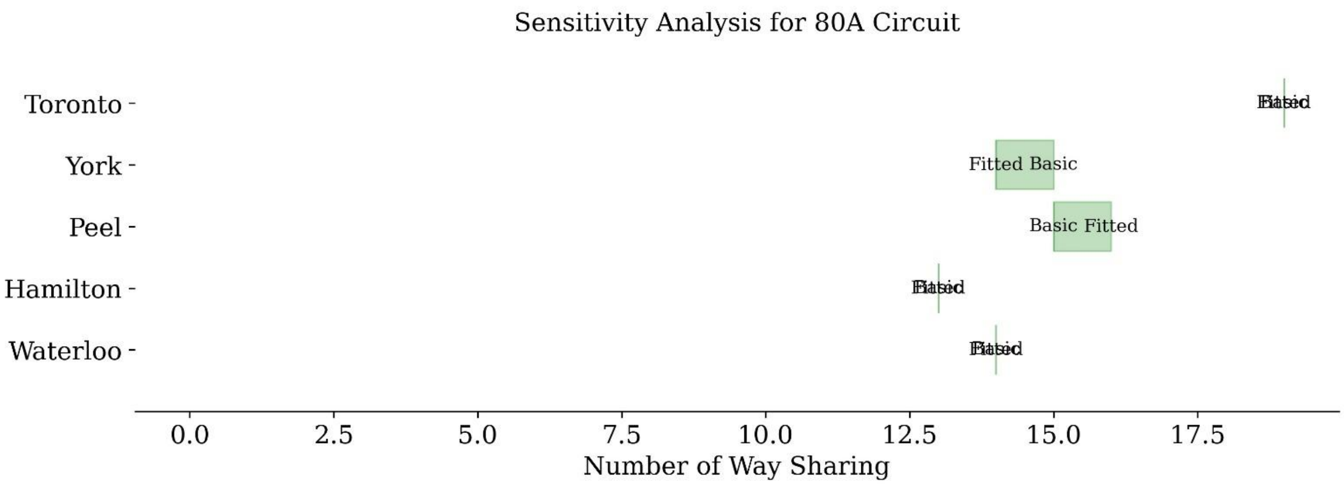

Figure 26: Sensitivity analysis of maximum sharing on an 80A circuit with specified metric thresholds.

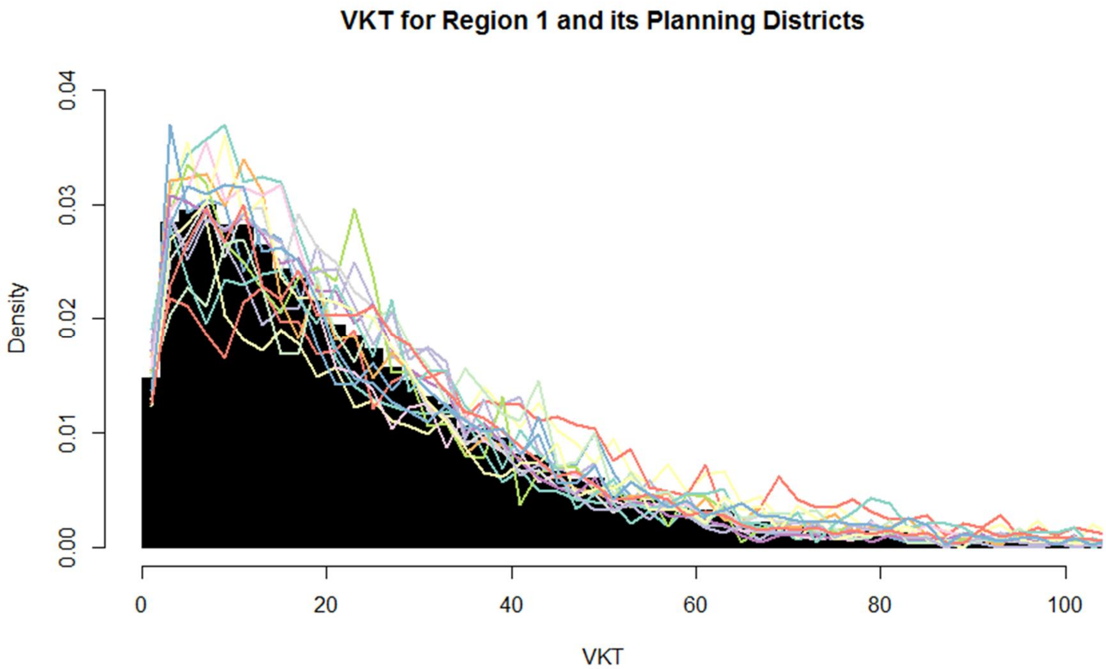

Figure 27: Histogram of VKT for Toronto region (black) and its planning districts (colored lines).

