

Identifying and Optimizing Electric Vehicle Corridor Charging Infrastructure for Medium and Heavy-Duty Trucks

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Final Report

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Table of Contents

Chapter 1. Introduction	1
1.1 Background and Motivation	1
1.2 Electrification Potential of Commercial Vehicles	2
1.3 Electric Truck Market	2
1.4 Research Gap and Opportunities	4
Chapter 2. Conventional and Renewable Power	6
2.1 Grid Impact Analysis	6
2.1.1 Proximity to Electrical Substation	8
2.1.2 Power Capacity	8
2.1.3 Power Reliability	9
2.1.4 Results	9
2.2 Power from Zero Emission Sources	12
2.3 On-Site Solar Generation Availability	13
Chapter 3. Identifying Candidate Charging Station Locations through a Multicriteria Decision Analysis	14
3.1 Selection Criteria	14
3.1.1 Main Criteria	14
3.1.2 Sub Criteria	15
3.2 AHP Structure	16
3.3 GIS Layers	18
3.4 High Priority Corridors for Charging Stations	34
Chapter 4. Optimization of Charging Station Locations	35
4.1 Problem Description	35
4.2 Numerical Experiment	36
4.2.1 Experiment Settings	36
4.2.2 Results	39
Chapter 5. Conclusions and Recommended Future Studies	44
Appendix A: Vehicle Classification	
Appendix B: Mathematical Optimization Model	

List of Figures

Figure 1 Total U.S. greenhouse gas emissions by economic sector in 2019.....	2
Figure 2 US Historical and Projected Sales of Medium- and Heavy-duty Trucks.....	3
Figure 3 Electric Grid Suitability Rating in Minnesota.	10
Figure 4 Electric Grid Suitability Rating in Twin Cities Metro Region.	11
Figure 5 AHP Structure for e-trucks charging station location analysis.....	17
Figure 6 Heavy commercial annual average daily traffic (HCAADT) map.	19
Figure 7 Heavy commercial annual average daily traffic (HCAADT) layer.	20
Figure 8 Land cover map.....	21
Figure 9 Water resource layer.	22
Figure 10 Flood risk layer.	23
Figure 11 Proximity to truck stop.....	24
Figure 12 Proximity to gas station.	25
Figure 13 Proximity to DCFC.	26
Figure 14 Distance to power substations, weighted by the suitability of each power substations according to Section 2.1 analysis.	27
Figure 15 Solar radiation layer.....	28
Figure 16 Land price layer.....	29
Figure 17 Classified final objective layer. Grouping is done by standard deviation (STD) of scores from the mean score. The black points are the locations with the highest scores, i.e., more than 2.25 standard deviations from the mean score.	31
Figure 18 Candidate locations and truck stops. Grouping is done by standard deviation (STD) of scores from the mean score.....	32
Figure 19 Candidate charging stations and power substations. Grouping is done by standard deviation (STD) of scores from the mean score.....	33
Figure 20: The Minnesota highway network developed for e-truck charging optimization in this study. Red points represent candidate charging stations.	37
Figure 21: Truck trip distribution in the State of Minnesota, obtained from StreetLight's Trip Index.....	38
Figure 22: Charging station locations in the Minnesota network under the base assumptions. Selected charging stations are almost uniformly spread across the network and are generally located on highways with a higher percentage of e-truck flows.	40
Figure 23: Penetration rate of e-trucks for different driving ranges and number of charging stations. The e-truck penetration rate could increase sharply after the first few public charging stations are deployed.	41
Figure 24: The effect of charging infrastructure development and driving range on total system cost.....	42
Figure 25: Daily vehicle miles traveled (total VMT) for different values of e-truck range and number of charging stations. As e-truck range increases and public charging infrastructure develops, more e-trucks are adopted and VMT increases.	43
Figure 26: Daily vehicle miles traveled (VMT) for each truck type. As public charging infrastructure develops, more e-trucks are adopted and their VMT surpasses diesel trucks VMT.	43

List of Tables

Table 1 E-truck Charging Station Feasibility Weighting 7

Table 2 AHP Criteria Weights. 17

Table 3 List of Data and Analysis Type in the AHP Framework..... 18

Executive Summary

This project studies the benefits and barriers of increased adoption of medium-duty and heavy-duty electric trucks, referred to as e-trucks, and presents a methodology for optimizing the location of e-truck charging stations in Minnesota. In general, e-trucks provide zero tailpipe emissions and lower operating and maintenance costs. However, some barriers to adopting e-trucks include higher initial purchase costs, lack of charging and maintenance infrastructure, limited range, and charging time. The methods presented in this study aim to address the charging infrastructure planning, which provides information about e-trucks charging activities, changes in vehicle miles traveled (VMT), and potential operating cost savings.

A two-stage planning method was presented, including a geographic information system (GIS)-based multicriteria decision tool for identifying candidate charging stations and an optimization model to select an ideal subset from the candidate locations. An Analytic Hierarchy Process (AHP) method, including ten criteria, was adopted in the first stage. According to a stakeholder survey and AHP analysis, the following three criteria were found to be most important in planning e-truck charging stations:

- Ease of access for e-truck users, represented by *truck traffic volume*, with 36% weight
- *Proximity to power substations* with 20% weight
- *Proximity to existing truck stop stations* with 16% weight.

Moreover, I-35, I-94, I-90, US10, and US169 were identified as priority corridors for e-truck charging stations.

In the second stage, a customized network model and an optimization tool were developed to optimally select a predetermined number of public charging station locations from the candidate set. The optimization model considered the truck origin-destination demand in Minnesota, the routing and charging activities of e-trucks, and the penetration rate of e-trucks. The objective of the optimization model was to minimize the total travel cost of electric and diesel trucks combined to promote the higher adoption of e-trucks. Several input assumptions were tested, including number of charging stations, e-truck driving range, and customers' perception of cost savings. Numerical results led to the findings summarized below:

- *E-truck adoption rate* would increase significantly as publicly available charging stations increase. Also, an increase in e-truck driving range enhancement would increase the e-truck market penetration rate.
- *The e-truck market share* could increase when about 30-40 charging stations are optimally deployed in Minnesota.
- *Total VMT* would increase in the early stages of deployment as e-trucks could follow longer routes to access charging stations. Diesel truck VMT would decrease significantly as e-truck adoption increases.
- *Total system cost* (i.e., the combined travel time and cost of diesel and e-trucks) would decrease due to the lower per-mile cost of e-trucks.

Further studies on the proposed methodology and its adoption are recommended to address policy questions regarding e-truck infrastructure planning. Broader economic factors, government incentives, and equity goals in the planning process are among the suggested topics for future studies.

Chapter 1. Introduction

1.1 Background and Motivation

Building a clean energy economy and addressing the climate crisis is a top priority of the Biden Administration¹. The Biden Administration aims to achieve carbon pollution-free electricity by 2035, "deliver an equitable, clean energy future, and put the United States on a path to achieve net-zero emissions, economy-wide, by no later than 2050²." Furthermore, the 2007 Next Generation Energy Act³ signed by former Minnesota Governor Tim Pawlenty set a greenhouse gas emission reduction goal of 80% below 2005 levels by 2050. The goal includes benchmarks of a 15% reduction by 2015 and a 30% reduction by 2025. Since then, Minnesota has successfully changed the trajectory of its emissions profile, so it is no longer increasing. Minnesota published its Climate Solutions and Economic Opportunities in 2015, which aligns with the state's Next Generation Energy Act goals. Based on this guideline, developing mass transit, improving the fuel efficiency of vehicles, enhancing the renewable electricity standard, and eliminating coal plants are the principal aspects of this plan (MEQB, 2015)⁴.

The United States Environmental Protection Agency (EPA) 2019 report (Figure 1) reveals that the transportation sector has the highest share of greenhouse gas emissions in the United States (USEPA, 2019)⁵, which is also true in Minnesota. Enhancement in the transportation sector, such as improving the vehicles' energy efficiency and pollutant emissions, could lead to emissions reduction. MN Statute 174.01 directs the Minnesota Department of Transportation (MnDOT) to reduce greenhouse gas emissions from the transportation sector. The state has examined corridor charging infrastructure needs for light-duty cars but has not studied charging needs for medium- and heavy-duty trucks. This study addresses the research need identified by MnDOT and investigates infrastructure needs to support the adoption of medium- and heavy-duty electric vehicles (e-trucks) in Minnesota.

¹ <https://eere-exchange.energy.gov/Default.aspx?foald=a431a2fd-4bd8-49ab-9fe4-2d0a244c4090>

² Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad," January 27, 2021.

³ <https://www.pca.state.mn.us/air-water-land-climate/climate-change-initiatives>

⁴ <https://www.dot.state.mn.us/ofrw/mfac/pdf/white-paper-electrification-of-freight.pdf>

⁵ U.S. Environmental Protection Agency. "Sources of Greenhouse Gas Emissions".
<https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions>

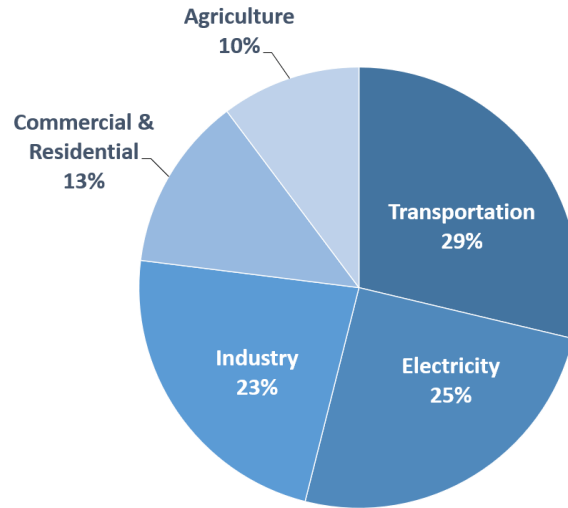


Figure 1 Total U.S. greenhouse gas emissions by economic sector in 2019

1.2 Electrification Potential of Commercial Vehicles

Trucks are a major energy consumer and producer of greenhouse gas emissions in the U.S. and globally. Commercial trucks in classes 4 through 8 used a total of approximately 44 billion gallons of fuel in 2015 (ATA, 2018)⁶. Class 4-8 trucks are only 4% of the total number of U.S. on-road vehicles but represent a quarter of the annual vehicle fuel use (ATA, 2018). According to the United States Environmental Protection Agency (EPA) 2021 report, the medium- and heavy-duty (classes 3-6 and classes 7-8) trucking sector currently accounts for 23% of greenhouse gas emissions from transportation and is the largest contributor to mobile NOx (i.e., nitric oxide and nitrogen dioxide) emissions in the U.S. There are new opportunities in commercial vehicle classes to dramatically reduce emissions through the use of new energy sources such as electricity, biofuels, and hydrogen.

1.3 Electric Truck Market

The electric truck (e-truck) market size has observed remarkable growth in recent years due to its low maintenance cost, initiatives of governments and regulations, and dropping battery prices. The global e-truck market is predicted to reach a high of 1.5 million units, in terms of volume, by the end of 2025 with a rate of 18.5% compound annual growth rate (CAGR) during the forecast period⁷. Figure 2 shows historical and projected sales of medium- and heavy-duty trucks in the U.S. (Initiative, 2020).

⁶ American Trucking Associations, 2018. American Trucking Trends 2018.

⁷ Global Electric Truck Market Research Report, 2021

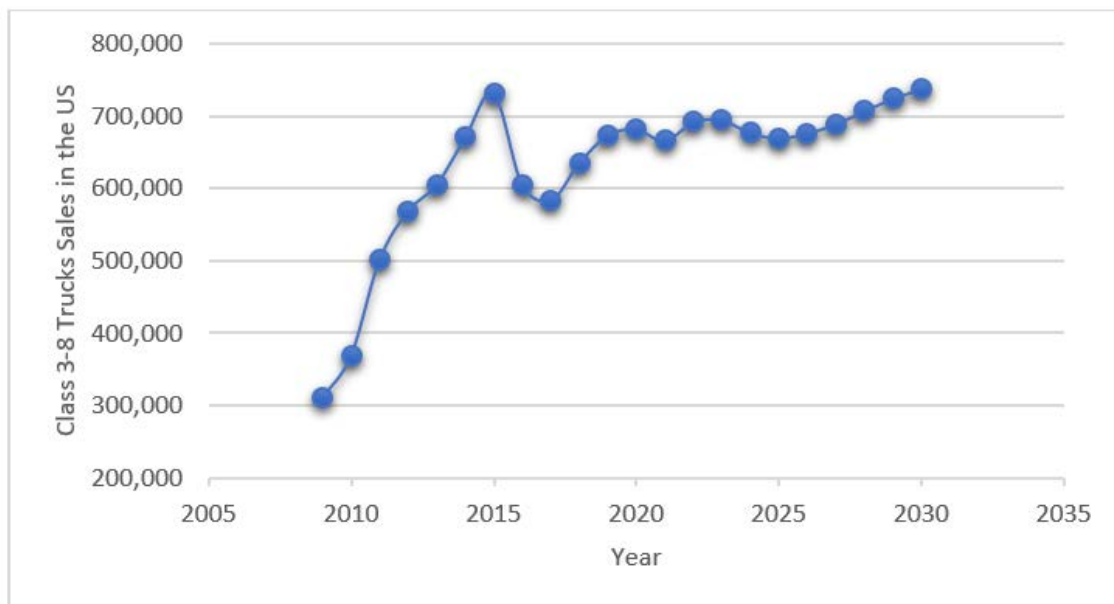


Figure 2 US Historical and Projected Sales of Medium- and Heavy-duty Trucks^{8,9}.

Several large transportation companies have decided to electrify their fleets. For instance, FedEx Corp. as the second-largest global transportation provider announced its goal to convert its fleet to carbon-neutral operations and has set benchmarks for purchasing commercial electric vehicles beginning in 2025 (Ronan, 2021). Also, Walmart announced plans to electrify all its vehicles, including long-haul trucks, by 2040 (Ronan, 2021). Some other big companies also plan to use e-trucks in their fleet. For example, Amazon took a laudable step toward the massive adoption of fleet electrification by ordering 100,000 electric vans (Ronan, 2021).

In December 2021, the Biden Administration issued an executive order calling for most federal vehicle purchases to be zero-emission vehicles (such as electric vehicles) by 2035. This order impacts about 380,000 federal vehicles that need to be replaced¹⁰. Likewise, under an executive order, Governor Gavin Newsom in 2020 signed California's plans to mandate by 2045 that all operations of medium- and heavy-duty vehicles be zero emission where feasible¹¹. Several other states, e.g., Washington, Oregon, New York, New Jersey, Massachusetts, and Vermont, have adopted California's truck standards¹². These executive orders are likely to boost e-truck market growth throughout the nation.

⁸ West Coast Clean Transit Corridor Initiative report, June 2020

⁹ This forecast was conducted before Covid 19 pandemic.

¹⁰ <https://www.reuters.com/business/autos-transportation/us-allow-california-require-half-all-trucks-be-electric-by-2035-nyt-2023-03-31/>

¹¹ <https://www.reuters.com/business/autos-transportation/us-allow-california-require-half-all-trucks-be-electric-by-2035-nyt-2023-03-31/>

¹² <https://thehill.com/policy/energy-environment/3927717-biden-administration-approves-californias-electric-truck-mandate/>

A white paper published by the Minnesota Freight Advisory Committee (MFAC) identifies current benefits and barriers to the uptake and adoption of e-trucks in freight systems¹³. In summary, the challenges of e-truck adoption can be categorized into six main groups as follows:

- Technical performance, including:
 - a. Infrastructure availability: the lack or scarcity of e-truck charging and maintenance stations makes operation of e-trucks more challenging compared to diesel trucks.
 - b. Driving range: most e-trucks have a lower operating range than diesel trucks and need more frequent charging stops.
 - c. Battery capacity: batteries are the most expensive part of e-trucks and degrade by time.
 - d. Charging needs: besides frequent charging needs, the long charging time of e-trucks reduces their operational efficacy.
- Operational performance, including:
 - a. Operational efficiency: depending on the operational characteristics of e-trucks, e-truck operators may prefer at-home vs. *en-route* charging and overnight vs. during-the-day charging.
 - b. Loading capacity: heavy batteries take a notable weight capacity of e-trucks, making them more appropriate for hauling light-weight goods only.
- Economics: e-trucks are still more expensive than diesel trucks and their batteries need to be replaced at some point in their lifecycle, making them more expensive to own.
- Utility impacts: current grid networks may not have enough capacity to support e-trucks' energy demand. Grid expansion would require significant investments, that may partly be passed to trucking industries.

1.4 Research Gap and Opportunities

This literature review shows there are barriers to large adoption of e-trucks. Besides technical and operational challenges, the main barrier is high upfront costs. However, if the barriers are overcome, there are benefits to e-truck adoption, including zero tailpipe emissions, reduced noise, and lower operation costs. A new total cost of ownership study¹⁴ from the National Renewable Energy Laboratory finds that e-trucks (i.e., battery electric and fuel cell electric commercial trucks as considered in the study) could be economically competitive with conventional diesel trucks by 2025 in some operating scenarios¹⁵.

Although some governments and private companies have started purchasing e-trucks, most other companies are waiting for further technology development and a viable business case. MnDOT aims to support the adoption of e-trucks by providing appropriate charging infrastructure. Therefore, this study

¹³ <https://www.dot.state.mn.us/ofrw/mfac/pdf/white-paper-electrification-of-freight.pdf>

¹⁴ <https://www.energy.gov/eere/fuelcells/articles/new-doe-national-lab-report-examines-total-cost-ownership-battery-electric>

¹⁵ <https://www.energy.gov/eere/fuelcells/articles/new-doe-national-lab-report-examines-total-cost-ownership-battery-electric>

identifies the needs and opportunities in developing a network of public charging stations for medium-duty and heavy-duty electric vehicles in Minnesota and develops decision-making tools to aid in planning efforts. This study does not specify a particular charging type or technology.

