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A Strategic Assessment of Needs and Opportunities for the Wider Adoption of Electric Vehicles in Indiana

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COVER IMAGES

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16. Abstract

The primary objective of this study was to assess the challenges and opportunities associated with the provision of appropriate infrastructure to support electric vehicle (EV) operations and electrification across Indiana. A secondary objective of this study was to develop a strategic plan for INDOT that outlines new business opportunities for developing EV charging stations. To achieve these objectives, the project team assessed current and emerging trends in EV operations, particularly EV charging infrastructure and EV demand forecasting. They also examined opportunities for the strategic deployment of EV charging stations by identifying EV infrastructure deficit areas; investigated the impact of EV adoption on highway revenue and the feasibility of new revenue structures; and evaluated strategic partnerships and business models. The agent-based simulation model developed for future long distance EV trip scenarios enables INDOT to identify EV energy deficient areas for current and future energy charging demand scenarios, and it can support Indiana's strategic plans for EV charging infrastructure development. The results of the revenue impact analysis can inform INDOT's revenue model. The estimations of the recovery EV fee, the VMT fee, and pay-as-you-charge fee that break-even the fuel tax revenue loss can be used by INDOT in pilot programs to capture users' perspectives and estimate appropriate fee rates and structures. The insights obtained from the stakeholder interviews can be used to enhance preparedness for increasing EV adoption rates across vehicle classes and to strengthen the engagement of different entities in the provision of charging infrastructure.

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EXECUTIVE SUMMARY

Introduction

The emergence of electric vehicles (EVs) can reduce fuel consumption, fuel emissions, vehicle operating costs, and enhance energy security. As such, transportation agencies are encouraged to be strategic and adapt to the ongoing evolution in vehicle propulsion by identifying and pursuing a strategic assessment of needs and opportunities for wider adoption of EVs. In 2020, the Indiana Department of Transportation (INDOT) commissioned a study to address this issue. This study is intended to investigate the challenges and opportunities of providing appropriate infrastructure to support EV operations and electrification across the state and to develop a strategic plan that outlines new business opportunities for developing EV charging stations. To achieve these goals, this study had the following objectives.

- Assess current and emerging trends in EV operations with a focus on EV charging infrastrucre and EV demand forecasting.
- Examine opportunities for the strategic deployment of EV charging stations, including the identification of EV infrastructure deficit areas and the evaluation of strategic partnerships.
- Investigate the impact of EV adoption on highway revenue and the feasibility of new revenue structures.

Findings

The following section summarizes the key findings and methods involved in this study.

The research team developed a framework to identify EV infrastructure deficit areas and analyze potential EV charging station deployment. The simulation and GIS analysis also identified areas that could demand significant EV charging energy. Marion and Hendricks Counties were identified as the top two counties where long-distance EV trips may run out of energy. Other areas that are potential future charging deserts are Morgan, Johnson, Madison, Bartholomew, Hamilton, Marshall, Boone, Grant, LaPorte, Cass, White, Shelby, Huntington, Putnam, Decatur, and Owen Counties. To minimize the impact of energy deficient areas for the EV charging station deployment, these counties will be considered in the future EV infrastructure investment plan. The study outcomes also provide the geographical magnitude of the EV energy demand as defined by the ISTDM regions. The study confirms that among the 17 ISTDM regions, the Greater Indy area will potentially require the most EV energy, which is followed by the SR-46 Corridor, SIDC, and NCIRPC.

The study also created a framework to estimate the impact of EV adoption on the fuel tax revenue and identify the optimal EV fee based on scenarios of EV market penetration levels. The fuel tax revenue loss for Indiana and INDOT were estimated for *most likely*, *optimistic*, and *pessimistic scenarios*. In the most likely scenario (5% EV market penetration level for light duty vehicles in 2030, 30% EV market penetration level for medium or heavy duty vehicles in 2030), the statewide fuel tax revenue will decrease by 21% and the INDOT fuel tax revenue will decrease by 24% by 2035, relative to 2030. To maintain the same fuel tax revenue per vehicle, annual fees ranging from \$241 (in 2021) to \$342 (in 2035) for automobiles, \$344 to \$435 for light trucks, \$1,246 to \$1,488 for buses, \$969 to \$1,243 for single-unit trucks, \$6,192 to \$7,321 for combination trucks, and \$26 to \$35 for motorcycles would be needed over the analysis period (2021–2035).

Alternative ways to implement the estimated recovery EV fees were also proposed. The recovery EV fee was converted to vehicle miles travelled (VMT) (\$/mile) and the pay-as-you-charge (\$/kWh) fee was converted to per vehicle class and per year. Potential barriers to the implementations of these options (e.g., sustainability, costs, and privacy concerns) and policy aspects (e.g., implementation process, partnerships, and equity considerations) were examined. Although EV users may pay additional charges that can hinder the adoption of EVs, this is only one aspect of the user total cost of ownership, since EVs have lower operating costs.

To gather knowledge on the main aspects related to the promotion of EVs and evaluate the strategic partnerships and business models, semi-structured interviews were conducted online with 23 stakeholders who represent the EV ecosystem. The content analysis showed that stakeholder partnerships and appropriate business models may depend on various factors, including the type of charging (private vs. public or Level 2 vs. fast charging); the location (local, state, or regional level); and the vehicle type (commercial fleets vs. privately-owned vehicles). Most interviewees supported that the provision of charging infrastructure involves mainly private entities, while public sector provides direct or indirect incentives to users, as well as planning the charging infrastructure, raising awareness, and educating all stakeholders involved.

EV ecosystem stakeholders identified transit buses as having the highest potential for electrification. Other vehicle types with high potential are buses and small freight vehicles or delivery vans. Equity concerns were raised related to the availability of charging infrastructure in rural areas as well as the various fees/taxes to be charged per EV to address the potential for decreasing fuel tax revenue. A VMT fee was argued as a fair approach to generating highway revenue, but privacy concerns were viewed as a major barrier to its implementation. Lastly, the need for grid management and renewable energy integration was pointed out as a high priority as EV adoption and commercial electric vehicle adoption increases.

Implementation

- The agent-based simulation model of the study was developed for future long distance EV trip scenarios in Indiana. The model uses unique geographical information and model parameters for Indiana. This model enables INDOT to identify EV energy-deficient areas for current and future energy charging demand scenarios, and it can also support the state's strategic planning for the EV charging infrastructure development.
- The results of the revenue impact analysis can inform INDOT's revenue model and assist decision makers in establishing reliable plans for prospective future EV operations. The estimations of the recovery EV fee, the VMT fee, and pay-as-you-charge fee can be used by INDOT in pilot programs to capture users' perspectives and willingness-to-pay and to estimate appropriate fee rates and structures so that sufficient revenue is raised and public acceptance is achieved.
- The study proposed an EV recovery fee to offset the revenue loss from fuel tax. It is anticipated that the revenues from the EV recovery fee will be split between the state and the local governments. A state share of 75% or higher will ensure that INDOT's revenues move beyond break-even to a surplus.
- Implementing the recovery EV fee as an annual flat fee for EVs may generate opposition from the public and road

users, particularly commercial vehicles. Therefore, to offset the gasoline revenue loss, a VMT or pay-as-you-charge fee may be more appropriate and equitable. To address equity further, such fees could be adjusted to account for weight. To facilitate implementation, the agency must develop appropriate technology solutions to address privacy concerns.