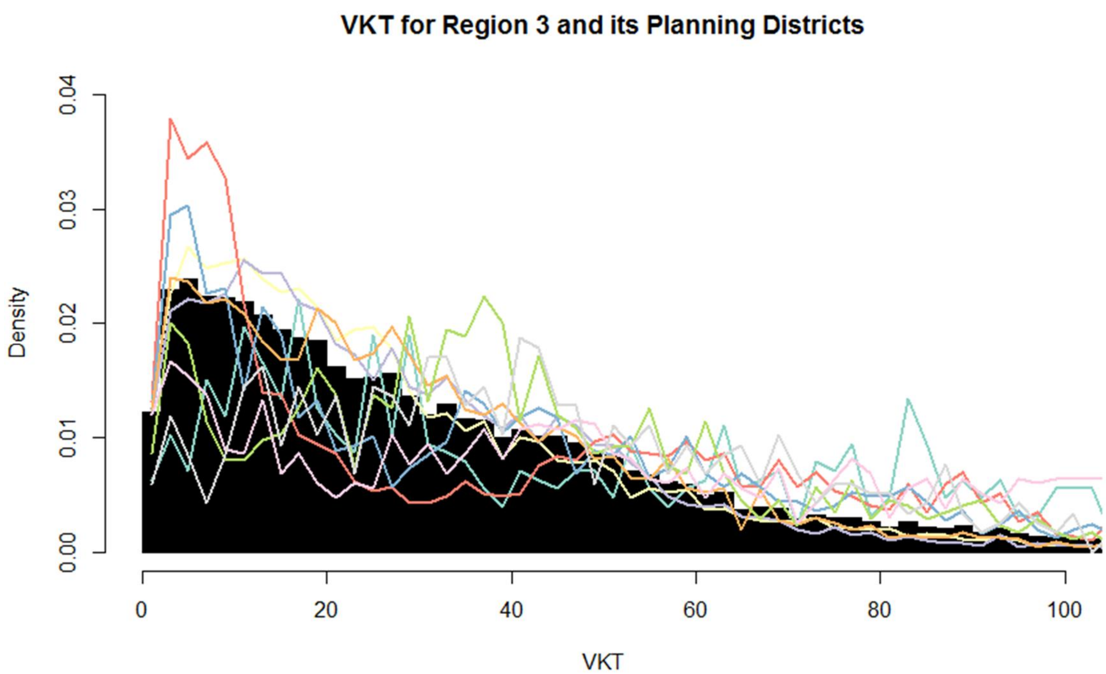

Figure 28: Histogram of VKT for York region (black) and its planning districts (colored lines).