Chapter 2. Conventional and Renewable Power

To identify the best possible public e-truck charging station locations, this study examined the electric load required by the stations. This electric load could potentially be between 500 kilowatts (kW) and 4 megawatts (MW) or higher depending on the size and number of chargers. A watt is a unit of power, and power is the rate at which energy is produced or consumed. A kW is equivalent to 1,000 watts, and it is used to describe energy consumption at lower levels such as households. A MW equals 1,000 kilowatts, and it is used to describe energy consumption at high-capacity levels such as industrial facilities. Because e-truck charging stations require a larger electrical load, they are more likely to require upgrades to the electric grid, which can be costly.

If a proposed e-truck charging station will be sited near existing electric utility service feed, it is highly likely that this circuit will need to be upgraded to support the added electrical load. Electrical upgrades can include replacement of the distribution transformer, switches, conductors, switchgear, or electrical panels. If the circuit serving the proposed e-truck charging station cannot be upgraded, a new dedicated circuit is needed. Dedicated circuits require more capital investment because there is a higher likelihood of needing new equipment at the substation, poles, conduits, conductors, switches, and other electrical equipment. Distribution circuits serving homes, commercial properties, and industrial properties are usually operated between 4 kilovolts (kV) and 16kV (a volt is the electrical unit of voltage, and a kV is 1,000 volts), originating at an electrical substation nearby. A distribution circuit with these voltages can typically carry between 2MW and 8MW, which could support between 5 and 22 direct current (DC) fast chargers operating at 350kW, that would be suitable for e-truck charging stations.

If a proposed e-truck charging station is in an undeveloped area, a new electric service to the station is required. This new electric service can be a short connection from an existing distribution circuit on the street (or a few streets away), or it could also come from a new distribution circuit from a nearby substation. Large electric loads (i.e., 10MW and larger) may require their own dedicated substation.

Installing e-truck charging stations requires early communication and involvement with the electricity utility serving the proposed area. The electric utility will perform a system impact study to determine the best way to serve the required electrical load while maintaining the system reliability and operational flexibility. The utility's goal is to avoid circuits that are highly overloaded and ultimately minimize or avoid outages in the system.

While it is not feasible to know the exact impacts to the electric grid without the utility's system impact study, the research team developed an approach, detailed in the next section, to identify areas with the highest potential to accept a new electric load while reducing impact to the grid. Minimizing grid impact saves costs for both the station developer and the utility.

2.1 Grid Impact Analysis

Table 1 summarizes the approach and scoring. The approach focused on three criteria—power capacity, proximity to a substation, and reliability.

Table 1 E-truck Charging Station Feasibility Weighting

Criteria	Logic	GIS Layer	Suitability Threshold	Score	Weight
Proximity to electrical substations	E-truck charging stations close to an electrical substation are more feasible due to reduced electric utility interconnection costs, system upgrades, and construction complexity	Electrical substations (from MnDOC layer)	< 0.5 miles to interstate/freeway (functional class 1 & 2)	10	50%
			0.5 - 1 mile to interstate/freeway (functional class 1 & 2)	9	
			< 0.5 miles to remaining US highways/trunk highways (not an interstate/freeway) (functional class 3)	8	
			0.5 - 1 mile to remaining US highways/trunk highways (not an interstate/freeway) (functional class 3)	7	
			< 0.5 miles to other principal arterial roadways (functional class 4)	4	
			0.5 - 1 mile to other principal arterial roadways (functional class 4)	3	
Power capacity	Power needed for an e-truck charging station would likely be served through a distribution circuit. Substations with distribution voltages can usually be found in substations with lower sub-transmission voltages such as 69kV and 115kV. Substations with higher voltage have higher capacity. The higher the capacity, the greater the likelihood that power is available for an e-truck charging station.	Electrical substations (from MnDOC layer)	Lowest voltage 115kV (20+ MW power capacity)	10	30%
			Lowest voltage 69kV (10+ MW power capacity)	7	
			Voltage below 69kV (6+ MW power capacity)	3	
Power reliability	The more substations that are closer to each other, the higher chance there are transmission lines connecting to each other and the higher the reliability of power that would be available for an e-truck charging station.	Electrical substations (MnDOC layer)	3+ substations within a 5-mile buffer	10	20%
			2 substations within a 5-mile buffer	7	
			1 substation within a 5-mile buffer	3	
			0 substations within a 5-mile buffer	1	

2.1.1 Proximity to Electrical Substation

The distance from a substation to a main road was selected to capture the feasibility of serving an e-truck charging station. Although the study does not identify actual e-truck charging station locations, it was determined that the most accessible locations would be located closest to a highway exit or a main road intersection. Thus, the closer a substation is to a road where the charging station can be located, the lower the costs to bring power to the charging station and the higher the suitability score.

Roads were also classified by road type or functional classification¹⁶. Higher scores were given to higher functional road classes, which can accommodate more medium and heavy-duty vehicles. The ranking is based on the vehicle volume of each road classification¹⁷. Functional classes 1 and 2 (interstates and other freeways) were given the highest score, while functional classes 3 and 4 (Principal and minor Arterial) were given lower scores.

2.1.2 Power Capacity

Power is transferred between substations with the use of transmission lines (with voltages of 69kV and above). Substations have power transformers that change voltage from transmission levels (69kV and above) to distribution levels (34.5kV and below). Power is then provided to customers with the use of distribution circuits.

The substation power available for a new electric load (such as an e-truck charging station) is unknown to the public since only electric utilities have access to this information. However, higher substation voltage generally means a higher substation power capacity. This study used the following substation voltage ranges to help identify suitable e-truck charging station locations:

- 115kV
- Between 69kV and 115kV
- 69kV or lower voltage

Substations with a base voltage greater than 115kV were not considered as these do not typically have distribution facilities within the substation and therefore would not be able to serve the charging stations. Connecting to a substation that does not have distribution voltages would also require higher costs since additional electric distribution facilities would be needed.

The score assigned in Table 1 is based on the available MW capacity for each range of voltages. Usually, the higher the voltage, the larger the available capacity. However, the actual available capacity depends on the total number of residential, industrial, and commercial customers and their respective electric loads.

¹⁶ Functional Class means the grouping of streets and highways into classes or systems according to the character of service they are intended to provide. More information can be found in <https://gisdata.mn.gov/dataset/trans-functional-class>.

¹⁷ The grouping of streets and highways into classes or systems according to the character of service they are intended to provide. Source: <https://gisdata.mn.gov/dataset/trans-functional-class>.

The substation voltage identified in the GIS map was determined by reviewing the substations included in an available power flow model, which has sufficient detail of Minnesota's transmission system. This substation voltage data was then compared with the Minnesota Department of Transportation's data to evaluate potential charging station locations.

2.1.3 Power Reliability

Reliability is a key component when locating facilities that require minimal interruptions in electric service. This category evaluates the number of substations located near each other. Substations connect to one another either with transmission lines (where they carry large amounts of electricity) or with distribution circuits (where they carry lower amounts of electricity). Connections between substations provide flexibility and reliability since they offer the ability to re-route power shared between the substations. In the event of a power outage in one of the transmission lines or distribution circuits, multiple connections between substations typically lead to fewer electrical outages from these substations.

Multiple substations close to one another have a higher potential of having more power sources connecting to each other. This study examined the number of substations located within a 5-mile radius to determine potential electrical service at a e-truck charging station. More substations within a 5-mile radius led to a higher connection probability and a higher reliability score.

2.1.4 Results

The results of the analysis are shown in Figures 3 and 4. Each point on the maps shows a power substation with its corresponding rating. According to the results, most stations with a highly suitable or moderately suitable rating (red and orange points respectively) are in and around major urban areas. These stations could have high power demand already, which is not considered in the analysis due to data unavailability. The stations that are rated suitable (dark blue points) are located mostly along freeways and major highways.

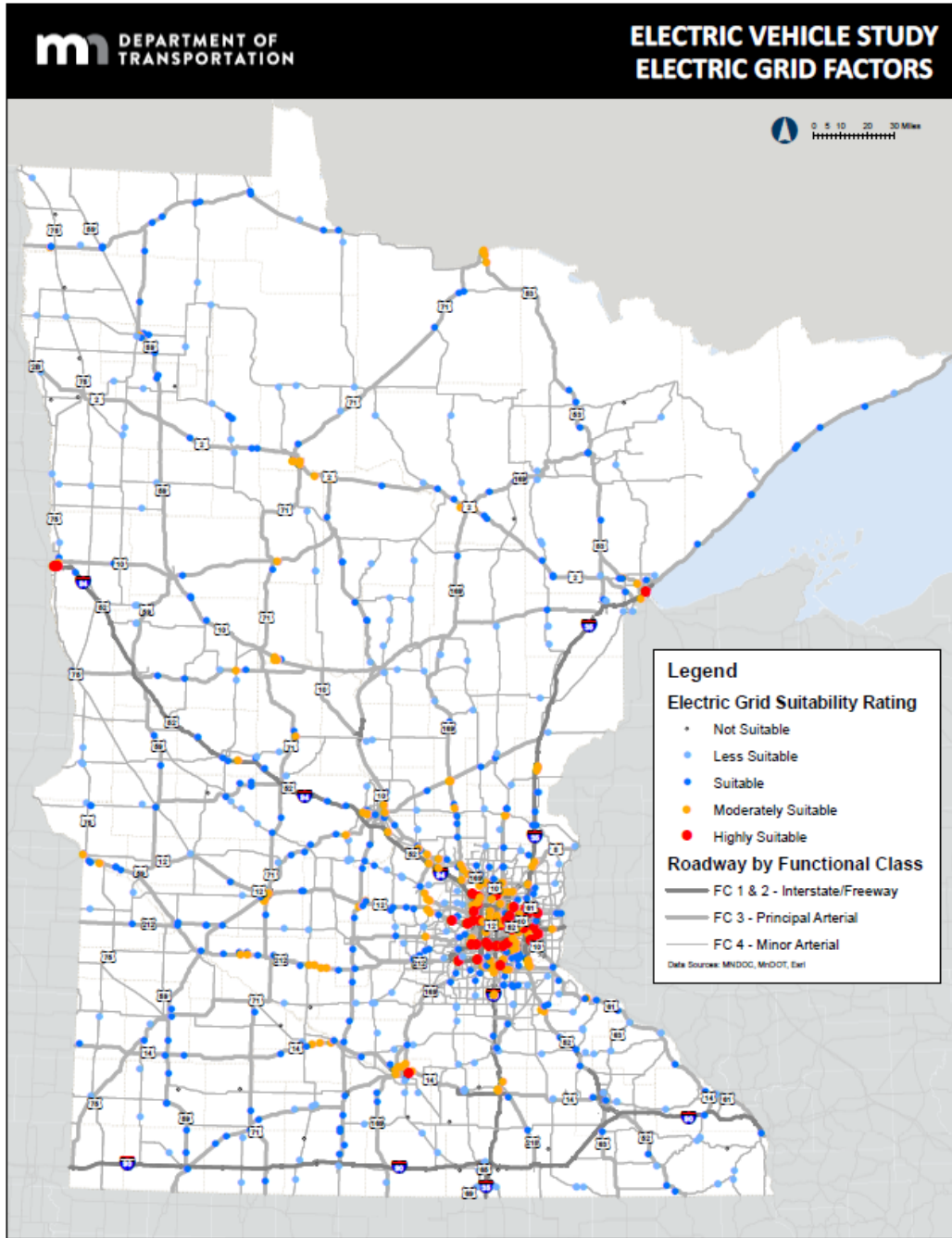


Figure 3 Electric Grid Suitability Rating in Minnesota.

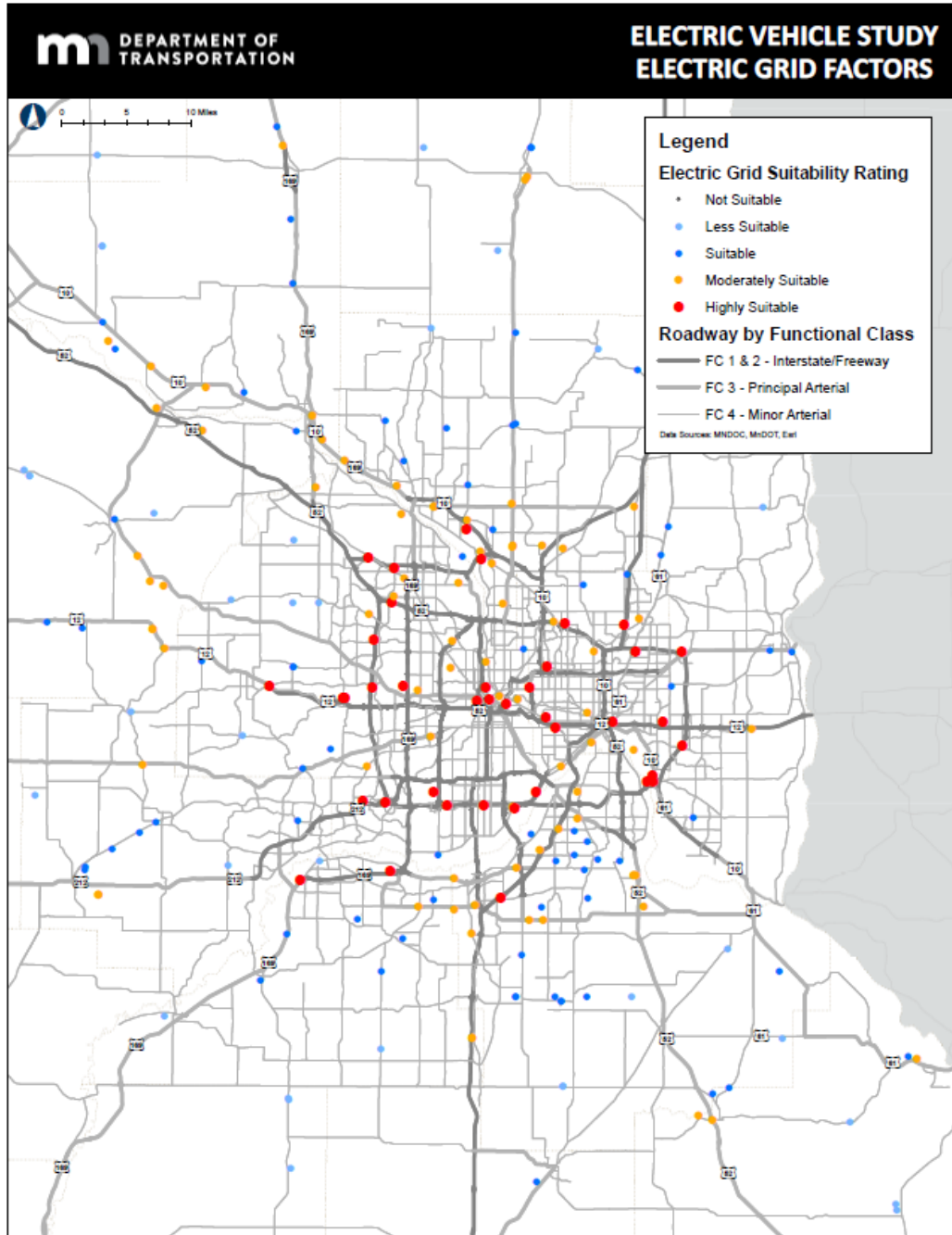


Figure 4 Electric Grid Suitability Rating in Twin Cities Metro Region.

2.2 Power from Zero Emission Sources

Although e-trucks have zero tailpipe emissions, there are concerns about the carbon footprint from generating electricity for them. According to the US Energy Information Administration in 2020, the generation mix in the State of Minnesota consisted of 29% in-state renewables, 26% nuclear, 25% coal, and 20% natural gas¹⁸. The drive to clean energy is spurred on by policy makers and utilities alike. Minnesota's Next Generation Energy Act¹⁹ was passed in 2007 and required utilities to obtain at least 25 percent of their electricity from renewable sources by 2025. This goal was effectively met by the end of 2017, while during the same span, coal-generated energy declined from 59 percent to 39 percent and is still declining. In 2023, Governor Walz signed a new legislation²⁰ to further increase renewable power consumption through four parts:

- *100 Percent Clean Energy by 2040*: This requires all Minnesota electric utilities to use only carbon-free energy resources by 2040 as well as setting interim goals along the way.
- *Clean Energy First*: This requires that when power generation is added or replaced, the utility must prioritize energy efficiency and clean energy over fossil fuels.
- *Energy Optimization*: This raises the Energy Efficiency Resource Standard for larger electric utilities and expand conservation programs for more efficient, cleaner energy.
- *Carbon Reduction Goals for Existing Building*: This goal targets the reduction of greenhouse gas emissions from existing buildings by 50 percent by 2035.

Minnesota has multiple electric utilities across the state. These range from large investor-owned utilities (IOUs) that serve large population centers to electric cooperatives that typically serve rural customers as well as municipal utilities. The electricity that public charging stations for medium- and heavy-duty trucks receive would come from one of these types of electric utilities. Each utility has different clean energy and efficiency goals that may even exceed the state regulations. Four of Minnesota's largest electric utilities, along with many others, have plans in place to reduce emissions.

- Xcel Energy plans to eliminate coal generation by 2030 and produce carbon-free electricity by 2050.
- Minnesota Power plans to eliminate coal generation by 2035 and produce carbon-free electricity by 2050.
- Otter Tail Power Company projects that customers will receive 35 percent renewable energy by 2023 and plans to reduce carbon emissions by 50 percent of 2005 levels by 2025 and by 97 percent of 2005 levels by 2050.
- Great River Energy, a wholesale energy provider, committed to voluntarily providing 50 percent renewable energy by 2030. Great River Energy also met the state requirement of 25 percent renewable by 2017, eight years ahead of the state requirement.