- Extensive public outreach and education should be undertaken to inform users about the overall long-term cost savings associated with EV use, which can help earn public support. Furthermore, the best combination of alternative policy options can be identified through pilot programs. This study highlights an opportunity to prepare INDOT for participating in pilot programs on a road usage charge, following the examples of other states.
- The insights obtained from the stakeholder interviews can be used to better prepare for increasing EV adoption rates across vehicle classes and strengthen the engagement of different entities in the provision of charging infrastructure. Among other things, collaboration between utilities and policy makers is needed to plan for increasing EV demand (especially for commercial vehicles that have increased power requirements). The planning process may consider making upgrades to the transmission and distribution network; grid management technologies, such as vehicle-to-grid; integrated plans for renewable energy projects; and new tariff structures to reward charging behaviors and investigation of the impacts of EV demand on transportation system operations.

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1. INTRODUCTION

1.1 Problem Statement

Transportation is recognized as the final frontier for major advancement in energy efficiency. In the United States (U.S.), the transportation sector accounts for 29% of greenhouse gas emissions (EPA, 2019). As a result, awareness of the environmental impacts of traffic is growing rapidly. Efforts are being made towards reducing emissions, including the improvement of vehicle and fuel technology as well as the promotion of alternative, sustainable modes of transportation. The emergence of electric vehicles (EVs) is among those technological innovations that can reduce fuel consumption, emissions, and vehicle operating costs.

Transportation agencies are encouraged to be strategic and adapt to the ongoing evolution in vehicle propulsion. The inevitable transition from diesel and gasoline internal combustion engine vehicles to EVs may offer various benefits to Indiana. The benefits include opportunities (1) to encourage operations on the existing highway system to be more environmentally sustainable, (2) to improve air quality by reducing emissions of criteria air pollutants as well as to increase fuel savings that can become additional disposable income which may be spent mostly in the local economy, creating additional jobs in the state, (3) to revise and enhance highway financing as a result of dwindling revenues caused by EVs. These prospective benefits motivate the development of new systems to accommodate EV demand.

However, the EV market is developing slowly mainly due to reasons including range anxiety concerns, particularly for larger light duty vehicles and heavy duty vehicles. From a demand perspective, there is a need to develop reliable estimates of the growth in EV demand and operations. From a supply perspective, there is a need to assess the current state of EV supporting infrastructure, and identify additional investments that are needed, as well as define the role of the private sector. As Indiana proceeds to the next step of transportation electrification, there is a critical need for EV charging infrastructure which, at any given point in time, can serve the growing EV demand with limited situations of capacity underutilization (excess supply) or station queuing and delay (excess demand).

Moreover, the state's revenue is largely based on fuel taxes. These funds were mainly distributed to state highway road construction and improvement funds as well as local road and bridge matching grants. Recognizing the fast-growing market share of EVs in Indiana, it seems reasonable to be concerned that there will be declining fuel tax revenues tax, and therefore, inadequacy of highway funding in Indiana.

Against this background, the Indiana Department of Transportation (INDOT) commissioned this study to assess the demand (needs) and supply-related opportunities for wider adoption of electric vehicles in Indiana. It is anticipated that addressing the demand and supply issue regarding EV operations in Indiana will put the state in a better position to also plan for other emerging transport technologies that are synergistic with EV operations, including connected and autonomous vehicles, and shared mobility. To achieve this, it would also be essential to explore and advance opportunities for INDOT engagement with the private sector and utilities to enhance the state's preparation for EV operations. Overall, the EV initiative is consistent with INDOT's strategic plan (McGuinness, 2019), which includes restructuring the state highway infrastructure systems regarding EV expansion, public charging station infrastructure, and financial income structure.

1.2 Objectives

The objectives of this study are to investigate the challenges and opportunities associated with the provision of appropriate infrastructure to support EV operations and electrification across the state and develop a strategic plan for INDOT that outlines new business opportunities for developing EV charging stations. To achieve this objective, the research approach of this study involves the following.

- Assessing the current and emerging trends in EV operations, with a focus on EV charging infrastructure and EV demand forecasting.
- Examining opportunities for the strategic deployment of EV charging stations, including the identification of EV infrastructure deficit areas and the evaluation of strategic partnerships.
- Investigating the impact of EV adoption on highway revenue and the feasibility of new revenue structures.

The study results can guide INDOT regarding strategic partnerships and enhanced infrastructure preparedness for prospective EV operations in the coming future, as well as inform the next generation of INDOT revenue model. Addressing the demand and supply issue regarding EV operations in Indiana will benefit the state by placing it in a better position to plan for this growing technology. The implementation of the research outcome will also advance the state's economy by enhancing the INDOT's revenue structure with the conjunction of public and private sector's participation. As this study provides guidance for the strategic deployment of EV charging infrastructure, significant environmental benefits and economic development potential along the EV infrastructure are also expected.

1.3 Organization of the Report and Work Plan

The work plan of the project is reflected in the structure of this report, which is as follows.

Chapter 2 reviews literature on EV types, charging methods and charging behavior, EV demand forecasting studies and tools, EV charging infrastructure studies, studies on stakeholders' views about electrification, and impact of EV adoption on highway revenue.

Chapter 3 examines current trends on electrification and current electrification projects within Indiana as well as the current state of Indiana's electric grid.

Chapter 4 discusses the framework developed for identifying EV infrastructure deficit areas and for analyzing the potential locations for EV charging station deployment.

Chapter 5 presents the financial analysis conducted to quantify the impact of EVs on state highway revenue and examine potential funding mechanisms to mitigate the decline in revenues generated.

Chapter 6 describes the process and results of interviews conducted with multiple stakeholders for the evaluation of strategic partnerships and business models for the provision of EV infrastructure.

Chapter 7 provides a summary of the key findings and implications, limitations and recommendations for future work.

2. LITERATURE REVIEW

This chapter presents a review of electric vehicle (EV) types, charging methods and charging behavior (Sections 2.1–2.3); EV demand forecasting studies and tools (Section 2.4); and EV charging infrastructure studies (Section 2.5). Additionally, this chapter summarizes previous work on stakeholders' views about electrification (Section 2.6) as well as the impact of EV market on highway revenue (Section 2.7). Lastly, a summary of the chapter is provided in Section 2.8.

2.1 EV Types

EVs use electricity stored in their batteries to improve vehicle efficiency and are classified in three main vehicle types that vary in range and capability (Liao et al., 2017; U.S. Department of Energy, n.d.c.).

Hybrid Electric Vehicles (HEVs) are vehicles include both a conventional internal combustion engine and a battery system. HEVs are based on gasoline to operate the internal combustion engine when additional range is needed but can also be based solely on electricity for a certain distance. HEVs do not have the ability to be plugged in to recharge their battery packs. Their batteries can be recharged while driving on engine power or by reclaiming energy through regenerative braking.