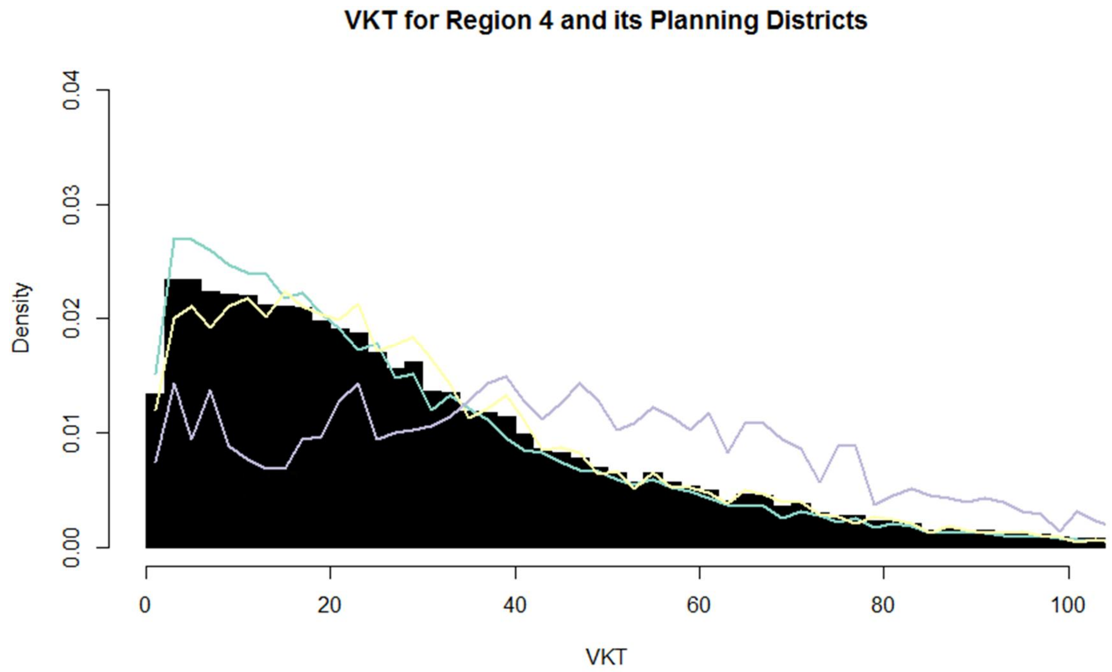

Figure 29: Histogram of VKT for Peel region (black) and its planning districts (colored lines).

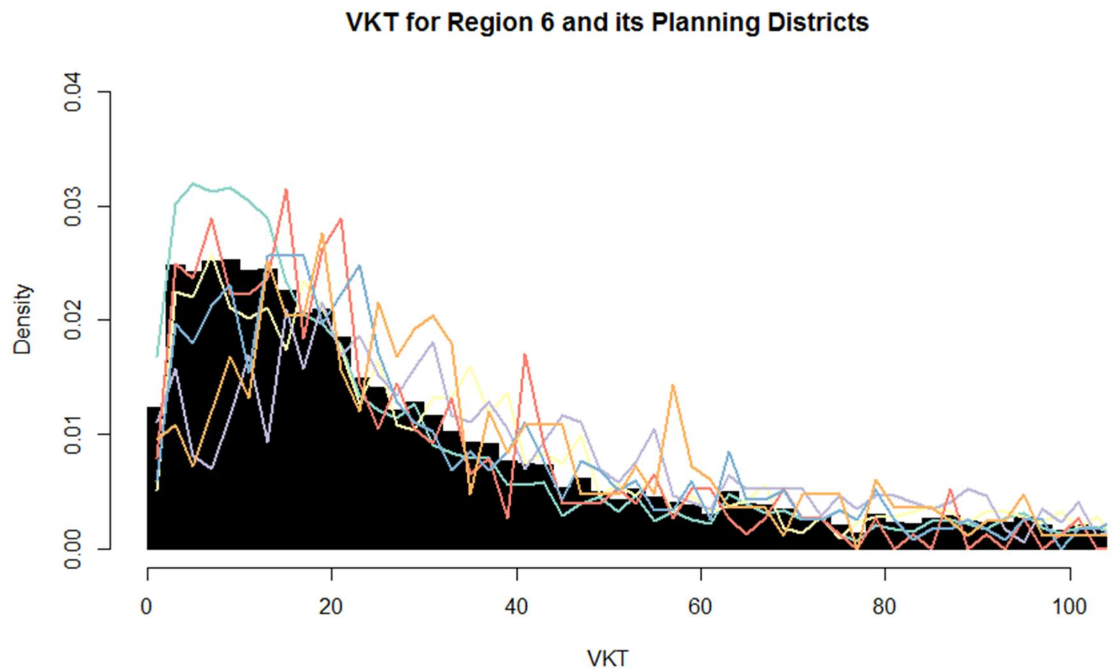

Figure 30: Histogram of VKT for Hamilton region (black) and its planning districts (colored lines).