¹⁸ <https://www.eia.gov/state/?sid=MN#tabs-3>

¹⁹ <https://www.pca.state.mn.us/air-water-land-climate/climate-change-initiatives>

²⁰ <https://mn.gov/commerce/news/?id=17-563384>

The electricity source that would be used to charge e-trucks in Minnesota will continue to change in the next 30 years. Although it is unclear what exactly this mix will be, existing and proposed state mandates and voluntary carbon reductions will continue to increase renewable sources and decrease carbon fuel sources. This would further support the transition to electric vehicles by ensuring that the electricity needed for electric vehicles will be generated from more environmental-friendly sources.

2.3 On-Site Solar Generation Availability

Solar power is often brought up as a complementary technology to electric vehicles since it is considered a form of electric generation without harmful emissions to the environment. Photovoltaic (PV) power generation is only suitable for certain types of loads. The limitations of the technology are closely related to the power density and cost of the PV system. Solar generation can also be augmented with a battery energy storage system to allow for excess energy to be recovered.

According to the National Solar Radiation Database published by National Renewable Energy Lab²¹, solar radiation provides a maximum of 1 kW of power per square meter. This high-power level only occurs near the equator at noon on a perfectly clear day. PV systems have a maximum efficiency of around 20% when converting solar radiation into electrical energy. The total annual solar energy available on average in the Minneapolis area is 4.9 kWh/m²/day with a range of 3.11 kWh/m²/day to 6.08 kWh/m²/day depending on time of year. Due to conversion efficiency, PV installations in the Minneapolis area can expect to produce a peak of 1 kWh/m²/day of energy, though a 0.6 kWh/m²/day is more likely due to shading, system losses, etc.

The energy required for charging e-trucks at a publicly available charging station would be much higher than what can be expected from a PV installation based on the following analysis. A single 350kW charger with a 20% utilization rate would consume 1,680 kWh per day. A truck stop in Minnesota estimated at 5 total acres may have approximately 20% available space for canopy solar generation (one acre). It should also be noted that only about one-third of the canopy footprint is able to be translated to usable solar array in the area due to the northern latitude and the need to tilt the solar panels for maximum efficiency. For this estimated station size, location, and PV panel arrangement, a solar canopy at the charging station with nameplate power rating of 267 kW, experiencing 4.9 kWh/m²/day, would generate an estimated 725 kWh per day and would not be sufficient to support the energy needed to support one 350 kW charger.

Based on the solar canopy's low generation capacity and the high charger energy requirements, on-site solar generation is not a viable option to fully offset the necessary public charging station energy; however, a solar canopy may be capable of offsetting other electrical consumption such as building and lighting loads at stations.

²¹ <https://www.nrel.gov/gis/solar.html>

Chapter 3. Identifying Candidate Charging Station Locations through a Multicriteria Decision Analysis

This chapter uses various traffic, energy, land use, and environmental data and applies the GIS-AHP²² tool to identify suitable locations in Minnesota for e-truck charging stations of medium-duty and heavy-duty vehicles (for brevity, referred to as charging station in this report). The analysis is based on selection criteria derived from industry needs and the feasibility for installation.

3.1 Selection Criteria

Evaluation of the literature review, elicitation of knowledge with experts and stakeholders (e.g., Minnesota Department of Transportation, American Transportation Research Institute, Freight Mobility Research Institute, American Trucking Associations, HDR Consulting Inc., etc.) and consideration of data availability led to a list of criteria that are most important for an ideal public charging station location. We used 10 criteria categorized into five groups. The criteria classification is based on their relationship to the study goal, which is finding suitable candidate locations for installing charging stations.

3.1.1 Main Criteria

There are five main criteria in the AHS structure. These criteria and their rationale are as follows:

- *Access for e-truck users*: The goal is to make charging stations more accessible to e-truck drivers. According to this criterion, stations should be easily accessible through the existing road infrastructure, ideally located adjacent to major truck corridors (0.5 miles from the centerline of the road), and able to meet the charging needs in high truck traffic areas.
- *Environmental condition*: The goal is to reduce the development impact on nature and the surrounding ecosystems. In other words, this criterion avoids putting charging stations close to special land covers, protected species areas, etc. Furthermore, considering the detrimental effect of significant water exposure on the functionality and accessibility of charging stations, as well as the potential for water contamination by charging stations, charging equipment exposure to water should be minimized. Therefore, placing charging stations in areas prone to flooding or close to standing water should be avoided as much as possible.
- *Proximity*: The goal is to locate charging stations close to other infrastructure such as truck stops, gas stations, etc., that can easily be configured to build charging stations. These locations are likely near the starting points, midpoints, or destinations of most common truck trips.
- *Power supply*: The goal is to reduce the impact on the electric grid, lower the cost for interconnections, and reduce the time needed to build the stations. Charging e-trucks can strain the electric grid if high-capacity DC fast chargers (such as 250kW and above) are used or if a

²² Analysis Hierarchy Process

large number of trucks are charged simultaneously, especially during peak hours. The results from the grid impact analysis in the previous chapter are used to rank power substations in the study area. Furthermore, this criterion considers the potential of using solar energy for supplementing the power supply of charging stations.

- *Land use*: The goal is to reduce the charging station investment cost and provide higher benefits to environmental justice (EJ) populations through easier access to charging stations, attracting traffic, and reducing air pollution. This criterion concerns the land use conditions, including the price of land and land occupation by EJ populations.

3.1.2 Sub Criteria

There are ten sub criteria under the main criteria explained above. These sub criteria are explained below.

- *Truck Traffic Volume*: The objective is to place charging stations near high volumes of truck traffic to meet anticipated charging demand. Therefore, it makes sense to put stations where e-truck users are most likely to drive. Roads with higher truck traffic volumes are well-suited for charging stations because more e-trucks are expected to travel on them. Furthermore, to make charging stations more accessible and visible to as many trucks as possible, they need to be located within a reasonable distance of roadways to capture the maximum number of trucks. Therefore, this criterion also ensures that charging stations are placed where e-truck users can quickly access the station from an adjacent roadway, get charged, and merge back into traffic with minimal effort.
- *Land cover*: The objective is to install charging stations at locations where impacts on the environment and protected areas are the least. This study identifies developed areas as the best locations. Additionally, forests and areas containing protected species are the least suitable locations to build charging stations.
- *Distance to water resources*: This sub criterion evaluates the presence of water resources, including lakes and streams, to reduce any potential pollutants near the lakes or streams. Because the construction of charging stations may have adverse effects on water resources, they should be away from water resources. Therefore, the closer the area is to surface water, the higher its impact on the water resource.
- *Flood risk*: Chargers can be damaged by significant water exposure, and placing charging stations in a flood zone can increase the risk of significant water exposure. Therefore, this measure is applied to reduce the chance of constructing charging station in zones with high flood hazards, thus increasing resiliency.
- *Proximity to truck stops*: The term truck stop refers to facilities that have food, fuel, and a garage. Due to the long charging time of e-trucks, these facilities can be suitable locations for charging stations. Also, these locations are currently common trip points for truck drivers and have already been designed to capture the maximum truck flow. Therefore, the goal of using this criterion is to place charging stations near truck stops which can be common locations where e-trucks will frequently stop for a long time.

- *Proximity to gas stations:* Here, the term gas stations refers to refueling stations used by light-duty vehicles as well as some medium-duty vehicles. These facilities are familiar refueling points and have already been put at top locations for capturing traffic flow. Therefore, they can help make the transition from conventional vehicles to electric vehicles. The aim of using this criterion is to place charging stations near as many gas stations as possible to capture the maximum medium-duty truck flow.
- *Proximity to existing DC fast chargers:* DC fast chargers (DCFCs) are currently placed in areas with the minimum electricity infrastructure needed (such as a grid line and power substations). This study assumes that locating charging stations near existing DCFCs will reduce infrastructure costs as long as there is enough capacity in the grid. Also, some of these facilities can serve small (considering length and height) medium-duty electric vehicles even if they do not have the space required to serve heavy-duty electric vehicles. Furthermore, existing DCFCs can be upgraded or repurposed to e-truck charging stations if there is additional land available in these locations and capacity in the grid. As a result, the goal of using this criterion is to locate charging stations as close to as many DCFCs as possible.
- *Distance to power substations:* Power substations transform voltage levels so electricity can be transferred over long distances and then used where it is needed. The closer charging stations are to high-ranked substations (based on the grid impact analysis), the lesser the impact they may have on the electrical grid and the lower the construction costs.
- *Solar energy:* Using solar energy to supply the electricity of charging stations could reduce the power generation's long-term cost and environmental impacts. Thus, this sub criterion uses solar radiation to examine the potential for solar energy in each area.
- *Land price:* This measure aims to minimize the charging station establishment cost.

3.2 AHP Structure

The selected criteria were organized in a relationship hierarchy based on stakeholder objectives and urban relationships. The AHP structure, shown in Figure 5, describes the relationships of each criterion and sub criterion with the final objective to find suitable charging station locations in Minnesota. The second level, shown in orange, highlights the main criteria of the study. From here, sub criteria branch off, which are represented by base GIS layers. A pairwise comparison survey was conducted to estimate the criteria weights based on expert knowledge. Pairwise comparison results were calculated from the expert survey and pairwise comparison matrices. Sixteen survey responses were received, and 11 out of 16 judgments met the consistency index²³ threshold. With the individual pairwise comparisons evaluated, judgments can be combined to find each measure's global and local (within branch) weights. Criteria weights are shown in Table 2.

²³ If a respondent rates criteria A higher than B, and B higher than C, criteria A should be rated higher than criteria C.

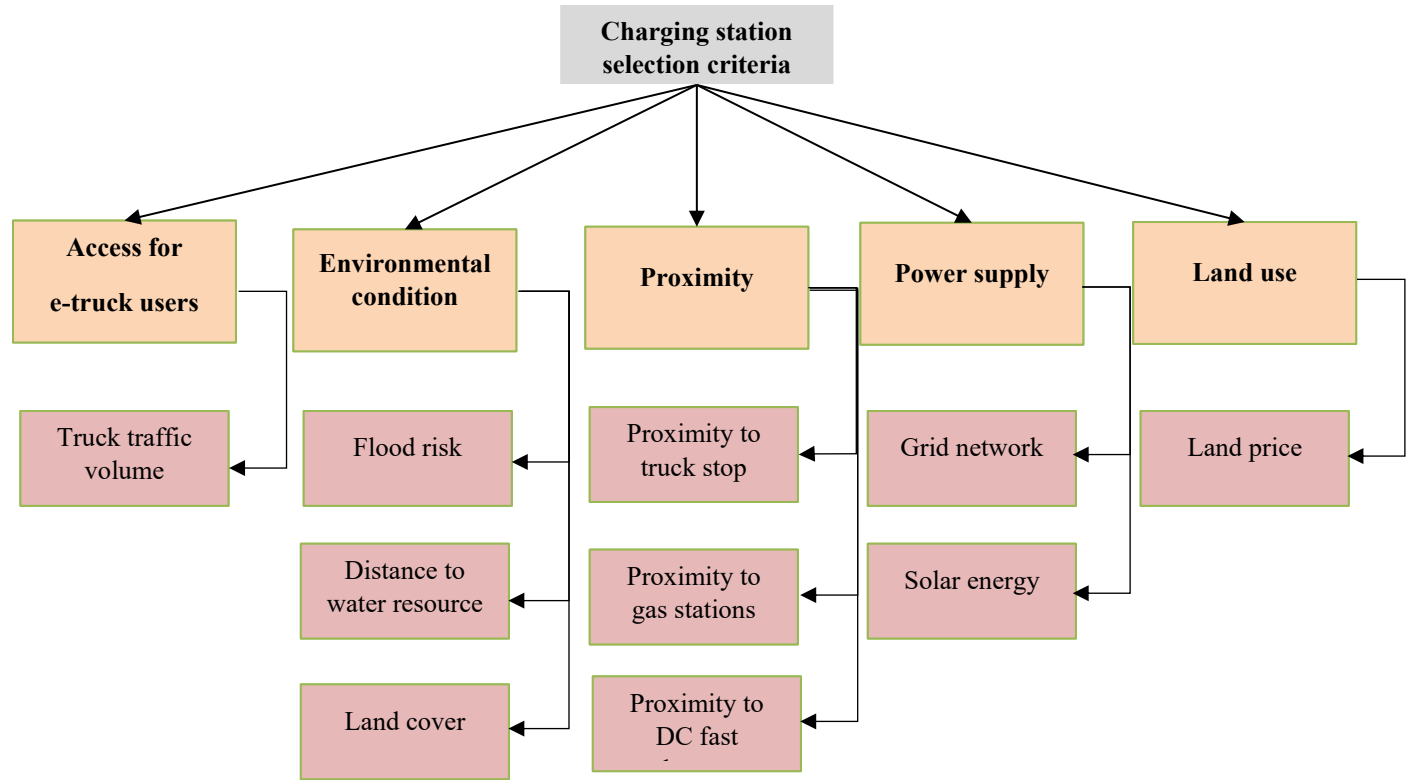


Figure 5 AHP Structure for e-trucks charging station location analysis.

Table 2 AHP Criteria Weights.

Level 2	Local weight (%)	Level 3	Global weight (%)	Local weight %	Standard deviation
Accessibility for e-truck users	36	Truck traffic volume	36	100	5.12
Environmental condition	11	Land cover	2	18	0.83
		Distance to water resources	3	27	0.82
		Flood risk	6	55	0.47
Proximity	24	Proximity to truck stop stations	16	67	3.73
		Proximity to gas stations	5	21	0.60
		Proximity to DC fast chargers	3	13	0.54
Power supply	23	Distance to power substations (grid network)	20	87	5.35
		Solar energy	3	13	1.69
Land use	6	Land price	6	100	0.38

3.3 GIS Layers

The geographic values of each criterion were obtained using ArcGIS Pro ESRI software. Table 3 describes the GIS data type and analysis method for each measure. To ensure measurement integrity, the geographic data of each criterion were normalized between 0 and 10. However, we use intuitive phrases to describe each map. Figures 6 through 16 show map layers of each measure with normalized values. After normalization, the layers were combined, and the candidate locations for charging stations were identified.

Table 3 List of Data and Analysis Type in the AHP Framework.

Criteria	Analysis Method	Comment
Truck traffic volume	Buffer distance	Truck traffic volume is buffered 0.5 miles from road centerline to represent the effect of the road. Roads are weighted based on HCAADT ²⁴ .
Land cover	Used directly	Developed area is considered as the most suitable area.
Distance to water resources	Euclidean distance	Maximum analysis distance is 0.25 miles from the edge of lakes and rivers.
Flood risk	Used directly	
Proximity to truck stop	Euclidean distance	
Proximity to gas stations	Euclidean distance	
Proximity to DC fast charging stations	Euclidean distance	
Distance to power substations (grid network)	Euclidean distance	Substations are weighted based on their scores obtained in the grid impact analysis.
Solar energy	Used directly	
Land price	IDW ²⁵	Average census block group land price.

Notes:

All criteria have a 31.8m x 31.8m raster cell size

Buffer distance is the determination of a zone around a geographic feature containing locations that are within a specified distance of that feature

Euclidean distance gives the distance from each cell in the raster to the closest source.

²⁴ Heavy commercial annual average daily traffic

²⁵ Inverse Distance Weighted

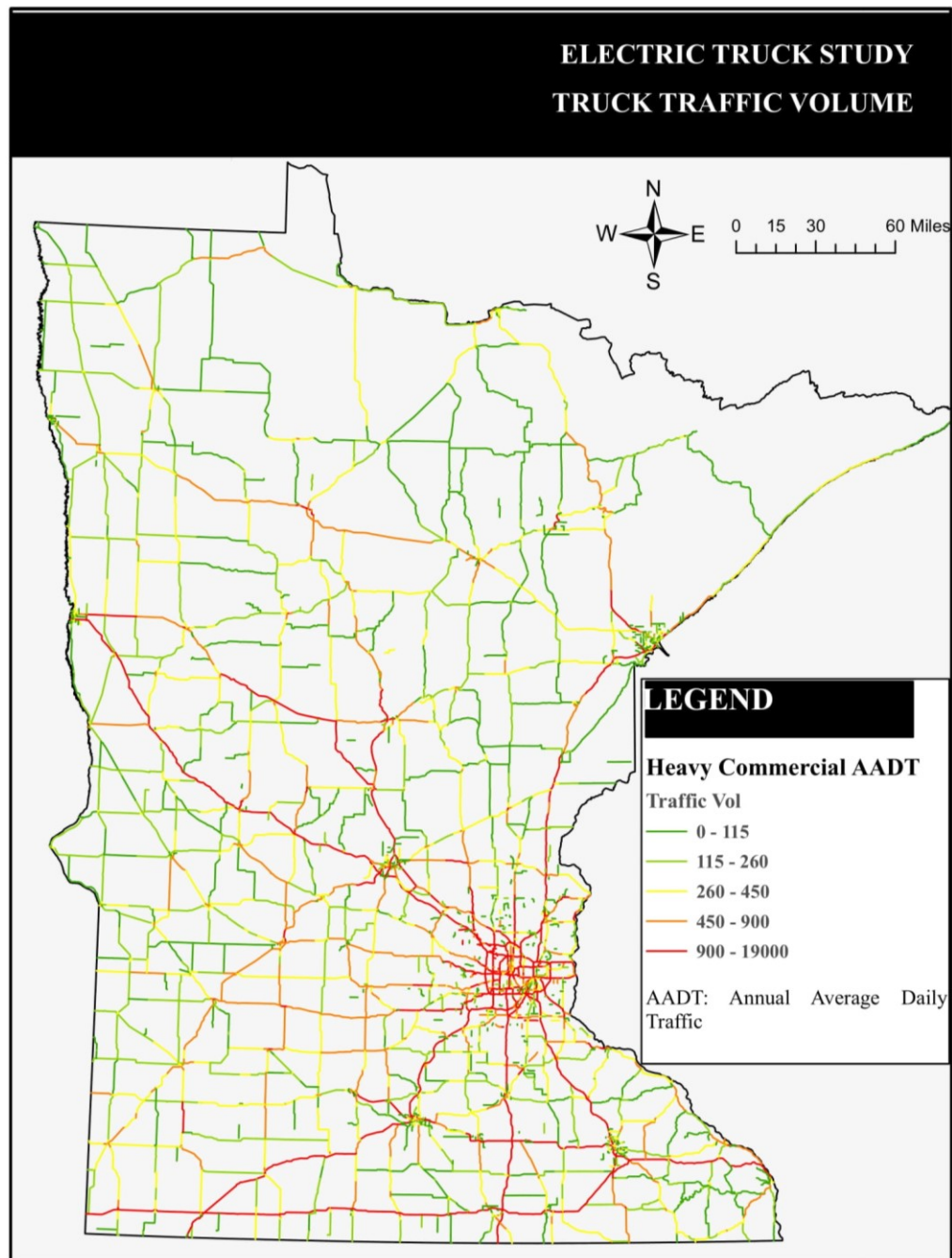


Figure 6 Heavy commercial annual average daily traffic (HCAADT) map.