Plug-in Hybrid Electric Vehicles (PHEVs) are vehicles use gasoline to power the conventional internal combustion engine and batteries to power the electric motor. The main difference compared to HEVs is that the batteries of PHEVs can be charged using external electric charging equipment in addition to regenerative braking. PHEVs typically run on electric power and automatically switch to use the internal combustion engine when the battery is almost depleted. Most PHEVs can travel around 20–40 miles operating in all-electric mode.

Plug-in Electric Vehicles (PEVs) or Battery Electric Vehicles (BEVs) are vehicles have no internal combustion engine and are based only on power from their battery packs. Their battery is charged by plugging the vehicle into an external electrical power source. Typical driving ranges for BEVs vary between 150–300 miles.

2.2 Charging Methods

This section discusses the various charging methods: stationary plug-in charging, stationary wireless charging, dynamic conductive charging, dynamic wireless charging, and battery swapping.

2.2.1 Stationary Plug-in Charging

The most common form of EV charging is the charging station, where vehicles are parked and charged by an external electric power supply. Electricity can be supplied by the following types of charging stations (U.S. Department of Energy, n.d.a).

Alternating Current (AC) Level 1 uses standard 120V AC residential power and only requires a charging cable that comes with the EV. The charge time is slow at only 3–5 miles per hour of charging (around 8 to 12 hours, depending on the vehicle's battery).

AC Level 2 uses 240 V AC power to enable faster EV battery recharging, providing 10–20 miles per hour of charging (around 4 to 6 hours).

Direct Current Fast Charging (DCFC) converts high voltage AC to 480 V DC power for accelerated charging speeds. It can charge an EV's battery to 80% of full capacity in 20–30 minutes.

In addition to standard DCFC chargers, there also exist specially designed DCFC chargers for buses. These chargers are designed to attach to the top of a bus semi-autonomously without the driver needing to leave the vehicle (Eudy et al., 2016). These are ultra-high-powered chargers and, in the case of that study, they can charge a bus in under 10 minutes.

It is recognized that these different charging levels serve different purposes with optimal use scenarios. Due to its low power consumption, Level 1 charging is most appropriate for at-home charging, though some public uses such as charging vehicles in long-term parking at airports may still be appropriate (Smith & Castellano, 2015). It may also be used at some workplaces. Level 2 charging is the most flexible, as it is often used for both at-home charging as well as charging in public areas. Public Level 2 charging is most suitable in areas where vehicles may be parked for a couple of hours, such as malls, workplaces, and shopping centers (Smith & Castellano, 2015). DCFC is most suitable to drivers that must significantly increase their state of charge in a short amount of time. Due to its high-power levels, it is only suitable for public use. This includes areas along highways, charging stations in cities, and some shopping areas (Shareef et al., 2016).

DCFC has seen rapid technological advancement in recent years, spurred by private companies. In 2016, the SAE had two classifications of DCFC, with the higher level outputting 40–100 kW (Shareef et al., 2016). A 90 kW charger, for example, can provide 90 miles of range in 20 minutes of charging (Smith & Castellano, 2015). Currently, however, major charging companies such as Tesla and Electrify America offer charging at over double these power levels. Tesla superchargers can charge vehicles at up to 250 kW, providing 200 miles of charge in 15 minutes (Tesla, n.d.). Electrify America offers stations with charging powers varying from 50–350 kW of power (Electrify America, n.d.). However, it is important to note that while higher charging power yields faster recharge time, the vehicle must also be able to accept high power levels. Older EVs cannot charge at levels above 50 kW (EV Safe Charge, n.d.), so a 350 kW charger will not provide them with any added benefit over a 50 kW charger.

The costs related to AC versus DC charging are also drastically different. Level 1 charging is the least expensive type, as it can be provided via a standard 120V electrical outlet. A single Level 2 charger can cost in the range of $400–$6,500K, while a single DCFC port costs between $10–$40K. The wide range of these values is due to the level of sophistication of the charger. This includes features such as the number of charging ports per device, point-of-sale systems, energy monitoring and management systems, systems to communicate with the electric grid and/or the provider's network, aesthetic design, and other features (Smith & Castellano, 2015). Additionally, installation costs will vary depending on the location.

DCFC costs are substantially higher due to the complexity of the charging station. DCFC stations must transform the electric grid's current from AC to DC prior to delivering it to the vehicle. In Level 1 and 2 charging, the station does not perform this transformation. This also necessitates more regular maintenance on DCFC stations compared to AC stations (Shareef et al., 2016; Smith & Castellano, 2015).

While DCFC provides much more rapid charging than its AC counterparts, it comes with a number of additional issues. One problem is that the high power required for DCFC chargers can place strain on the electrical grid at peak usage times and degrade grid components such as transformers (Yilmaz & Krein, 2013). This will likely require some combination of regulatory framework, infrastructure improvements, and coordination methods if DCFC becomes widespread. It should be noted that Level 2 charging can also cause a similar scenario, but DCFC's higher power levels make it more susceptible to this issue. Additionally, the high power levels of DCFC will cause an increased rate of battery degradation in vehicles if used consistently (Shareef et al., 2016).

There have been numerous proposed methods to alleviate the potential strain caused by DCFC on the electric grid. These include the use of coordinated charging, bidirectional charging, and energy storage devices. Coordinated charging allows vehicle to grid communication to alter charging times and power levels so as not to overstrain the grid (Yilmaz & Krein, 2013). This typically attempts to focus most charging in the nighttime hours when the grid sees less strain (Duan et al., 2014). Bidirectional charging is a method that allows the grid to charge the vehicle, but also allows the vehicle to add charge back into the grid (Yilmaz & Krein, 2013). At times of high grid strain, the vehicle battery provides power back into the grid. When this is performed *en masse*, grid strain can be alleviated. This can be considered a subtype of coordinated charging. Energy storage devices have also been proposed for the sites of charging stations (Falvo et al., 2014). These devices could act as a reservoir to mitigate direct strain on the electric grid during times of peak charging. While there has been continual research in these areas (e.g., Davis & Bradley, 2012; Nimalsiri et al., 2021; Yang et al., 2021), it is not yet apparent which of these methods may be implemented in the future, nor is it obvious how such an implementation would be structured.

Additionally, it should be emphasized that DCFC may not be widely needed by typical commuters. Research has shown that most charging is anticipated to occur at the driver's home or workplace (Li et al., 2020), and may be most appropriate more long-distance trips, rideshare drivers (Smart et al., 2020), and drivers without access to home or workplace charging. However, it should also be noted that the presence of DCFC can reduce the effect of range anxiety (Ashkrof et al., 2020), which is considered an impediment to EV uptake. Table 2.1 shows the comparison of the three charging levels discussed.

2.2.2 Stationary Wireless Charging Stationary

Wireless charging systems use electromagnetic induction to transfer electricity into an EV, instead of using a traditional charging cable. Charging is achieved while the EV is not operational and parked for an extended period in stationary modes, such as in a parking lot or garage (Jang, 2018). A wireless charging station uses charging coils embedded in the ground (charging pads) to convert electricity from the grid into a controlled magnetic field, which then induces a current in a receiving coil attached to the underside of a vehicle (Covic & Boys, 2013).