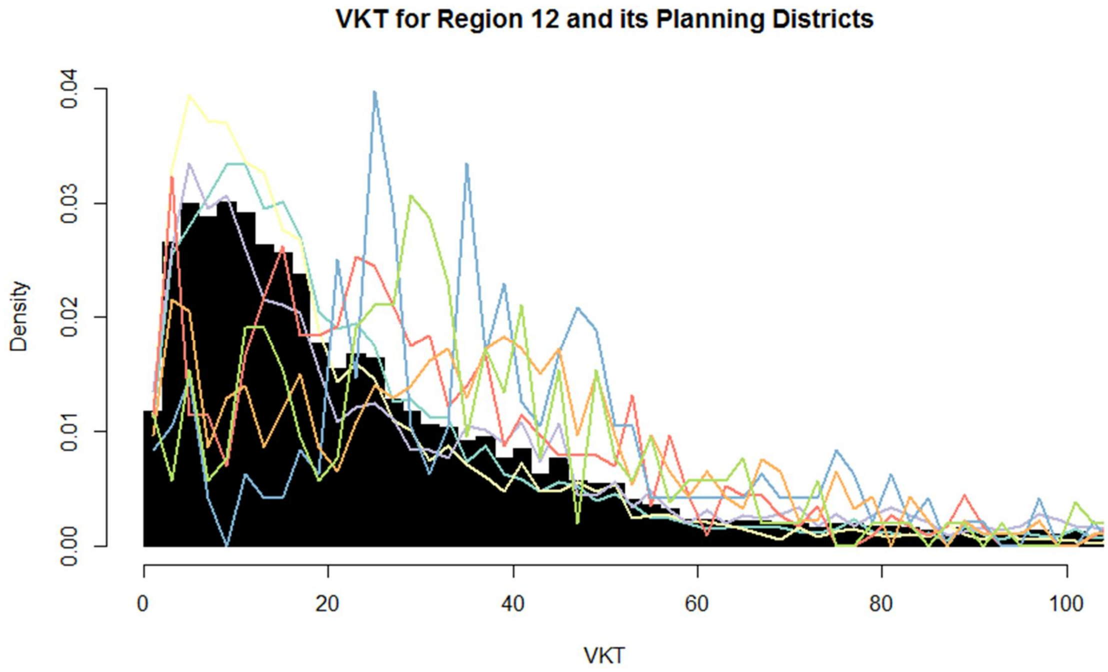

Figure 31: Histogram of VKT for Waterloo region (black) and its planning districts (colored lines).