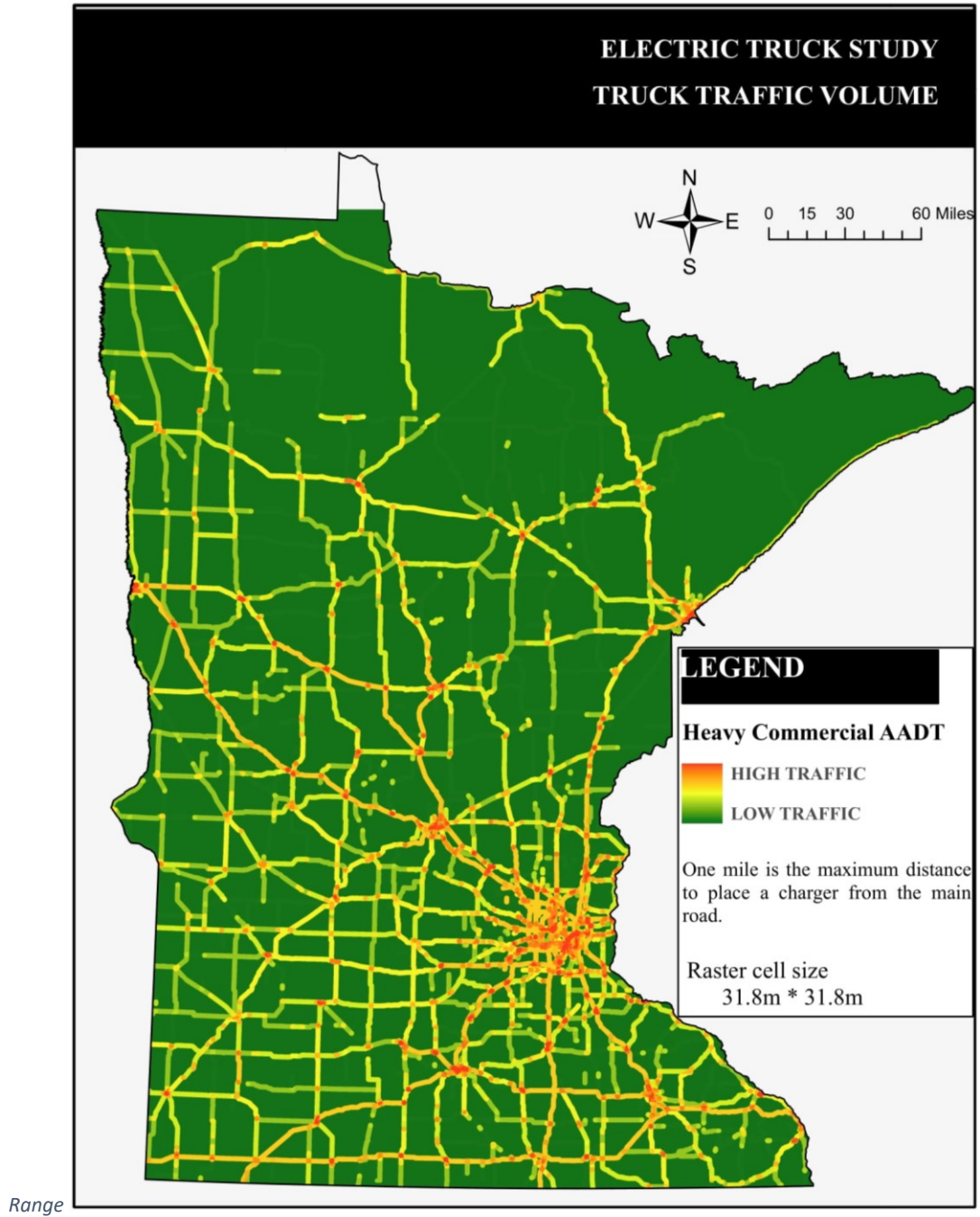


Figure 7 Heavy commercial annual average daily traffic (HCAADT) layer.

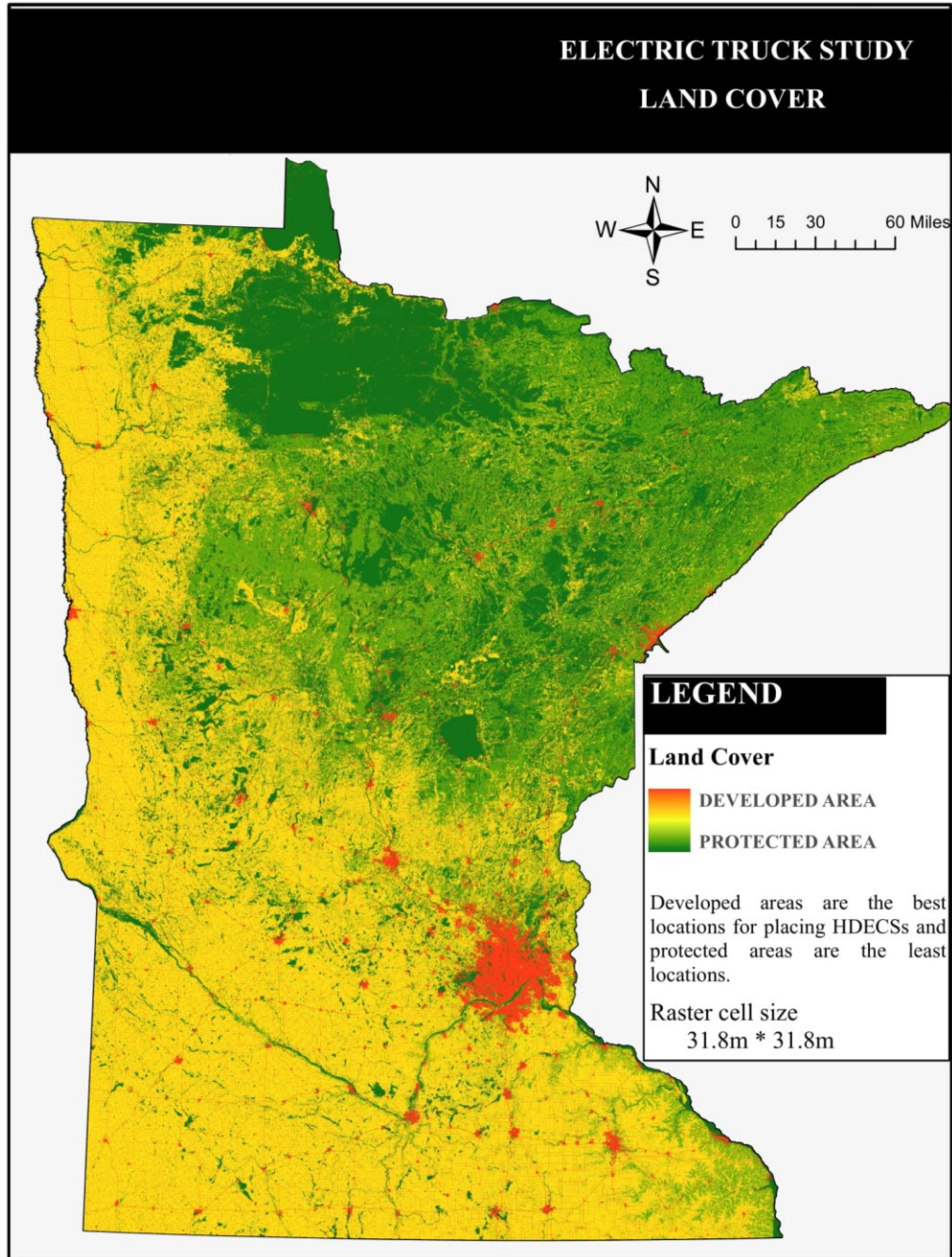


Figure 8 Land cover map.

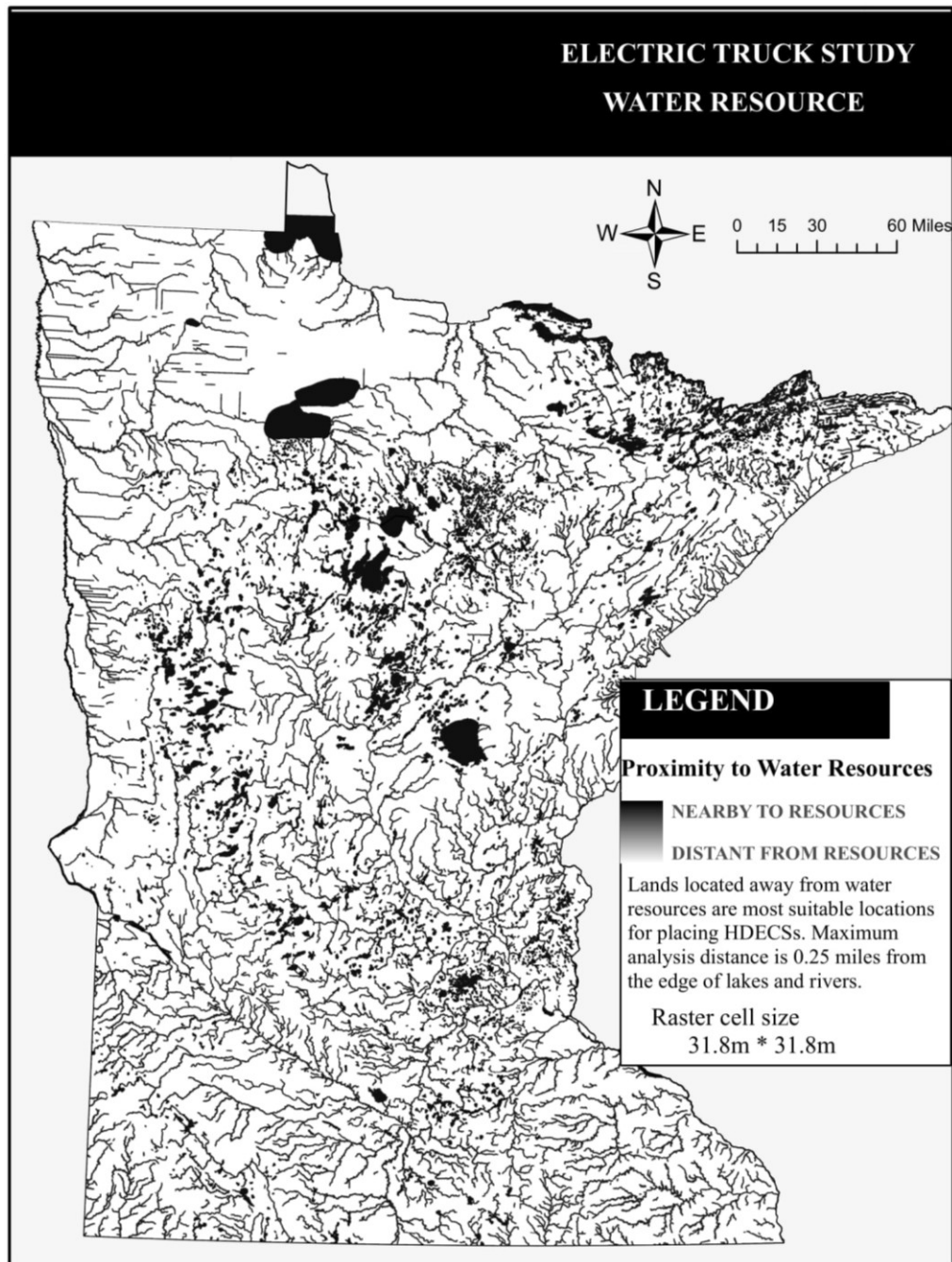


Figure 9 Water resource layer.

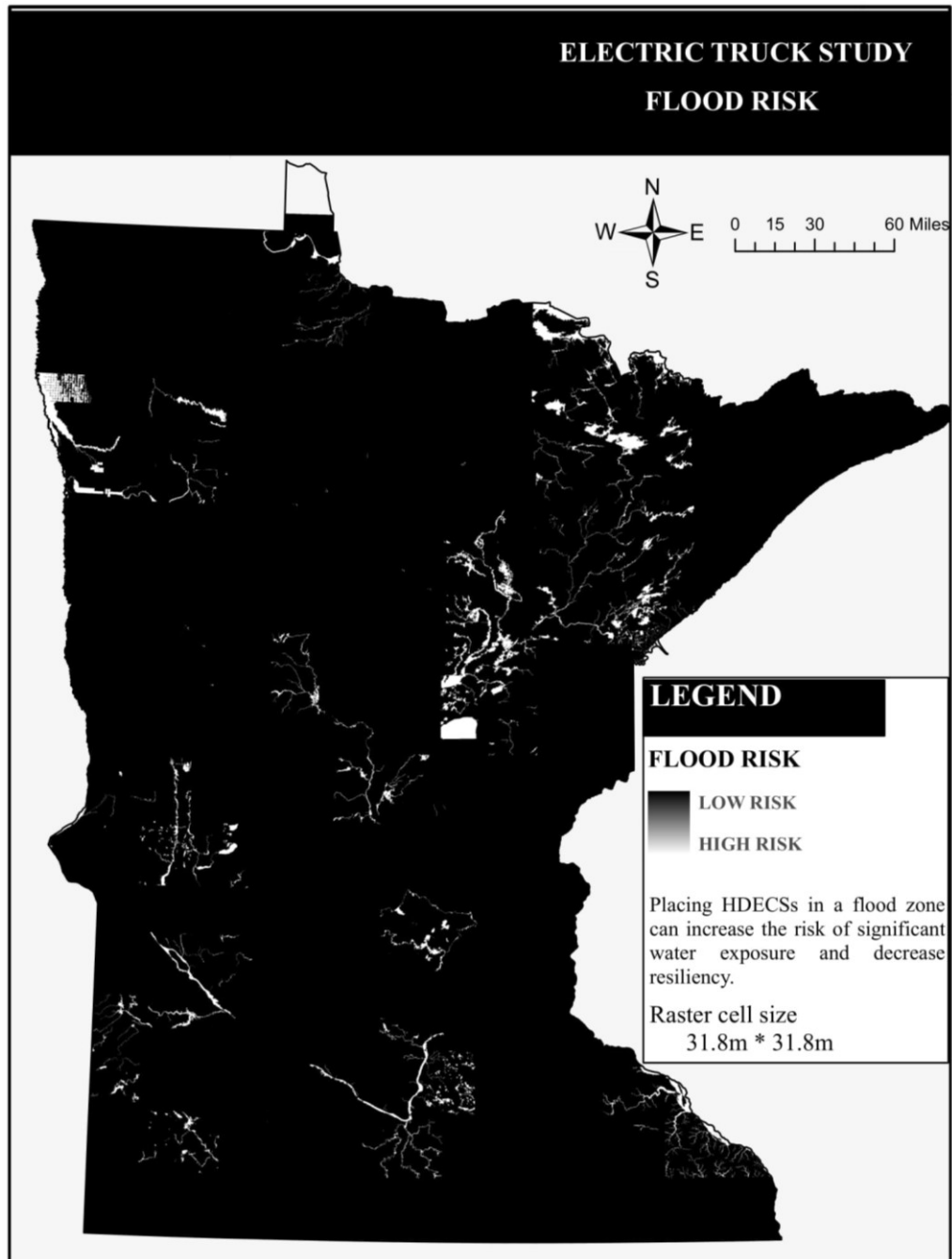


Figure 10 Flood risk layer.