This charging method can ease the user interaction with the grid, can offer an automatic operation without user intervention and is safer compared to conductive charging where cables carrying high electrical current are utilized (Triviño et al., 2021). A major concern for wireless EV charging technology is the efficiency lost by the air gap between the charging pad and the receiving coil (Jeong et al., 2015). Additionally, the cost of installing the charging equipment for this technology is higher compared to plug-in charging and has been reported to range between $40–60K/charger (Jang et al., 2016).

Stationary wireless charging of EVs has become commercially available. Advances in the charging

TABLE 2.1
Comparison of charging levels

	AC Level 1	AC Level 2	DCFC
Charging Power (kW)	1.4–1.9	3.4–19.2	24–350
Charging Rate	4–6 mi/h	10–60 mi/h	24 mi/20 minutes (24 kW) 200 mi/15 minutes++ (250 kW)
Cost ($)	300–1,500	400–6,500	10,000–40,000
Application	Home, long-term parking, some workplace charging	Home, workplaces, retail locations, other short-medium term parking locations	Provide large amounts of charge in short timeframe (e.g., for travelers, TNC drivers, fleet drivers, vehicle owners without access to home or workplace charging) Determination of optimal locations is quite important

technology have made it feasible for multiple companies to develop and provide this type of product to the market. Some of the primary companies with commercial stationary wireless charging solutions are WiTricity, Qualcomm, Conductix Wampfler, Momentum Dynamics, and HEVO power, promising power transfer as fast and efficient as the conventional plug-in charging.

WiTricity, which is a startup from the Massachusetts Institute of Technology, provides charging rates for static inductive wireless charging from 3.6 to 11 kW. The highest efficiency reported is 94% from grid to battery using a circular coil architecture. Tolerance to parking misalignment of +/-10 cm side to side and +/- 7.5 cm front to back. The charging pad can be installed on-ground or buried in pavement (WiTricity, n.d.). WiTricity have also recently acquired Qualcomm's EV wireless charging unit Halo (WiTricity, 2019). Halo was tested for dynamic in Versailles, France, through the FABRIC project (CORDIS, 2018). Conductix Wampfler offers contactless charging solutions for industrial applications such as transfer cars, skillet lines with lift tables, Automated Guided Vehicles (AGV) or Rail Guided Vehicles (RGV). Their solutions operate at 20 kHz (Conductix Wampfler, n.d.). Momentum Dynamics developed high power inductive charging technologies for the automotive and transportation industries that is capable of delivering energy safely through air, water, and ice (all weather conditions). They offer up to 75 kW chargers for EVs and up to 200 kW charging systems for mass transit (Momentum Dynamics, n.d.). HEVO power also offers a 10-kW static charger.

SAE International published *SAE J2954 Recommended Practice (RP) for Wireless Power Transfer (WPT) for Light Duty Plug-in/EVs and Alignment Methodology* in May 2016, and its latest revision was published in April 2019 (SAE International, 2019). The RP defines acceptable criteria for interoperability, electromagnetic compatibility, EMF, minimum performance, safety, and testing for wireless charging of light duty electric and plug-in EVs. Four levels of charging according to power levels are categorized up to 22 kW. It supports home (private) charging and public wireless charging. A standardized single coil test is developed for power classes 1, 2, and 3, up to 11 kW (1 through 3) using circular topology but also provides a way to demonstrate compatibility to other coil topologies.

For more information about the standards of this charging type, the interested reader can refer to Konstantinou et al. (2021).

2.2.3 Dynamic Conductive Charging

An alternative mechanism for EV charging is the dynamic charging (or in-motion charging), also referred to as charging-while-driving. This subsection refers to dynamic charging where electric power is transmitted by conductive energy transfer through overhead wires (catenary) or rails imbedded in the roadway. Originally developed for electric traction on railroads and in use on many passenger rail systems, these technologies have recently been adapted for use in EVs. Siemens opened the first highway with dynamic conductive charging capability (eHighway) in Sweden (Siemens, n.d.) and Scania manufactures compatible electric trucks with pantographs (Siemens, 2017). In Sweden, three dynamic conductive charging solutions are being developed and tested: Alstom APS, Elways, and Elonroad (Collin et al., 2019).

2.2.3.1 Catenary. The catenary system is based on overhead wires connected to electrical substations along the road corridor. A pantograph is located on the top of the vehicle and contacts the wires as it drives, supplying electricity to the vehicle for charging and propulsion. Depending on the operation mode, the pantograph can be lowered or raised automatically or manually while the vehicle is moving, providing the flexibility to change lanes, cross under bridges, or drive on roads that lack catenary (Jelica, 2017). This flexibility is the main difference of this technology with the technology used for many years for trains and trolley buses. This system can be completely incorporated into existing road infrastructure, without significant modifications. It is also able to offer high power transfer efficiency rates of over 80% (Siemens, 2017). Certain safety regulations and standards apply for these systems to prevent from hazards. For example, overhead wires should be installed in a height of at least 20 feet allowing for vehicles only with a corresponding size to connect to them (e.g., trucks and buses) (Andersson & Edfeldt, 2013). One of the main advantages of this charging system is that it can provide high levels of power to heavy duty vehicles and that it constitutes the most mature solution compared to other dynamic charging methods (Collin et al., 2019). However, the catenary system is only suitable for heavy duty vehicles, can be susceptible to damage and defects, and may create negative visual impact (Bateman et al., 2018). According to case studies that have tested this technology, its cost may vary from around \$2–\$4 million/lane-mile (Bateman et al., 2018).

2.2.3.2 Rail. In the rail system, a conductive rail that is located on the top of the road supplies the power to the vehicle. This rail is in turn supplied by and is connected to the electrical grid via transformer substations installed along the roadway at a certain density (Jelica, 2017). The rail is divided into different segments that are activated when a vehicle is detected on them (Konstantinou, 2019), eliminating the possibility of accidental electrocution. Vehicles have moveable arms which automatically lower to contact the electrified rail in the road and move horizontally to stay centered on the rail. The conductive rail approach has a total system efficiency of approximately 82% (Viktoria Swedish ICT, 2013). One of its advantages is that the rail system can be compatible with all types of vehicles and that its components are easily accessible for inspections (Bateman et al., 2018). It is also expected to have a minimal impact on the road in terms of function and maintenance, as rational solutions for installation and maintenance are being developed and tested by different companies around the world that are interested in this concept (Konstantinou, 2019). However, there are safety concerns for motorcycle users passing over the conductive rail system (Bateman et al., 2018). Additionally, as with the conductive overhead system, it may be vulnerable to damage. The cost of the conductive rail system can range from around \$800K–\$3 million/lane-mile (Bateman et al., 2018).

For more technical details and case studies about the conductive overhead or rail charging systems, the interested reader can refer to Bateman et al. (2018), Collin et al. (2019), and Konstantinou (2019).