APPENDIX C: MAPS OF VEHICLE KILOMETERS TRAVELLED

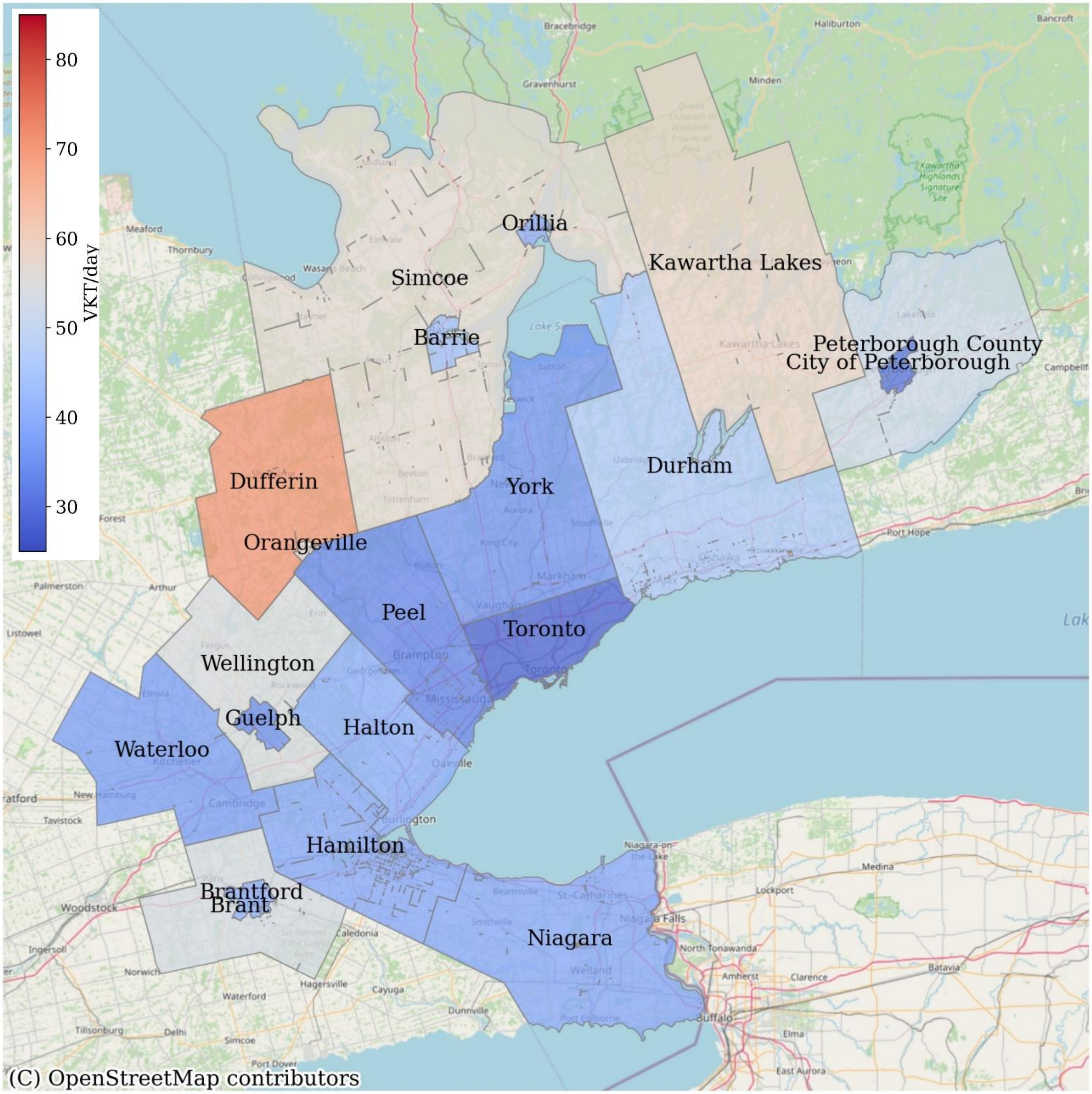

Figure 32: Map of mean VKT by region.