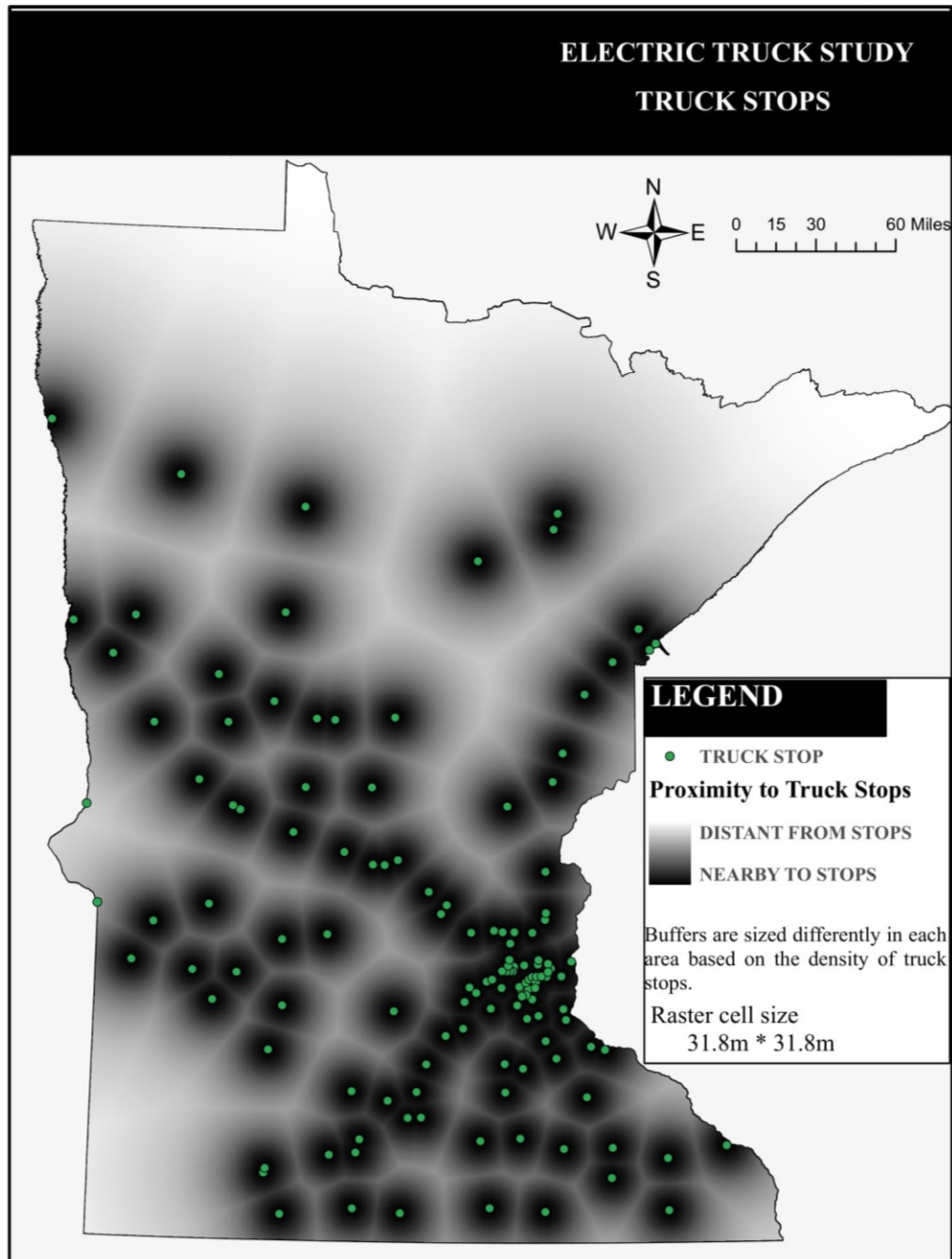


Figure 11 Proximity to truck stop.

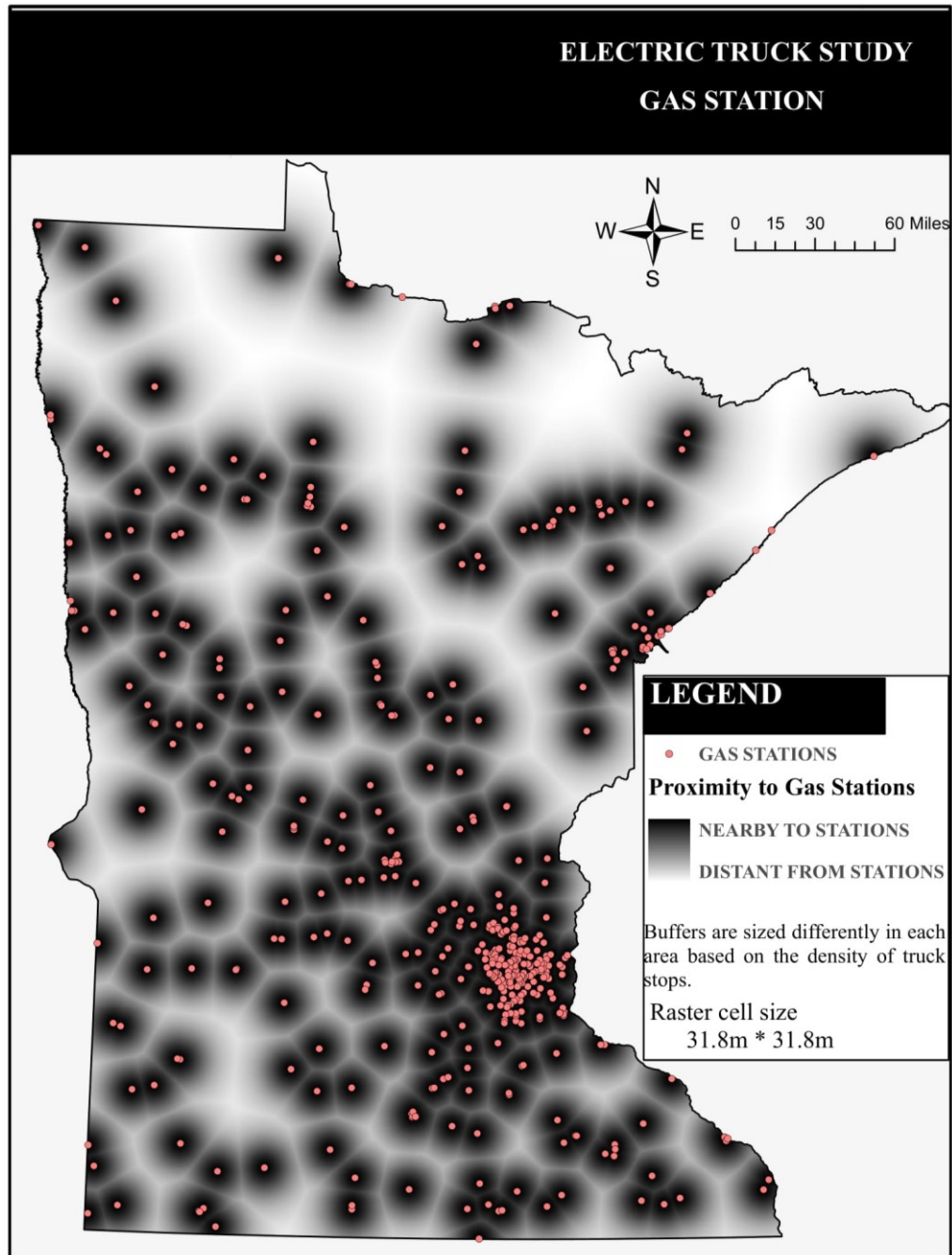


Figure 12 Proximity to gas station.

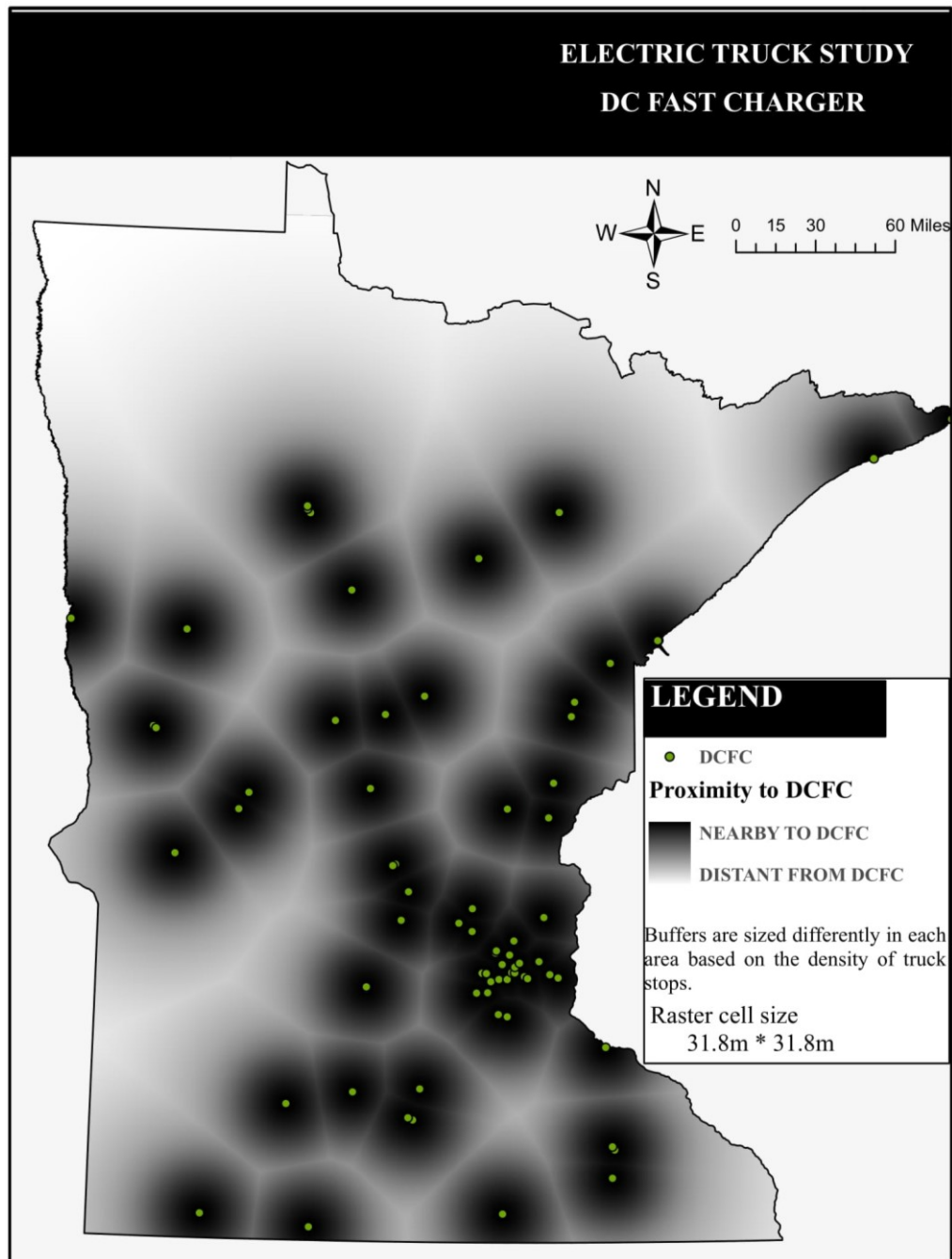


Figure 13 Proximity to DCFC.

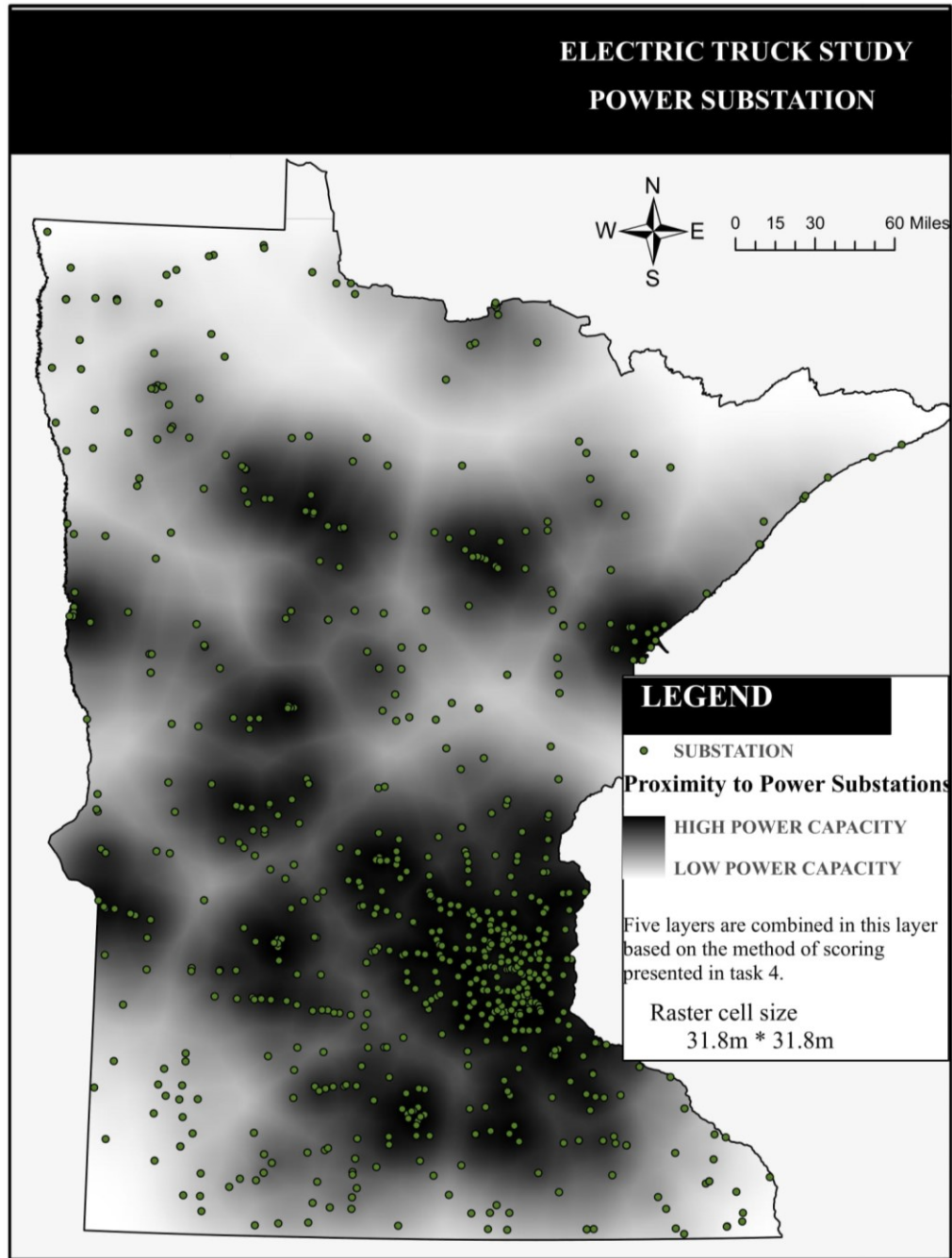


Figure 14 Distance to power substations, weighted by the suitability of each power substations according to Section 2.1 analysis.

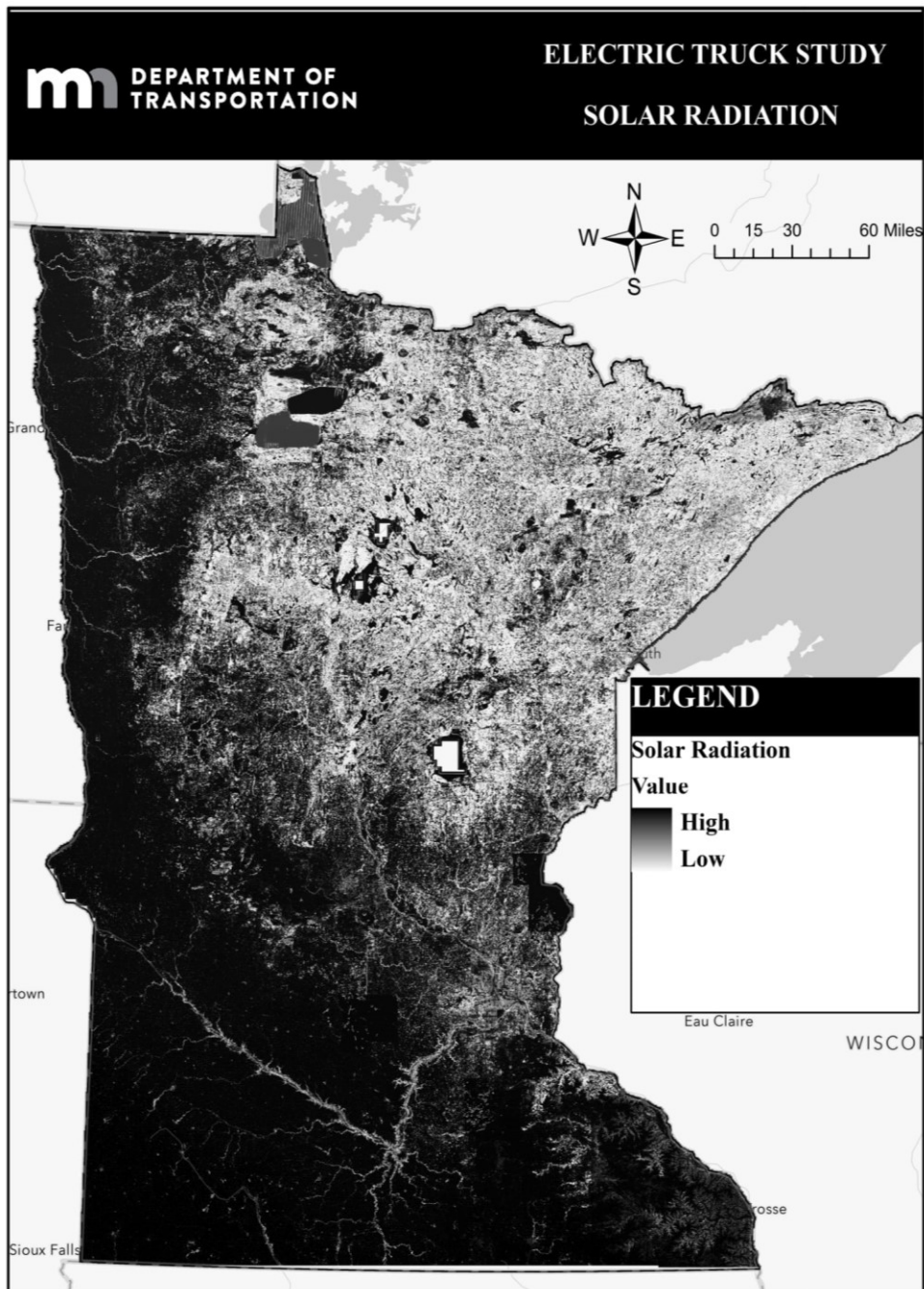


Figure 15 Solar radiation layer.