2.2.4 Dynamic Wireless Charging

Dynamic wireless charging is achieved through wireless power transfer while the EV is in full motion. The main components of this technology are the same as in the stationary wireless charging system but in this case a series of charging pads are embedded along the roadway (power track or electric road) to enable dynamic charging. The embedded coils can be powered individually and energized only when an equipped EV passes on top of each coil (Choi et al., 2015).

Dynamic wireless charging can be suitable for all vehicle types, is safer for users and maintenance workers, and is less susceptible to damage since it is installed in the roadway pavement (Bateman et al., 2018). One of the main challenges of the wireless charging technology though is the high initial investment cost (e.g., Ahmad et al., 2018; Konstantinou et al., 2019; Mohamed et al., 2019). According to Bateman et al. (2018), the cost of implementing the technology may vary from around \$900K–11 million/lane-mile and depend on multiple factors such as the accessibility to the power network, the type of installation, and materials of the charging infrastructure. Nevertheless, the high initial investment cost can be compensated by reducing the battery size and increasing driving range due to the elimination of recharging downtime (Mohamed et al., 2019). As in the stationary wireless charging method, dynamic wireless charging faces the challenge of the power transfer efficiency through the air gap.

Dynamic wireless charging is still not commercially available due to multiple challenges in infrastructure modification and the requirement of highly efficient power transfer (Patil et al., 2017). Different studies across the world focus on exploring this type of charging technology and are being conducted by the University of California-Berkeley (the Partners for Advanced Transit and Highways project), the Utah State University (Electric Vehicle & Roadway (EVR) Research Facility and Test Track; Advancing Sustainability through Powered Infrastructure for Roadway Electrification Engineering Research Center) and the Oak Ridge National Laboratory (National Transportation Research Center). Pilot programs outside the U.S. are found in Italy and France (FABRIC project), Spain and Germany (Unplugged Project), Israel (Elect Road), Sweden (Smartroad Gotland Project) and South Korea (OLEV by the Korea Advanced Institute of Science and Technology). Examples of charging efficiency may come from case studies and tests that have shown capabilities to dynamically charge a light duty EV at up to 20–40 kW at highway speeds with around 80% charging efficiency (FABRIC, 2017) and a hybrid electric truck at 180 kW, with around 89% energy power transfer efficiency (Sundelin et al., 2016). For more technical details, information on the case and research studies and costs of the dynamic wireless charging technology, the interested reader can refer to Konstantinou et al. (2021).

2.2.5 Battery Swapping

Battery swapping is a charging technique where a battery with low charge is removed from a vehicle and replaced with a full battery. This technique has received attention within the research community, though it has only been implemented in limited cases.

The benefits of battery swapping are that it is a fast procedure for the vehicle and that there is not extensive strain on the electric grid. The time to remove and replace the battery from a vehicle is a matter of minutes and is even a faster process than DCFC. The expended battery can then be charged at the station at low power levels and at off-peak hour to avoid straining the electric grid (Zheng et al., 2014). There are several issues, however. One major problem is that it is capital intensive, as there must be a battery surplus and as the stations are more complex than typical charging stations, with costs estimated at about $2.3 million per station (Budde Christensen et al., 2012). Additionally, swap stations require that vehicles have nearly identical battery architecture to integrate with the automated swapping system (Ahmad et al., 2020). Finally, there is the issue as to who owns the batteries (Ahmad et al., 2020).

There have been two instances of commercial use of battery swap stations for personal vehicles. The Israeli company Better Place failed in early 2013, but the Chinese company NIO currently sees success. This difference can be traced to how their business models differed in how they addressed the problems with battery swap stations—particularly the requirement of identical battery architecture. Better Place required that customers purchase vehicles from them and also, lease the batteries. However, Better Place only offered a single Renault Sedan, as they were unable to partner with any other car manufacturers. This is because manufacturers did not want to limit their battery architectures to meet Better Place's requirements (Budde Christensen et al., 2012). Better Place also was unable to convince Renault to make other vehicles that would be compatible with the stations. The Renault Sedans did not sell well in Better Place's markets, and Better Place's capital expenditures on swapping stations vastly outweighed revenue, ultimately leading to bankruptcy (Berman, 2013; Motavalli, 2013; Pearson & Toth Stub, 2013). Unlike Better Place, NIO does not have the issue of convincing vehicle manufacturers to build standardized batteries. This is because NIO is a manufacturer itself (NIO, n.d.). As a result, it sells multiple vehicles that are compatible with the swap stations that it also maintains. This indicates that while there are barriers to the use of battery swap technology for private vehicles, they are surmountable.

The majority of battery swapping research focuses on applications for fleet vehicles. There have been numerous studies on its use for transit buses Zheng et al., 2014 (e.g., Chao & Xiaohong, 2013; Zhang et al., 2018). Additionally, battery swap buses have been implemented in both China and South Korea-Edison Motors is a Korean company that currently offers battery swap buses. This is a promising area because fleet vehicles generally will not face the problems that face battery swapping. Fleet vehicles will generally have similar-or the same-battery architecture, and the issue of battery ownership is rendered moot.

2.2.6 Comparison of Charging Methods

Table 2.2 compares the charging methods described in the previous sections.

2.3 Impact of Value of Travel Time on Charging Behavior

Given the varying charging methods and their requisite charging time (presented in Section 2.2), when choosing a charging method to deploy, it is imperative to consider how drivers may value the time needed to charge a vehicle. Quantifying an EV driver's value of travel time (VOTT) as related to the need to pause a trip to charge can be useful when considering placement of additional charging stations. While it is recognized that there may be high levels of variance to VOTT, it is also noted that there does not appear to be a clear, systematic reasoning for that variance (Spurlock et al., 2020). However, despite this finding, there appears to be a general range found for VOTT as relating to EV charging.

One report, evaluating the impact of VOTT on charging network requirements, estimate a VOTT in the range of $5–$50/hr with a base case of $18/hr (Ghamami et al., 2020). This report's findings noted that increased VOTT increases the cost of the charging network, as more chargers must be built to remove delays due to detouring to reach chargers and queueing at a charger. However, total delay cannot decrease beyond the time needed to charge.

Another report (Ashkrof et al., 2020) estimates VOTT as $11.78/hr. However, this also finds that EV travelers appear more sensitive to monetary cost than time cost when choosing a route. Sun et al. (2020) does not estimate the VOTT of drivers, but instead estimates the VOTT ranges for charging stations and dynamic charging to be dominant. This study finds that charging stations are dominant with VOTT less than $21/hr while dynamic charging is dominant with VOTT between $24–$30/hr. Additionally, the study by Sun et al. (2020) develops an optimization model to determine where to deploy charging stations versus dynamic charging lanes while considering driver VOTT.

The *SMART Mobility Advanced Fueling Infrastructure Capstone Report* (Smart et al., 2020) does not speccify values for VOTT, though it provides important insight for commercial EV users. It notes that time truckers spend charging while on a route is included in the hour regulations for the amount they may work in a day. Additionally, the time that TNC drivers spend charging may be considered a lost revenue-earning opportunity. Thus, it appears that in the case of commercial drivers, one may estimate their VOTT for charging as the value that is lost from not driving.