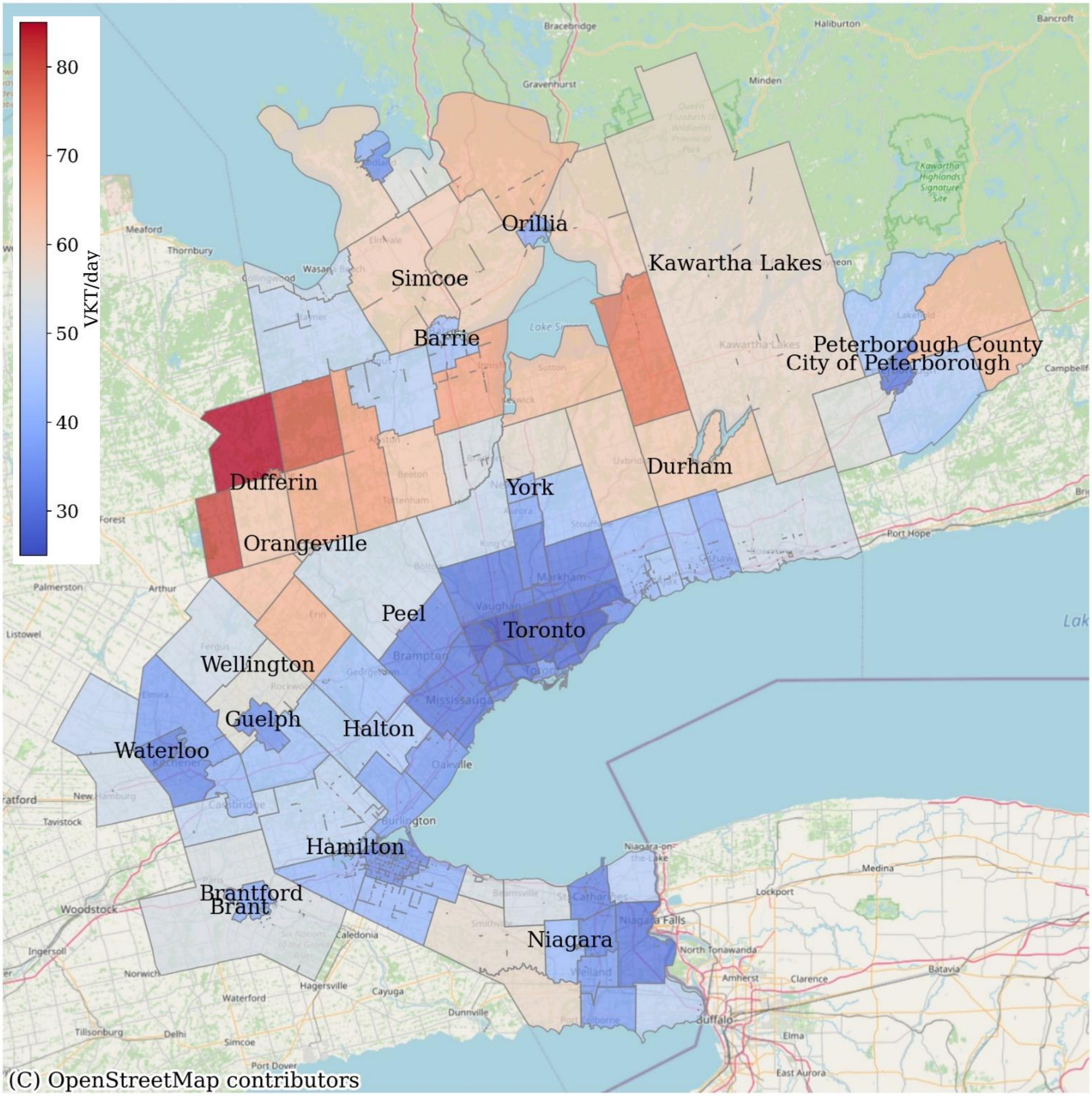

Figure 33: Map of mean VKT by planning district. Planning districts with low sample numbers have not been removed.