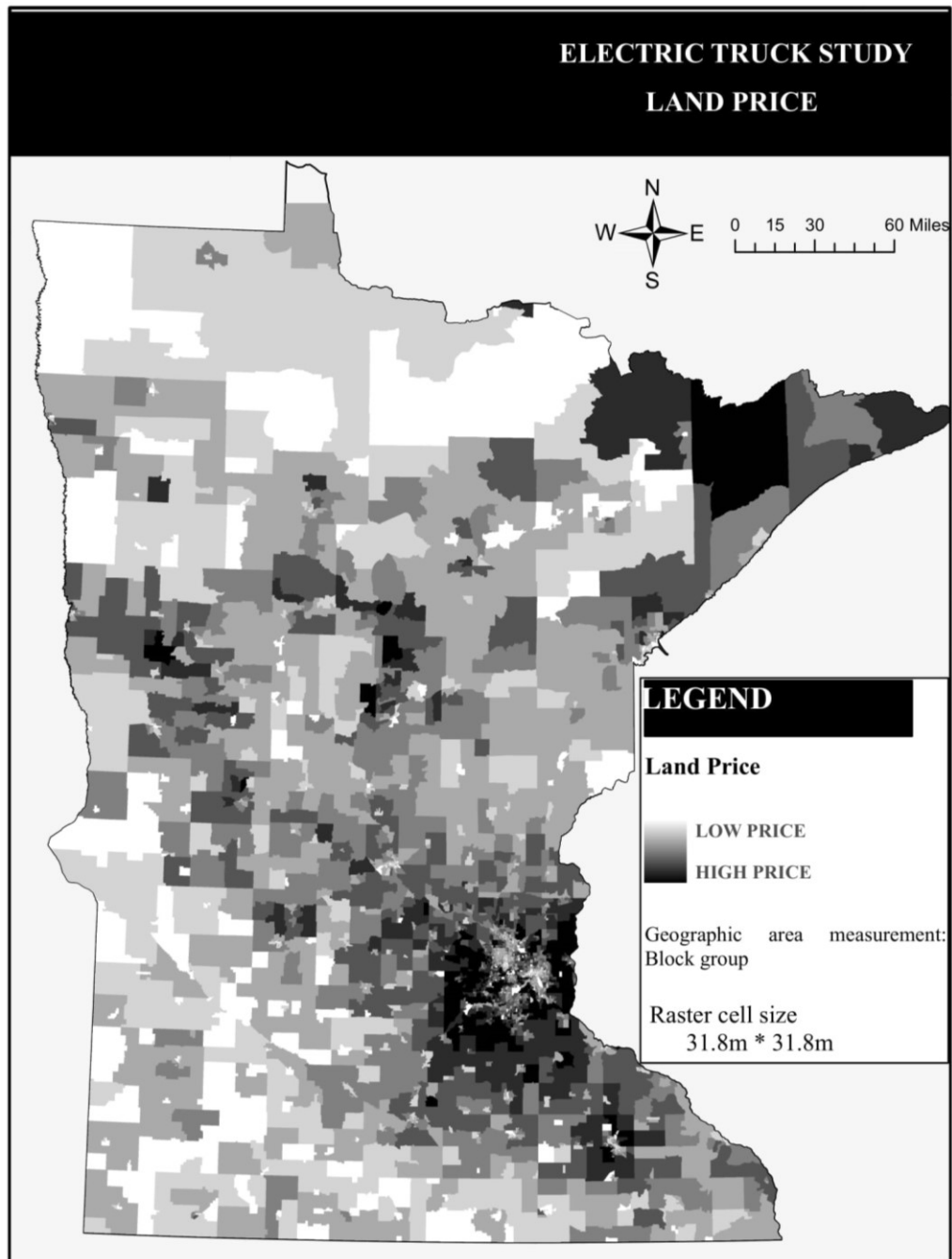


Figure 16 Land price layer.

The final objective layer is a combination of all criteria of the AHP structure weighted by their global weights calculated in Table 2. The weights represent the contribution of their respective layer in the final rating of the locations. Analyzing the final layer provides the top candidate locations in the State of Minnesota for charging stations.

To determine high score areas, the standard deviation classification method was used. The method shows how much a feature's attribute value, in this case the combined score, varies from the mean. By using the mean value and the standard deviations from the mean, class breaks were constructed with equal value ranges that are half of the standard deviation. Then, suitable candidate locations for charging stations (black pixels on the map in Figure 17) were identified. As shown on the map, most charging station candidate locations are situated close to road intersections. Therefore, they can cover a greater number of roads, and they are easier to reach.

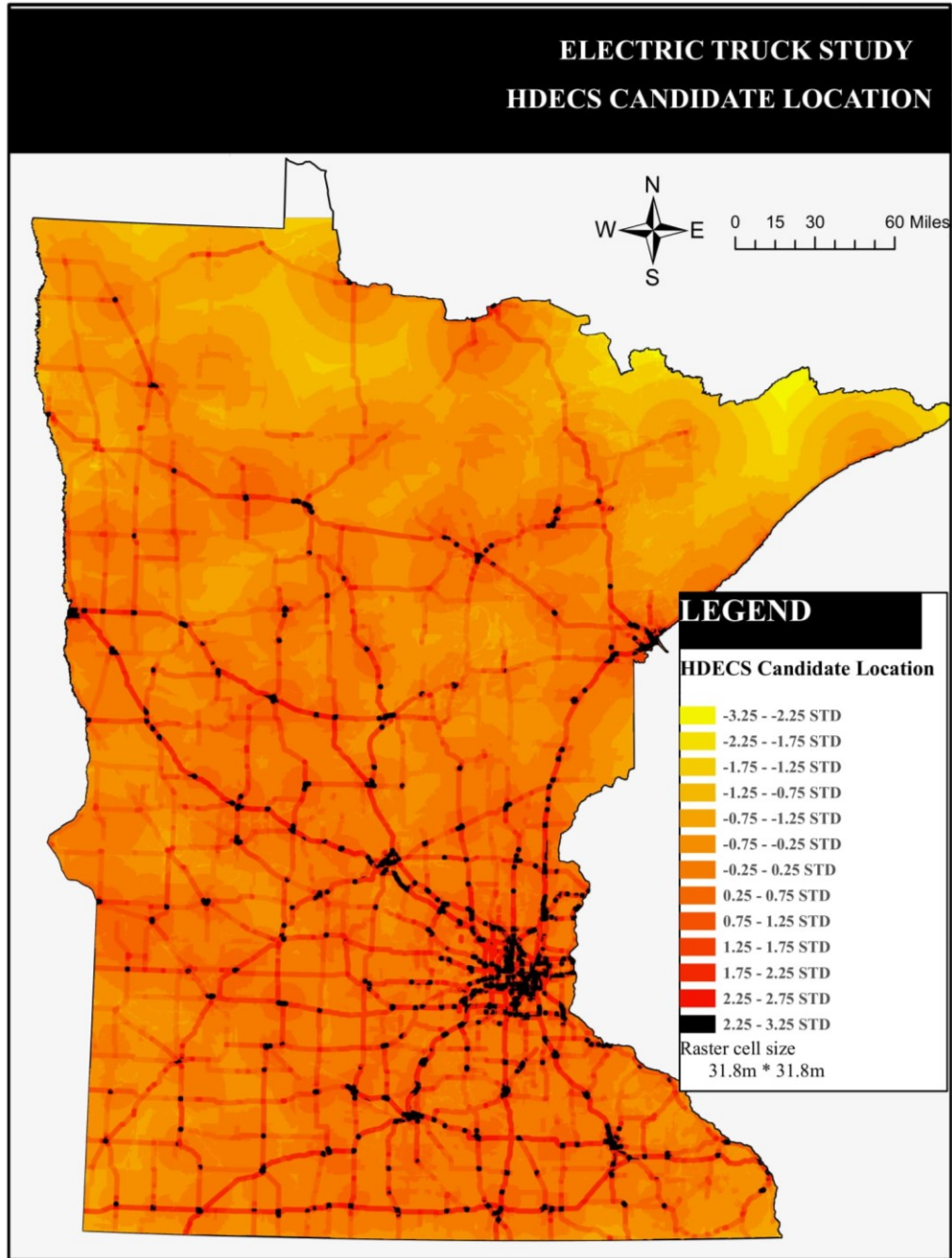


Figure 17 Classified final objective layer. Grouping is done by standard deviation (STD) of scores from the mean score. The black points are the locations with the highest scores, i.e., more than 2.25 standard deviations from the mean score.

Figure 18 shows the relative position of candidate charging stations and truck stops. As illustrated on the map, most candidate charging stations are located at or near truck stops and along the major freeways and highways.

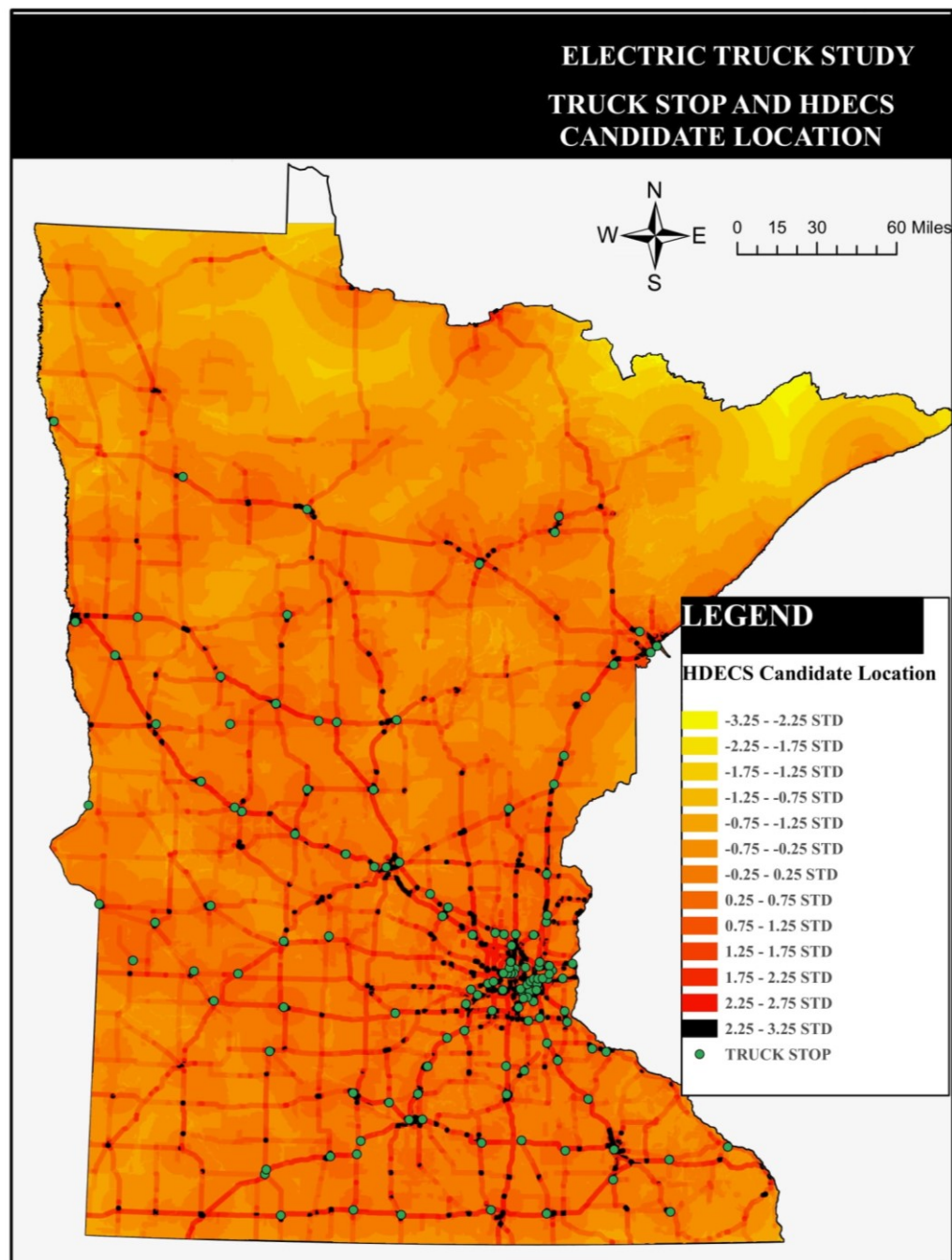


Figure 18 Candidate locations and truck stops. Grouping is done by standard deviation (STD) of scores from the mean score.

Figure 19 shows the relative position of candidate charging stations and power substations. As shown on the map, most candidate charging stations are located close to a power substation.

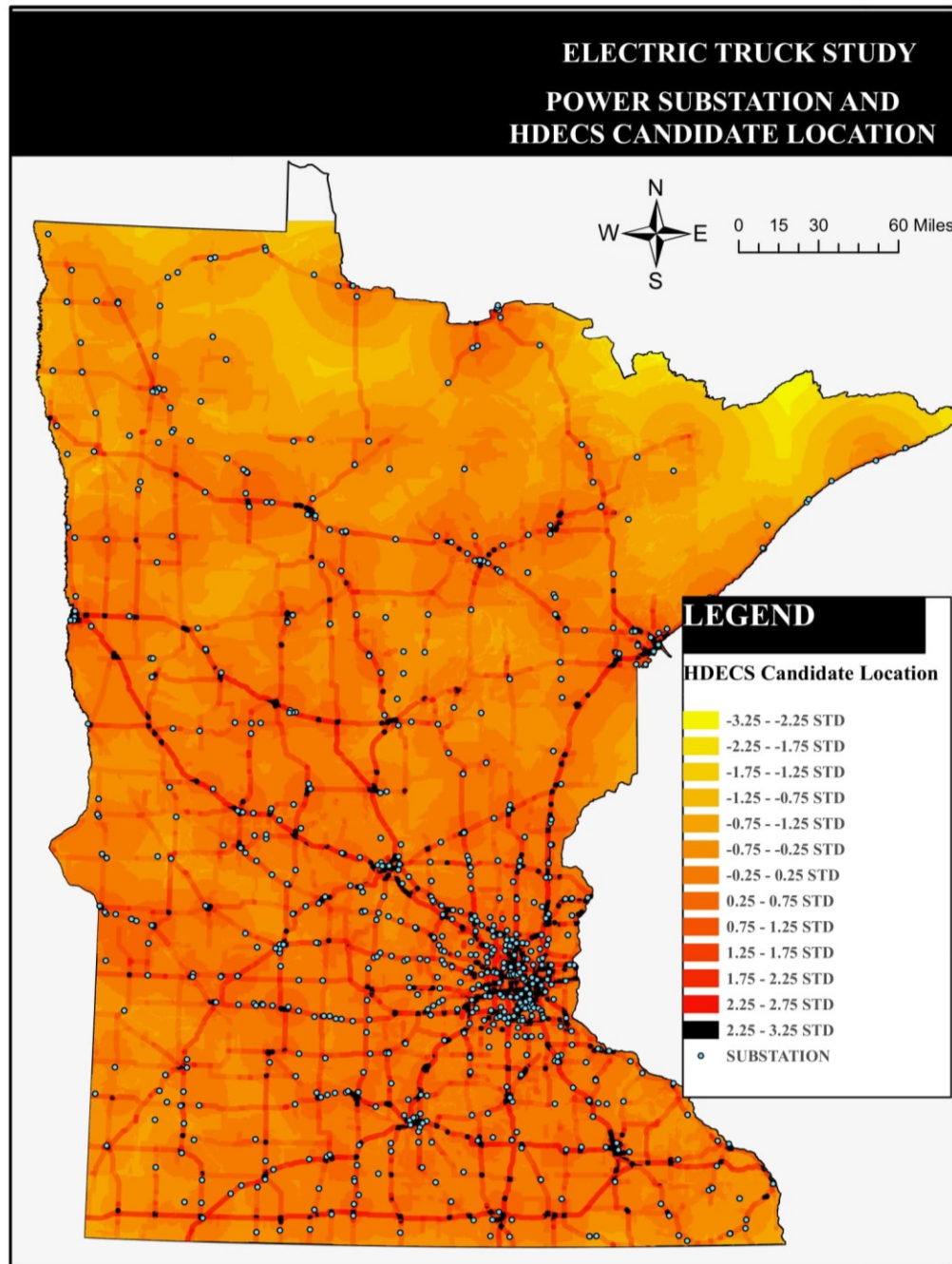


Figure 19 Candidate charging stations and power substations. Grouping is done by standard deviation (STD) of scores from the mean score.

3.4 High Priority Corridors for Charging Stations

According to the results, some high-priority corridors regarding the distribution of candidate charging stations are introduced. It should be mentioned that the following corridors have been identified because of the uniform distribution of candidate charging stations on them and the distance between consecutive candidate points.

- *I-35 from Albert Lea to Duluth*: candidate charging stations were identified every 30 miles (this is the maximum measured distance between every two consecutive black spots).
- *I-94 Lakeland to Fargo*: candidate charging stations were identified every 30 miles.
- *I-90 from Beaver Creek to La Crosse*: candidate charging stations were identified every 20 miles.
- *US 10 from Moorhead to Cottage Grove*: candidate charging stations were identified every 30 miles.
- *US 169 from Elmore to Grand Rapids*: candidate charging stations were identified every 30 miles.

With the AHP analysis that narrows down the candidate charging stations to a smaller subset of land, there are still a vast amount of location alternatives. Identifying the top locations needs customized quantitative models that analyze truck trips data and optimally locates a set of charging stations along major truck corridors to cover as many truck trips as possible. Such an optimization model is presented in the next chapter.