2.4 EV Demand Forecasting Studies and Tools

For an accurate prediction of EV demand, it is necessary to conduct a comprehensive review of the state of the art in EV demand modeling. This section focuses on presenting studies on EV demand forecasting as well as currently available forecasting tools.

Table A.1 of Appendix A includes research studies related to EV demand forecasting. These research

TABLE 2.2
Charging methods comparison matrix

	AC Charging	DCFC	Stationary Wireless	Dynamic Conductive	Dynamic Wireless	Battery Swap
Technology Maturity	Mature	Charger power continuing to increase, vehicle capabilities appear to lag charger abilities	Commercially available but still in the research and development phase related to health and safety, finances, power range limitations, infrastructure development and maintenance	Mature in railroad industry. Field trials have been conducted with heavy duty vehicles.	Numerous experimental test beds have been constructed. Limited examples of field use.	Battery capabilities continually increasing. The act of swapping seems to be mature as a technology. Business model and legal questions seem to be primary hurdle to use
Applicable Vehicles	All	All	All	Primarily heavy duty vehicles	All	All vehicles. Fleet vehicles specifically appear to be the most feasible business model
Cost	$300–$6.5K/charger	$10–$40K/charger	$40–$60K/charger[1]	$2–$4 million/lane-mile (catenary) $800–$3 million/lane-mile (rail)[1]	$900K–$11 million/lane-mile[1]	There is not significant literature detailing specific costs. A single Better Place station was estimated at about $2.3 million, and a battery surplus must also be purchased
Primary Advantages	Low cost Low grid impact Can charge at home overnight	Rapid recharge (~15–60 minutes for near-total recharge)	No need to insert a cable (convenience) Lower battery size	Charge while driving (reduce range anxiety and charge time) Less invasive installation than wireless charging Higher power levels compared to wireless charging	Charge while driving (reduce range anxiety and charge time) Easily used by any class of vehicle Lower battery size Less susceptible to damage compared to conductive charging	Vehicle gets newly charged battery in under 5 minutes Low grid impact
Primary Disadvantages	Low charging speed	High impact on grid	Air gap	Difficult or impossible for use by light duty vehicles Intrusive (requires catenary or above-ground rails) and more vulnerable to damage	Requires resurfacing of roadway to install and is expensive Coil misalignment and air gap High initial cost	Difficult to have a profitable business model Legal question about battery ownership

[1] The data, assumptions, and methods used across the various studies or projects are different. Therefore, the cost findings reported in the studies cannot be treated as conclusive.

studies found from the literature are either based on surveys to calculate demand or use already existing data fed into mathematical programming/optimization or other models to provide an estimation of the current or future demand. According to the table, the use of discrete choice and Bass diffusion models as well as the S-curve is more popular for calculating EV market penetration compared to the use of mathematical or agent-based models in these studies. Additionally, almost all studies focus on projections for light duty vehicles, indicating that there is limited research related to heavier vehicles. The research studies report the EV market penetration as a percentage of new vehicle sales or as a percentage of vehicle registrations or as absolute numbers. Thus, comparing the different EV projections becomes difficult. Overall, though, there is a wide range in the projections of EV demand found in the different studies, mostly depending on the location, policies (e.g., subsidies) and availability of charging infrastructure.

Table A.2 of Appendix A includes a list of tools that either directly forecast EV sales or use discrete choice and agent-based modeling frameworks. The main inputs used in the tools are vehicle and technology attributes, vehicle miles travelled, penetration rates, mobility and charging data, characteristics of charging infrastructure, consumer preferences, socio-demographic characteristics of drivers and policies. Some of these tools are publicly available and at least documented (e.g., ADOPT, POLARIS) and some are not publicly available (e.g., Compass, PEV Roadmap). The tools shown in Table A.2 mainly focus on providing outputs related to light duty vehicles, except for the EV Hub and SERA tools that also consider medium- and heavy-duty vehicles. Nevertheless, the modeling frameworks and assumptions used as well as the main inputs of all tools can provide guidance on building new models related to needs for EV demand and infrastructure. Lastly, the scale of most tools is global, regional, or national and only a few tools can provide results per state or zip code. Thus, there is a need to develop more models which can consider local scales.

2.5 EV Charging Infrastructure Studies

The electrification of the existing transportation infrastructure system requires substantial upgrades to overcome two major concerns from drivers and the public. The first is driver's range anxiety based on the current technology level of the EV. Drivers must consider their limited driving range to plan their long-distance trips. The second concern is the availability of the EV charging infrastructure in the proximity of the planned transportation networks (Bai et al., 2021; Bonges III et al., 2016; Jung et al., 2015). These two concerns need to be addressed before the electrification transition to enhance preparedness for EVs and drivers.

Several studies investigated the impact of the existing infrastructure on demand for EV charging stations by enhancing methodologies and developing model architectures. Pagany et al. (2019) proposed a positioning method based on user destination. The location was determined by the number of vehicles in the area, the number of drivers, the activity time, and other factors. Due to the small number of EV users, the fossil fuel vehicle data was tracked and assumed that EV users had the same vehicle usage habits. Su et al. (2018) developed the Agent-CA model to simulate the EV driving process as well as evaluate the EV charging load and random traffic conditions and predict the size and location of the charging stations. A software called CRUISE was used to calculate the power consumption under different conditions. The Monte Carlo method was implemented to calculate the charging demand, which was shown in heat maps, so as to evaluate the dynamics of EV charging loads and random traffic conditions, and design different strategies to reduce charging time. This Agent-CA model is limited to small scale short-distance trips only. Huang et al. (2016) created a model to design and locate charging stations with three different scopes (work, shopping, and dining). The authors used traffic analysis zone and polygon segmentation techniques to optimize model accuracy. By classifying the three levels, the charging speed and price were calculated to improve the utilization rate, using ArcGIS. Ge et al. (2011) considered using the grid partition method to partition regions, and a genetic algorithm to analyze the traffic density and the capacity of charging stations to predict the optimal locations. However, the traffic density of road network was not considered in the region division part, leading to a local optimal solution and not a global optimal solution. Based on demand priority and the usage of the existing gas station, Wang et al. (2010) designed a solution algorithm to develop charging stations. The priority of charging station was deployed according to the busy condition of the road section, but the demand between a gas station and EV charging station was assumed to be the same.