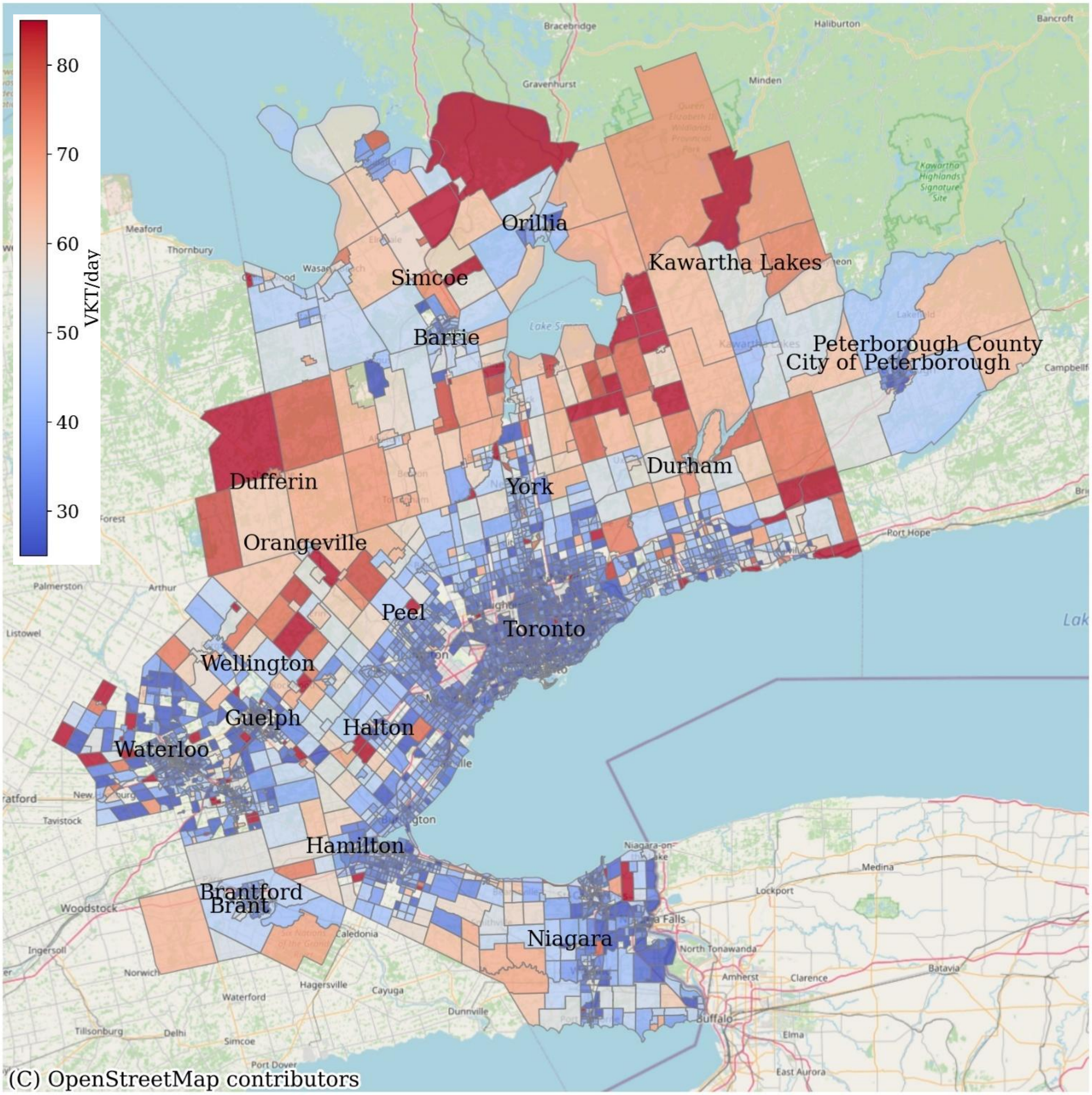

Figure 34: Map of mean VKT by traffic analysis zone. Traffic analysis zones with low sample numbers have not been removed.

References

[1] I. Boudway, "Batteries For Electric Cars Speed Toward a Tipping Point," Bloomberg, 16 December 2020. [Online]. Available: https://www.bloomberg.com/news/articles/2020-12-16/electric-cars-are-about-to-be-as-cheap-as-gas-powered-models. [Accessed 7 January 2021].

[2] Transport Canada, "Zero-emission vehicles," Government of Canada, 31 January 2020. [Online]. Available: https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles. [Accessed 7 January 2021].

[3] Data Management Group, "TTS Introduction," [Online]. Available: http://dmg.utoronto.ca/transportation-tomorrow-survey/tts-introduction. [Accessed 08 02 2021].

[4] Statistics Canada, "Table 20-10-0021-01 New Motor Vehicle Resgistrations," 1 February 2021. [Online]. Available: https://doi.org/10.25318/2010002101-eng. [Accessed 1 February 2021].

[5] United States Environmental Protection Agency, "EPA Green Vehicle Guide - 2021 Guide," U.S. Department of Energy, [Online]. Available: https://www.fueleconomy.gov/feg/EPAGreenGuide/xls/all_alpha_21.xlsx. [Accessed 9 February 2021].

[6] Government of Canada, "Historical Data," 10 December 2020. [Online]. Available: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. [Accessed 9 February 2021].

[7] C. Argue, "To what degree does temperature impact EV range?," GeoTab, 25 May 2020. [Online]. Available: https://www.geotab.com/blog/ev-range/. [Accessed 9 February 2021].

[8] AES Engineering Ltd., "Electric Vehicle Charging Infrastructure in New Multifamily Developments- Requirement Options and Costing Analysis," 4 April 2017. [Online]. Available: https://udi.bc.ca/wp-content/uploads/2017/06/Final-Report-r004-EV-Requirements-20170404.pdf. [Accessed 7 January 2021].

[9] Dunsky Energy Consulting, "City of Toronto Electric Vehicle Strategy," 9 December 2019. [Online]. Available: https://www.toronto.ca/wp-content/uploads/2020/02/8c46-City-of-Toronto-Electric-Vehicle-Strategy.pdf. [Accessed 7 January 2021].

[10] D. C. Doug Chandler, "Electric Vehicle Charging and the Power of Sharing," *Electrical Line,* pp. 43-45, July-August 2020.

[11] D. Chandler, "Statistical Modelling of Load-Managed Charging for Electric Vehicles in Multi-Unit Residential Parking," May 2020. [Online]. Available: https://www.researchgate.net/publication/341763845_Statistical_Modelling_of_Load-Managed_Charging_for_Electric_Vehicles_in_Multi-Unit_Residential_Parking. [Accessed 3 March 2021].

[12] SAE International, "J1772 SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler," SAE International, 2017.

[13] A. Agarwal, "A Comparison of Weekend and Weekday Travel Behavior Characteristics in Urban Areas," Scholar Commons, 2004. [Online]. Available: https://core.ac.uk/download/pdf/154474366.pdf. [Accessed 16 March 2021].

[14] R. S. S. R. Tim Triplett, "American Driving Survey: Methodology and Year One Results," AAA Foundation for Traffic Safety, 2015.

[15] R. B. Drew Dorian, "2021 Rivian R1T," Car and Driver, [Online]. Available: https://www.caranddriver.com/rivian/r1t. [Accessed 19 March 2021].

[16] Bollinger Motors, "Bollinger B2," Bollinger Motors, [Online]. Available: https://bollingermotors.com/bollinger-b2/. [Accessed 19 March 2021].