Chapter 4. Optimization of Charging Station Locations

When compared to diesel trucks, e-trucks have various advantages, such as zero tailpipe exhaust emissions, less noise, and lower operating costs. But an important disadvantage of e-trucks is their limited driving range (and long charging time) based on the current technology. More ubiquitous e-truck charging stations, can help extend e-trucks' daily operation ranges and increase e-truck adoption. This chapter presents an optimization model to identify the number and location of charging stations to minimize total transportation system cost. The system cost is affected by the operating cost savings due to the use of e-trucks and the additional energy and time cost due to charging stop detours. Both diesel trucks and e-trucks are accounted for in the network model, and the demand for each truck type is dependent on the path characteristics and operating costs.

4.1 Problem Description

Due to the comparatively lower operating cost per mile of an e-truck to a diesel truck, the goal is to maximize e-truck usage by optimizing the number and location of charging stations. Because the limited number of charging stations in early stages of deployment might not provide a full coverage of the entire network of roads, some e-trucks may require additional travel time or detours to access the stations. Since this extra cost is a loss to the system (i.e., it merely causes more traffic and wastes energy and time), it is important to consider this loss when identifying the most appropriate charging station locations. On the other hand, users of diesel trucks are less worried about access to refueling stations because there is already a substantial network of diesel stations. In addition, the time-consuming process of charging e-trucks, calculated based on the route length and charging rate, adds another expense to the system that should be considered in the analysis. Despite the barriers, e-trucks have some long-term economic and environmental advantages that encourage planners to work toward the widespread adoption of these vehicles.

A multinomial logit choice model was applied to estimate the demand of each truck type for every origin-destination (OD) pair. Multinomial logit is the most common type of model in travel demand analysis and determines the market share of each alternative (here diesel trucks and e-trucks) according to their utility. Travel time and operating cost of each truck type make up the utility function in the choice model. The effect of charging infrastructure supply, and thus e-trucks' charging detour cost/time, is considered while determining the demand for each type of truck.

In this study, it is assumed that trucks use routes with the least overall cost. This cost includes the operating cost of trucks (i.e., fuel cost) and the travel time cost. Additionally, this research assumes that travel times are constant and not affected by congestion. In other words, the time it takes for a single vehicle to traverse a segment of a road is not affected by traffic congestion. This assumption is adopted because, unlike urban networks, the statewide network is mostly uncongested. Therefore, truck detours for charging stops have negligible impact on overall traffic congestion.

Considering the end goal of maximizing e-truck usage by optimizing the charging station locations, the fundamental question is how to identify a set of charging stations from a list of candidate locations to achieve the best objective. The candidate stations set was determined from the multicriteria decision analysis in previous chapter. Budget constraints (i.e., the maximum amount of government dollars allocated to establish charging stations) determine how many new stations may be installed. An optimization model is developed that considers all the factors and constraints as well as a multimodal traffic assignment for e-trucks and diesel trucks. Mathematical details of the optimization model are presented in Appendix 2.

4.2 Numerical Experiment

4.2.1 Experiment Settings

The developed optimization model was applied to a custom-built Minnesota highway network. The network consists of 3,222 links (i.e., road segments), 1,551 nodes (intersections or junctions), and 81 zones (i.e., counties). All interstate and US highways are included in the network, and state highways are added in areas where there are no interstate or US highways. The National Highway Freight Network, Critical Urban Freight Corridors (CUFC), and Critical Rural Freight Corridors (CRFC) are captured in the network. From the multicriteria decision analysis in the previous chapter, 70 candidate charging station locations with the highest scores were identified and used in the optimization model (see Figure 20).

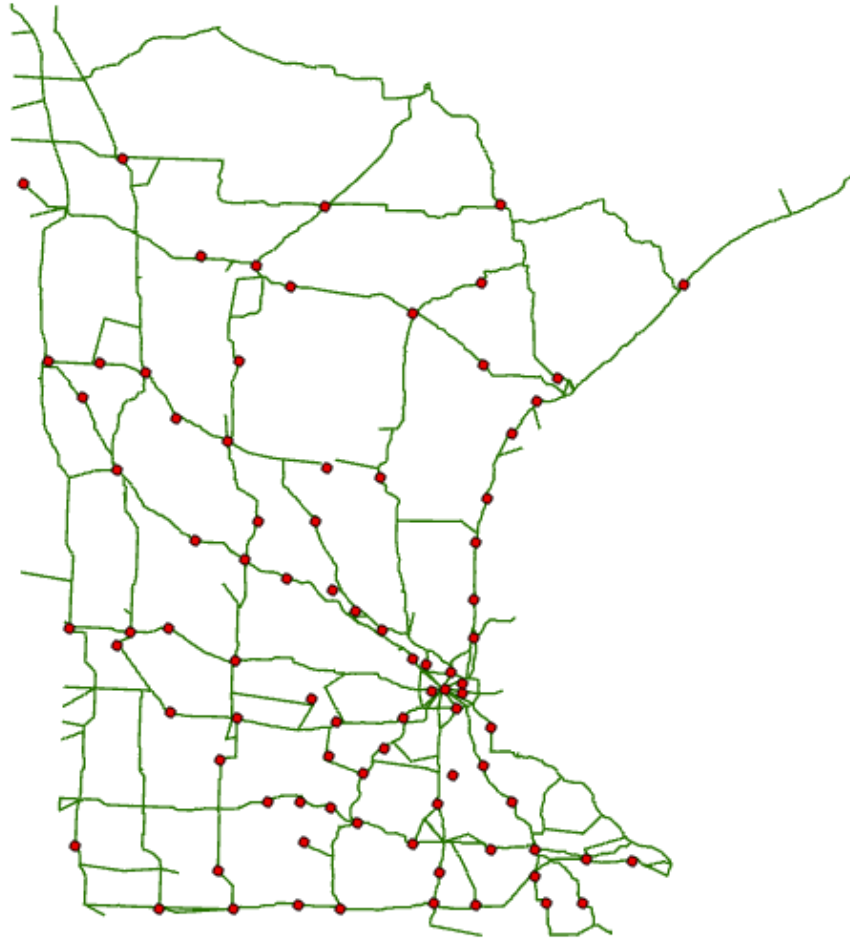


Figure 20: The Minnesota highway network developed for e-truck charging optimization in this study. Red points represent candidate charging stations.

The truck trip data was derived from streetlight data and was used to build the network demand. To do this, the state was divided into 81 regions to estimate the OD matrix for truck trips. The regions include the seven-county Twin Cities metropolitan area and the remaining 80 counties in Minnesota. Each region is partitioned into census tract zones to create the truck OD matrix. Streetlight data was used to estimate the average number of trucks that start and end their trips in each zone. Trips occurring within each region are not considered due to the difference in their trip patterns and charging behavior. Figure 21 shows how truck trips are distributed over the study area. To develop the model, the county's centroid (the area with the greatest concentration of truck trips) is regarded as the generation point of all trips in that county.

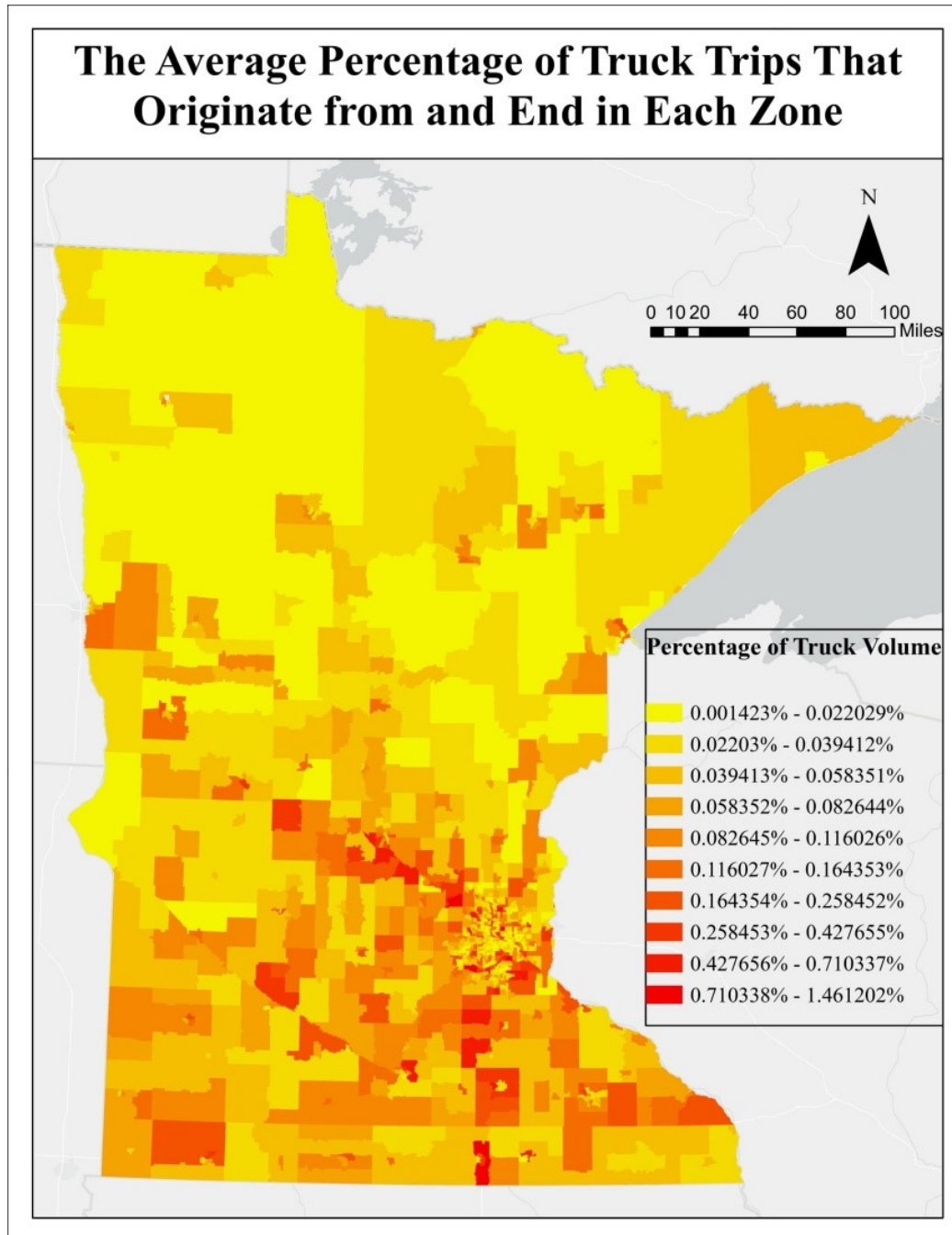


Figure 21: Truck trip distribution in the State of Minnesota, obtained from StreetLight's Trip Index.

To better understand the potential adoption and flow of e-trucks in the study area, several assumptions on the model parameters are evaluated. A set of base assumptions (starting points for the analysis) are presented first, and then sensitivity analyses with respect to the assumptions are presented. One assumption is that the average driving range of e-trucks is 200 miles. The study also assumes that system planners plan to build 20 charging stations in the state. It is assumed that e-trucks have an operating cost per mile of 0.21 \$/mile, and diesel trucks have an operating cost per mile of 0.34 \$/mile²⁶. Furthermore, three likely values of trip cost perception ($\theta=0.25, 0.5, 0.75$) are considered in the logit model for truck type choice. By definition, θ is a positive parameter that its higher values represent more rational users in selecting the most cost-effective choice. This parameter was not calibrated with actual data.

4.2.2 Results

Results of the model applied to the Minnesota highway network are shown in Figure 22. This figure shows the selected charging stations as well as the percentage of e-truck volumes from total truck volume on the links. Results indicate that charging stations should be located near regions with greater truck trip rates. Additionally, these stations are relatively uniformly distributed across the network.

26. <https://www.act-news.com/news/calculating-tco-for-medium-and-heavy-duty-evs/>

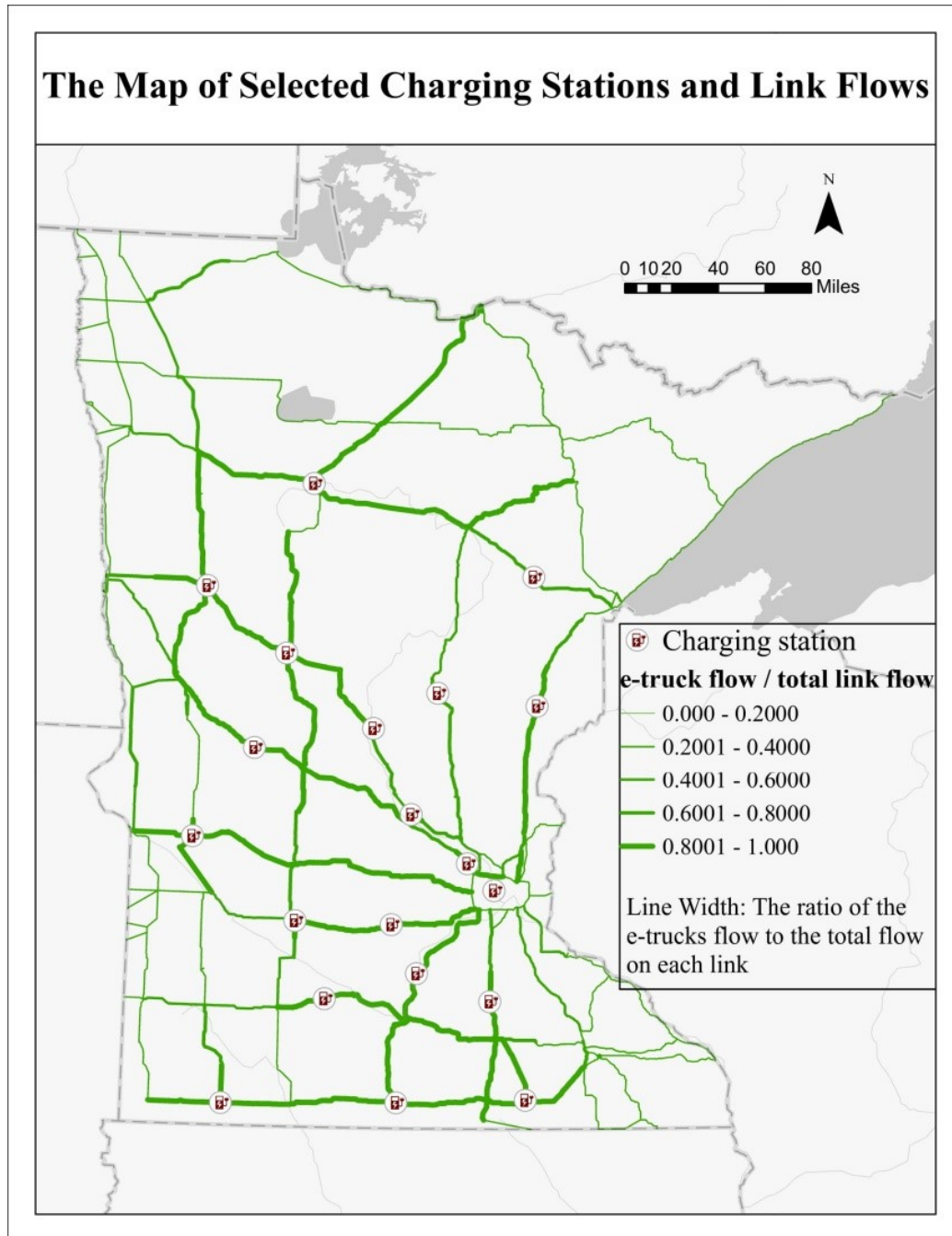


Figure 22: Charging station locations in the Minnesota network under the base assumptions. Selected charging stations are almost uniformly spread across the network and are generally located on highways with a higher percentage of e-truck flows.

The penetration rate of e-trucks for various driving ranges is the next metric produced in this analysis. Three different driving ranges for e-trucks (100, 150, and 200 miles) were assumed. By varying the number of charging stations from zero to 40, the model calculates the likely penetration rate of e-trucks. The results are shown in Figure 23. This figure shows that the tendency to adopt e-trucks grows sharply as the network's charging infrastructure develops; however, the growth rate slows down at a higher number of charging stations in network. The model outputs (without full calibration) show that when there is no public charging station in the network, e-trucks could gain about 5% of the truck market share. When 30-40 charging stations are added to the network, e-trucks can attain up to 55% market share. Based on the results, a large number of current diesel truck trip lengths are longer than e-truck driving ranges. Adding more e-truck charging stations will enable e-trucks to charge along their route and extend their range, leading to widespread adoption.

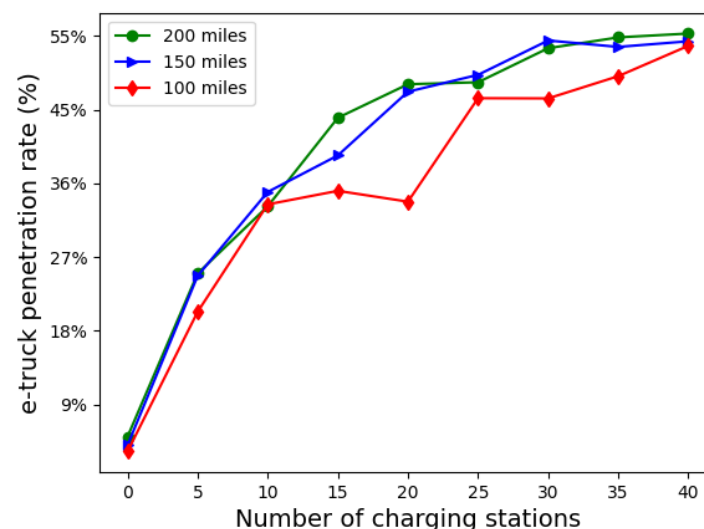


Figure 23: Penetration rate of e-trucks for different driving ranges and number of charging stations. The e-truck penetration rate could increase sharply after the first few public charging stations are deployed.