Based on trip data, many studies have tried to simulate scenarios or analyze requirements in a more direct way. Gan et al. (2018) used the Voronoi Diagram to divide the urban area and studied the trip data of users transferring bicycles in the city to redefine the city's functional zones. Using trip-based data, the behavior of ending the shared bicycle trip and changing to another bicycle to continue riding was detected. By researching this phenomenon, a more reasonable distribution of city functional areas was redesigned and proposed. In order to solve the costly problem of monitoring network-wide traffic dynamics with the link resolution, a probabilistic framework to estimate network-wide link travel time with trip-based data from automatic vehicle identification detectors was studied in Zhang et al. (2018). With the help of the accuracy of trip-based data, the travel time of each trip was allocated at a lower cost, and the average link travel time within the network was estimated online accordingly. Leclercq et al. (2017) studied on-street parking search according to the trip-based aggregate dynamic traffic model. According to trip-based data, the behaviors of different driver categories were simulated, and the relationship between travel distance to park and the parking occupancy was studied based on the parking strategy, starting point and destination data. Gong et al. (2008) modeled the trip-based data of traffic information to estimate the driving cycle of the power management optimization of plug-in hybrid EVs and used the dynamic programming algorithm to strengthen the charge-depletion control. Through the simulation experiment, compared with experiments that were not based on historical data, historical data improved the accuracy of battery management optimization.

In view of the above, it can be concluded that most previous studies only used scenarios in short-distance city level trips, one-way trips, and existing infrastructure within the city limit. This highlights the need for a more realistic simulation framework that takes into account long-distance, round trips and charging infrastructure on a wider scale in order to overcome range anxiety.

2.6 Review of Previous Work Soliciting Stakeholders' Views about Electrification

The deployment of charging infrastructure is a topic with high uncertainty to date, as both the public and private sectors have been involved in the provision of charging infrastructure and the roles of the different actors in this market is not clear (e.g., Hall & Lutsey, 2017; Nigro & Frades, 2015). Santos and Davies (2020) examined the responses from 143 participants in Germany, Austria, Spain, the Netherlands, and the UK who were asked to rate how positively or negatively a series of campaigns and approaches would influence purchasing of EVs. The results showed improvement of charging infrastructure, purchase subsidies, pilots/trials/demonstrations, and tax incentives as the most positively viewed incentives with other proposed incentives, such as differential taxation or public transport policies having fewer positive responses from the survey participants. In many cases, the survey subjects noted that a lack of existing strategies and infrastructure in their country or region triggered negative responses to the questions rather than a lack of belief in the system itself.

Wolbertus et al. (2020) used a quantitative methodology, the Q-methodology, which is based on qualitative inputs, in order to understand stakeholders' perspectives on the EV charging infrastructure in the Netherlands. Researchers revealed their main ideas and perspectives for the future of charging infrastructure by compiling the responses of 39 representative stakeholders of the EV ecosystem. The results of the interviews highlighted the policy importance, the need for an open, smart, fast, and wired charging network.

Zarazua de Rubens et al. (2020), in an effort to better understand the challenges around the EV socio-technical system, investigated infrastructure and business models around EV technology in multiple Nordic countries (Sweden, Denmark, Norway, Iceland, and Finland). Qualitative data was collected from semi-structured interviews with 257 participants from different stakeholder groups, such as national and local government, research, utilities and private sector manufacturing, service and information technology companies. The responses were analyzed to study patterns and common ground on barriers to EV adoption and use. The results of the interviews are presented in the study through four main sections: fossil fuel favoritism, mad about maintenance, supply chain, and charging concerns. These four sections delve into the issues around unfavorable manufacturing processes, marketing, sales and after-sales strategies, maintenance of EVs, supply and manufacturing issues, and charging infrastructure respectively. The paper aims to provide evidence of unfavorable EV business models and study both examples and impacts of this poor infrastructure across different industries and different countries. Finally, the paper discusses policy recommendations and the need for improved infrastructure to meet decarbonization goals.

Earl and Fell (2019) attempted to understand the role of EV manufacturers in the transportation electrification process by interviewing 11 representatives of the industry. Interviewees saw high potential for innovative grid management approaches with higher adoption rates of EVs but maturity and time for the market is necessary. Additionally, the importance of interrelationships and coordination with other main stakeholders of the EV ecosystem is needed and public sector should facilitate those connections.

Table 2.3 presents a list of research studies that focus on interviews of major stakeholders of the EV ecosystem. As can be seen, there is limited literature on the topic and existing studies are based on areas outside the U.S. Most of the studies mainly investigate the barriers to EV adoption without focusing on the structural challenges and the interrelationships between different stakeholder groups. Finally, certain topics regarding electrification such as the impact of EV adoption on highway revenue, the impact on the grid, and renewable energy integration remain unexplored through the interviews.

2.7 Impact of EVs on Highway Revenue

There is a wide variety of potential governmental and private revenue sources for highway finance, including user fees that are the primary source of highway infrastructure financing at the state and federal levels (Khan & Becker, 2019). In the U.S., revenue generation by the states has traditionally been based on user fee revenue sources for transportation funding such as vehicle registration fees, tolls and state and federal gasoline and diesel taxes, also known as motor fuel taxes, which constitute the largest percentage of revenue, ranging from 29% to 60% of each state's revenue (Varn et al., 2020).

The major impact of road-user charges on the road infrastructure funding has been highlighted in numerous

TABLE 2.3
List of research studies based on interviews of EV ecosystem stakeholders

Authors	Study Area	Number of Participants	Data Collection/Methodology	Objective
Santos & Davies (2020)	Germany, Austria, Spain, Netherlands, UK	143	Qualitative approach and content analysis of the text with word cloud software (Nvivo 10)	Examine the impact of a range of incentives for the uptake of EVs
Wolbertus et al. (2020)	Netherlands	39	Q-methodology implementation with representative stakeholders from the EV ecosystem	Reveal stakeholders' perspective on the future of EV charging
Zarazua De Rubens et al. (2020)	Denmark, Finland, Iceland, Norway, and Sweden	227	Semi-structured expert interviews with transportation and electricity experts	Investigate the challenges of EVs focusing on their current and future business implications
Earl & Fell (2019)	UK	11	Semi-structured expert interviews with EV manufacturers active in the UK	Determine the perceptions on the market potential for demand-side flexibility of electricity system by using EVs

earlier studies. For example, Varma and Sinha (1990) pointed out the importance of highway user charges, particularly in the form of fuel taxes for highway transportation infrastructure and the authors explored different practices of user charges in the U.S. The authors also described state-by-state differences in revenue generation, proposed a potential user charge structure incorporating emerging developments and discussed the impact of emerging alternative fuel vehicles on taxation and revenue. Based on that study, the elements included in future user taxes are titling and registration fees, tolls, weight-distance taxes and pollution charges. Berg (1990) discussed a number of considerations related to highway financing, including various taxation and revenue policies. The author emphasized the issue of cost allocation for all the highway use tax schemes and examined the factors that influence revenue sources. Among these factors, the promotion of alternative fuels was extensively discussed as a challenge that could affect the revenue productivity of transportation taxes. A variety of reports have pointed out concerns related to the decreasing sources of transportation funding (e.g., American Planning Association, 2010; ASCE, 2017; Coussan & Hicks, 2009). Some studies have called for gasoline tax increases and other measures to meet the transport infrastructure needs (e.g., AASHTO, 2007; American Planning Association, 2010; National Surface Transportation Infrastructure Financing Commission, 2009). Additionally, there are studies that underscored the disadvantages of the gasoline use tax, particularly in terms of its feasibility in funding opportunities, given the adoption of highly fuel efficient vehicles (e.g., Krishen et al., 2010; Watts et al., 2012). Pricing schemes for fees such as congestion charging fees (e.g., Hensher & Puckett, 2007) and access toll roads (Swan & Belzer, 2010) have also been examined and proposed.