This study also evaluates the system cost under different assumptions. System cost is the collective travel cost of both diesel trucks and e-trucks and is calculated by multiplying vehicle-miles traveled (VMT) of each truck type by their corresponding per-mile cost (referenced in Section 4.2.1). External costs such as grid improvement or charging infrastructure construction costs are not included in the system cost. Figure 24 illustrates how the system cost varies based on the number of charging stations and the driving ranges. Model outputs show that in general, the longer driving range of e-trucks results in a decrease in the system cost. Additionally, more charging stations lowers the system cost by supporting the adoption of e-trucks at a greater rate. As public charging infrastructure enables more e-trucks to travel in the state, the lower per-mile costs lead to a reduction in the system cost. Further, improved driving range and charging facilities would result in fewer detours for recharging. As a result, overall travel time and system costs will both drop. However, the effect of adding more charging stations gradually plateaus after a certain number of charging stations are deployed.

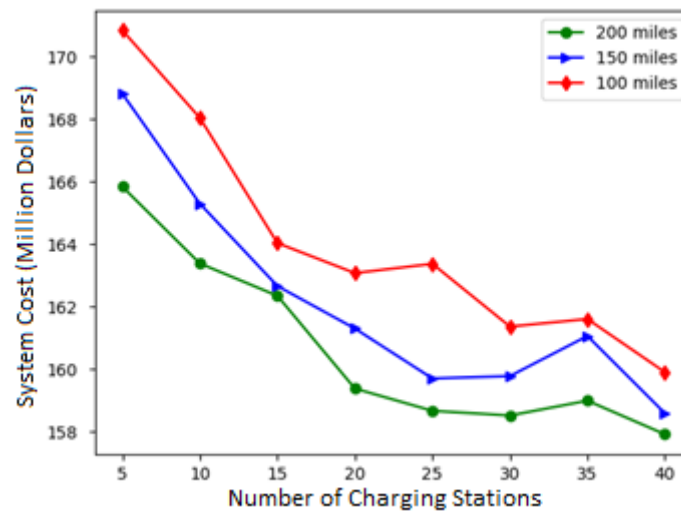


Figure 24: The effect of charging infrastructure development and driving range on total system cost.

Another metric evaluated in this study is VMT, which is widely utilized in transportation planning and is usually considered as a primary metric for evaluating the negative impacts of transportation. VMT represents the distance driven by all vehicles in a transportation network during a time period. Figures 25 and 26 depict how VMT alters under different e-truck assumptions. These figures show that by increasing the number of charging stations, e-truck VMT increases, diesel truck VMT decreases, and the total VMT increases. The increase in e-truck VMT can be attributed to:

- Growth in their adoption rate, especially for longer trips as their lower per-mile cost makes them more cost-effective
- Their potentially longer paths or detours for charging

The increase in e-truck VMT can be viewed as a positive outcome from an environmental perspective because e-trucks have zero-tailpipe emissions. Diesel truck VMT likely decreases because the market gradually shifts toward using e-trucks as more public charging infrastructure becomes available. As Figure 25 shows, total (diesel plus e-trucks) VMT would increase as charging stations are added to the network, which is due to longer paths and detours by e-trucks to visit charging stations.

Despite the above statement on e-truck VMT increase being a positive outcome for air quality, the traffic impacts of the increased total VMT should be further investigated. Moreover, the initial cost of vehicles and different rate of deterioration (e.g., tires, batteries, etc.) are not included in the analysis and further research is needed to capture the combined effect of initial and ongoing costs on e-trucks adoption rate.

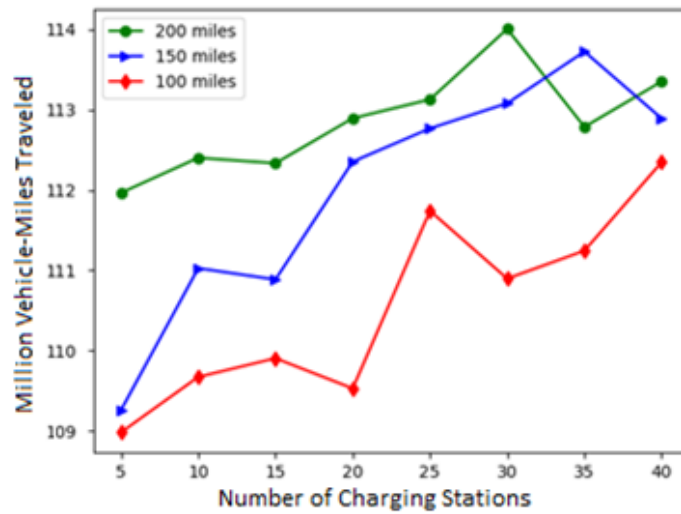


Figure 25: Daily vehicle miles traveled (total VMT) for different values of e-truck range and number of charging stations. As e-truck range increases and public charging infrastructure develops, more e-trucks are adopted and VMT increases.

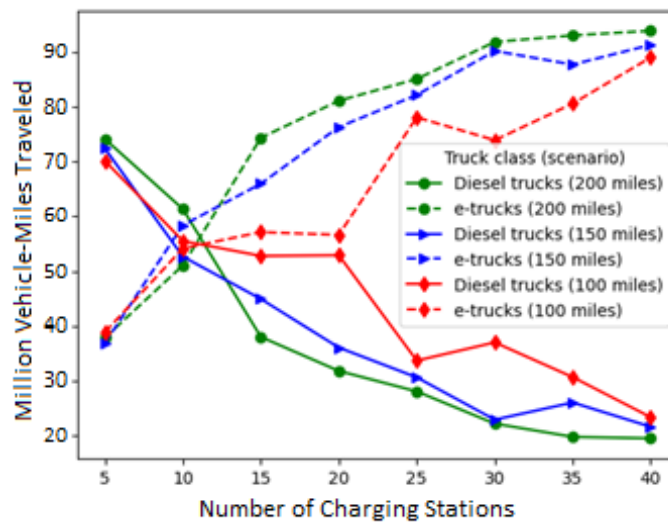


Figure 26: Daily vehicle miles traveled (VMT) for each truck type. As public charging infrastructure develops, more e-trucks are adopted and their VMT surpasses diesel trucks VMT.

Chapter 5. Conclusions and Recommended Future Studies

This study aimed to pave the road for supporting e-truck adoption in Minnesota. In the early part of the study, e-truck market growth, barriers for fast adoption, and opportunities for supporting e-truck adoption were reviewed. Then, a two-stage planning and optimization methodology for selecting the most suitable e-truck charging stations in Minnesota was presented.

In the first stage of the analysis, a multicriteria decision tool based on AHP was designed for identifying candidate locations for e-truck stations. A literature review, expert elicitation, and stakeholder consultation led to the development of ten criteria that should be considered in the process. Open-source GIS datasets and ArcGIS pro software were used to create GIS layers representing each of the selection criteria. The ten measures were combined into a single hotspot map, with weights derived from pairwise comparisons and expert judgments (i.e., the AHP survey). The most important criteria were identified to be:

- Ease of access for e-truck users, represented by *truck traffic volume*, with 36% weight
- *Proximity to power substations* with 20% weight
- *Proximity to truck stop stations* with 16% weight

Based on the multicriteria decision analysis, the high-priority corridors in Minnesota for installing e-truck charging stations were identified to be I-35, I-94, I-90, US10, and US169.

In the second stage of the analysis, an optimization model was developed to select the best locations for e-truck charging stations among the candidate locations identified in the first stage. The model aimed to minimize the total cost of truck trips in Minnesota, including diesel trucks and e-trucks. In doing so, the model endogenizes the adoption rate of e-trucks, routing of both e-trucks and diesel trucks, and charging activity of e-trucks in Minnesota's network. According to numerical tests with various assumptions, the following results were obtained:

- *E-truck adoption rate* will rise as the number of publicly available charging stations increases. In addition, enhancing e-truck driving range has a favorable impact on their market penetration rate.
- *E-truck market share* could achieve a sizable number when about 30-40 charging stations are available in the network. This result is solely due to the potential travel cost saving of e-trucks and is independent of broader economic market and policy trends.
- *Total VMT* would increase in the early stages of deployment as e-trucks could follow longer routes to access charging stations.
- *Total system cost* (i.e., the combined travel time and cost of both diesel and e-trucks) would decrease due to the lower per-mile cost of e-trucks.

This project was one of the first studies on planning and optimizing the location of e-truck charging stations. Despite uncertainties about e-truck technology, economics, and perceptions by operators and trucking associations, this study shed light on how MNDOT should plan for e-trucks public charging

stations and how they could affect the transportation system. This study developed the foundation of quantitative tools for optimizing charging station locations. It is recommended that the tool be expanded to capture other cost components (e.g., maintenance, depreciation, etc.) and characteristics of e-trucks. One way to do so is to calibrate the model with more reliable truck origin-destination trips to better model the charging needs of e-trucks. Moreover, government incentives that increase e-truck adoption could be added to the analysis. Finally, charging stations should be located according to equity considerations—incorporating equity in the overall methodology should be one of the studies to follow.

Appendix A: Vehicle Classification

The Federal Highway Administration's Vehicle Inventory and Use Survey classifies trucks in eight classes by their gross vehicle weight rating (Figure A.1).

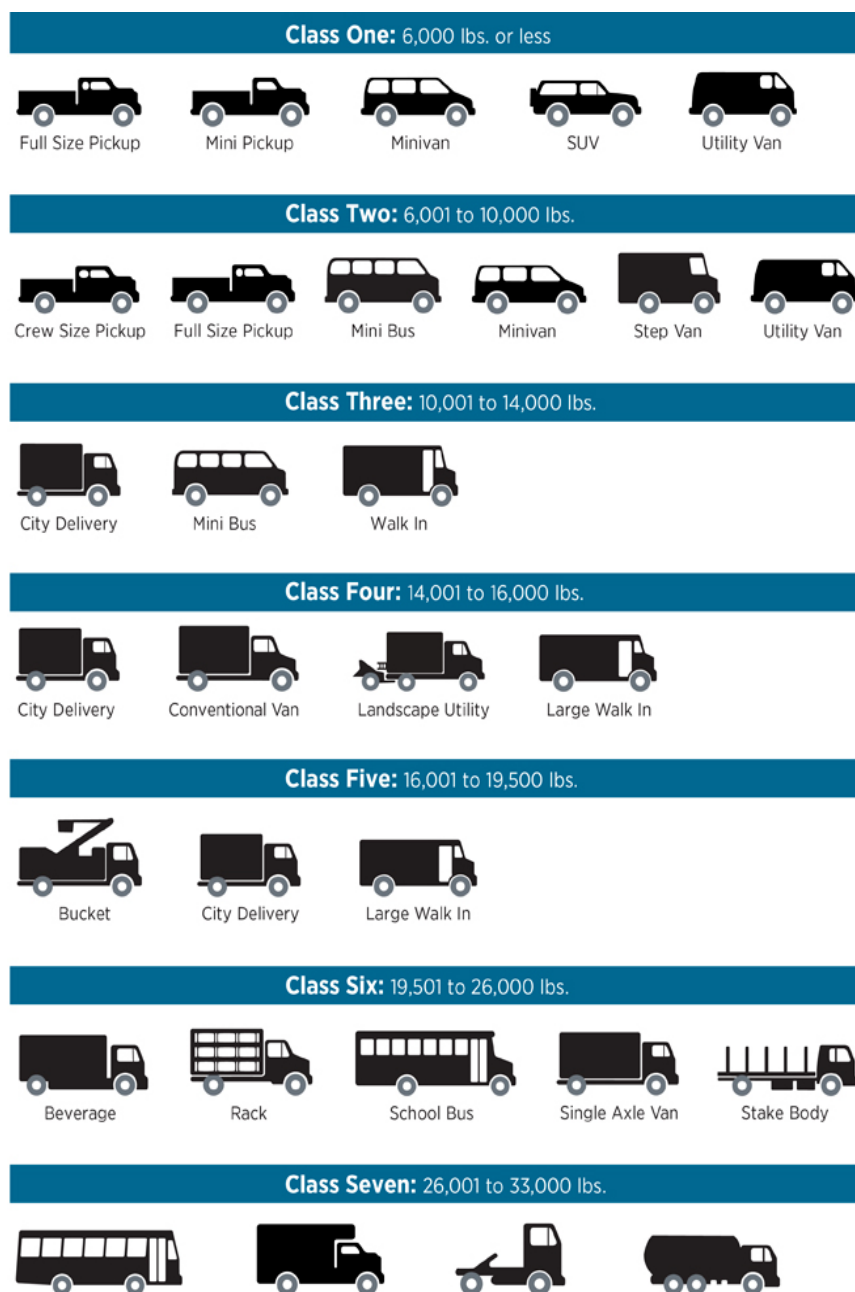


Figure A.1 FHWA's vehicle classification by gross vehicle weight rating²⁷.

²⁷ <https://afdc.energy.gov/data/10381>

Appendix B: Mathematical Optimization Model

The mathematical model along with the notation is shown below. For more information about the model, please refer to the conference paper²⁸ on “Charging Infrastructure Planning for Networks Including Electric and Diesel Trucks” by Behnam Davazdah Emami and Alireza Khani.

$$z = \min \rho \left(\sum_{a \in A} t_a x_a + \sum_{n \in N^e} t_n^{ch}(y) \sum_{rs \in W, k \in K_{rs,e}} f_k^{rs,e} \right) + \sum_{rs \in W} m_{rs} \times d_{rs}^d \quad (1)$$

subject to

$$(C_k^{rs,c}(f) - u_{rs}^c) f_k^{rs,c} = 0 \quad \forall k \in K_{rs,c}, rs \in W, c \in C \quad (2)$$

$$(C_k^{rs,c}(f) - u_{rs}^c) \geq 0 \quad \forall k \in K_{rs,c}, rs \in W, c \in C \quad (3)$$

$$\sum_{k \in K_{rs,c}} f_k^{rs,c} = d_{rs}^c(u) \quad \forall rs \in W, c \in C \quad (4)$$

$$\sum_{n \in N^e} y_n = P \quad (5)$$

$$f_k^{rs,c} \geq 0 \quad \forall k \in K_{rs,c}, rs \in W, c \in C \quad (6)$$

$$u_{rs}^c \geq 0 \quad \forall rs \in W, c \in C \quad (7)$$

where:

$$x_a^c = \sum_{rs \in W} \sum_{k \in K_{rs,c}} \delta_{a,k}^{rs,c} f_k^{rs,c} \quad \forall a \in A, c \in C \quad (8)$$

$$x_a = \sum_c x_a^c \quad \forall a \in A \quad (9)$$

$$C_k^{rs,e}(f) = \rho \left(\sum_{a \in A} \delta_{a,k}^{rs,e} t_a(x_a) + T C_k^{rs,e} \right) + c_e \sum_{a \in A} \delta_{a,k}^{rs,e} l_a \quad \forall k \in K_{rs,e}, rs \in W \quad (10)$$

$$C_k^{rs,d}(f) = \rho \left(\sum_{a \in A} \delta_{a,k}^{rs,d} t_a(x_a) \right) + c_d \sum_{a \in A} \delta_{a,k}^{rs,d} l_a \quad \forall k \in K_{rs,d}, rs \in W \quad (11)$$

$$d_{rs}^c(u) = d_{rs} \frac{e^{-\theta u_{rs}^c + \phi}}{\sum_{c \in C} e^{-\theta u_{rs}^c + \phi}} \quad \forall rs \in W \quad (12)$$

$$t_n^{ch}(w_{n,k}^{rs}) = \begin{cases} \alpha + \beta \times w_{n,k}^{rs} & w_{n,k}^{rs} > 0 \\ 0 & w_{n,k}^{rs} = 0 \end{cases} \quad (13)$$

²⁸ <https://trid.trb.org/view/2107870>

A	Set of Links,
N	Set of Nodes,
$G(N,A)$	Network,
C	Set of truck types consists of e-trucks (e) and diesel trucks (d),
W	Set of origin-destinations,
$K_{rs,c}$	Set of paths of type $c \in C$ from origin r to destination s so that $(r,s) \in W$,
$K_{rs,c}^w$	Set of active paths of type $c \in C$ from origin r to destination s so that $(r,s) \in W$,
N^e	Set of candidate charging nodes,
c_e	Operating cost of e-trucks (\$/mile),
c_d	Operating cost of diesel trucks (\$/mile),
$c_a(\cdot)$	Link travel cost function for link $a \in A$,
$C_k^{rs,c}(\cdot)$	Travel cost of type $c \in C$ in path $k \in K_{rs,c}$ from origin r to destination s ,
d_{rs}	The demand of OD pair $(r,s) \in W$,
d_{rs}^c	Demand of type $c \in C$ from origin r to destination s so that $(r,s) \in W$,
$f_k^{rs,c}$	Path flow of type $c \in C$ on path $k \in K_{rs,c}$ so that $(r,s) \in W$,
l_a	Length of link $a \in A$,
m_{rs}	Penalty cost of using conventional diesel truck between origin r and destination s (Difference between diesel and e-truck ownership cost).
P	Desired number of charging stations that system planners want to build
t_a	Link travel time for link $a \in A$,
$t_n^{ch}()$	total charging time at node $n \in N^e$ if charging station n is built,
$TC_k^{rs,e}$	Total recharging time of e-trucks on path $k \in K_{rs,e}$,
u_{rs}^c	Minimum path cost for type $c \in C$ from OD pair $(r,s) \in W$,
$w_{n,k}^{rs}$	Amount of charge of an e-truck at charging station n on path k between origin r and destination s
x_a	Link flow on link $a \in A$,
x_a^c	Link flow of type $c \in C$ on link $a \in A$,
y_i	A binary variable equals to 1 if charging station i is built, otherwise is equal to 0,
α	Fixed charging time,
β	The required time for charging one unit,
$\delta_{a,k}^{rs,c}$	A binary indicator which equals 1 if path $k \in K_{rs,c}$ between OD pair $(r,s) \in W$ with flow of type $c \in C$ uses link $a \in A$
ϕ	Logit constant,
ρ	Value of time \$/ (unit of time),
θ	Perception travel cost.