As can be realized, the value of certain revenue sources for transportation funding is affected by a combination of factors such as the rising fuel efficiency of vehicles, inflation and a shifting federal-state cost share on infrastructure investments (Varn et al., 2020). More specifically, the transportation sector is moving towards electrification and states support increased EV use. Achieving higher EV market shares is fundamental to the decarbonization of transportation and captures the advantages of oil dependency, reduced local pollution and noise emissions. However, large scale use of EVs poses challenges to the taxation system and thus, to the transportation funding scheme, as has been acknowledged by past and recent research works (e.g., Brown et al., 2020; Ford, 1995; Valenta, 2013; Varn et al., 2020).

Several studies have evaluated revenue impacts of EVs or alternative fuel vehicles. These studies have focused mainly on light duty alternative fuel vehicles, and lessons can be learned by reviewing the assumptions, methods and fee or policy structures that have been used and found. Short and Crownover (2021) explored options for charging EV users for their use of public roadways in the U.S. The authors were based on data for electric automobile, including EV sales projections, fleet size and assumptions for conventional vehicles' efficiency. The cumulative impact of electric cars on the Highway Trust Fund revenue from 2020 to 2029 was estimated (around $4.3 billion cumulative revenue loss) and approaches to taxing EV users for road use were discussed. These approaches included state-level registration fees, vehicle-miles traveled fees and electric fuel taxes. Focusing on the electric fuel tax, the authors estimated that a tax of $0.021/kWh is an equivalent charge to what is paid through the existing federal fuel tax.

Xu et al. (2020) developed a method to estimate proper annual registration fees for passenger electric and plug-in hybrid EVs in Alabama. Based on data on vehicle annual mileage traveled, average fleet fuel economy, and gasoline excise tax per gallon, the authors found that the change in fuel efficiency of gasoline vehicles could have a greater impact on the gasoline revenue loss than the advent of electric and hybrid EVs. Additionally, an additional \$181 registration fee for EVs (\$200 in total) and \$90 for plug-in hybrid EVs (\$100 in total) will be sufficient to cover the gasoline tax revenue loss per fiscal year. These fees will lead to an additional revenue generation of \$333,040 and \$176,040 in 2019 for 1,840 EVs and 1,956 plug-in hybrid EVs, respectively. This way, in 2023, the total amount of additional registration fees will generate up to \$1.3 million for highway maintenance.

A report by Plug In America (2020) includes a qualitative discussion about the potential of EV registration fees, mileage-based fees and fees per unit of electricity to fund road construction and repair. According to this report, EV registration fees are not an appropriate solution since they can slow adoption and the pace of EV cost reductions. Road fees on electricity can pose challenges associated with home charging because it is difficult to quantify the electricity consumption due to the EV and thus, dedicated meters or smart chargers would be needed. The mileage-based fee has a greater potential that can also be sustainable even with the greater use of ridesharing or carsharing systems. This funding mechanism can include congestion pricing to address potential concerns for rural, urban, and low-income drivers.

Ricciuti (2020) evaluated the impact of light duty EV sales on lost gasoline tax revenue for 50 states in the U.S. over a 10-year period (2019–2028) and provided recommendations for gasoline tax revenue recovery. The authors used the percentage of automobile registrations per state relative to the projected EV sales for the entire country to estimate EV sales by state. They inserted the projected EV sales by state in conjunction with data on current tax rates by state, annual mileage, and mileage consumption into the lost gasoline tax revenue function. The revenue loss per year by state depended on the tax rate that would have been applied to the unpurchased gallons of gas. The analysis results indicated that in all 50 states, the lost gasoline tax revenue per year by state could be overcome by imposing a yearly EV surcharge that is approximately 550 times the current sales tax per gallon. These yearly surcharges vary from \$80 (Alaska) to \$320 (Pennsylvania).

Harto and Baker-Branstetter (2019) compared existing and proposed annual EV fees with gasoline taxes, and they estimated the effectiveness of annual EV fees to increase highway funding revenues in the U.S. for 2 years: 2020 and 2025. To compare existing and proposed EV fees, the authors calculated a maximum justifiable fee as the highest level of an EV fee that could be established in a state and provide the same revenue as the average conventional/gasoline vehicle. The study results showed that EV users will need to pay double, triple or more compared to the amount they would have to pay for gasoline taxes for a new gasoline vehicle. Additionally, the authors found that the proposed EV fees will raise very little revenue to support highway construction and maintenance (0.04% of current state highway funding).

Jia et al. (2019) evaluated the fuel tax revenue impact of EV adoption in Virginia. Focusing on light duty battery and plug-in hybrid EVs, the study used vehicle registration data and applied a county-level EV ownership model (bivariate linear mixed count model) to predict EV counts in each county of the state from 2016 to 2025. To account for uncertainty of fuel economy improvements, they created scenarios combining different levels of vehicle average fuel economy and adoption levels. For each of these scenarios, the fuel tax revenue impacts were calculated for ICEs, battery, and hybrid EVs. The authors also examined the spatial distribution of fuel tax revenue. The results showed that the statewide fuel tax revenue will decrease in 2025 by 5%–19%, relative to 2016 receipts. Furthermore, the spatial distribution of revenue showed that by 2025, vehicles in rural areas are likely to pay 28% more in fuel taxes compared to those in urban areas.

Iowa DOT (2018) sponsored a study that examined existing and potential funding mechanisms in order to develop recommendations to lower administrative costs, promote equity, yield no net change in road use tax fund revenue and to promote a constitutional provision that ensured the spending of some collected revenue on road and bridge maintenance and improvement only. The Iowa report considered light and medium duty vehicles. The study was based on scenarios of low, medium, and high forecasts of light duty EVs for 2018–2040 derived from reports such as the *Energy Information Administration, Bloomberg New Energy Finance*, and *Energy Innovation: Policy & Technology*. Assumptions were also made for values for miles driven per year, average fuel economy and fuel tax rate. Medium duty EV forecasts were based in part on forecasted passenger EV growth but were also adjusted to account for later availability of medium duty EVs and faster turnover of such vehicle fleets. The results showed that lost road use tax fund collections would be approximately \$317K in the base year (2018). This impact is forecasted to substantially increase from \$40 to \$240 million by 2040 depending on the growth of the EV market. Based on these results, the Iowa DOT proposes and qualitatively describes three mitigation strategies that include adding a per kilowatt hour excise tax for charging at non-residential charging locations, adding a supplemental registration fee for passenger EVs and adding a hydrogen fuel excise tax.

Chamberlin et al. (2016) estimated statewide fuel tax revenue in Utah by 2040, assuming three EV market penetration rates (1%, 2%, and 32% of new vehicle sales). The vehicles considered were battery, plug-in hybrid and hybrid light duty EVs. The authors were based on the Energy and Emissions Policy Analysis Tool from the Federal Highway Administration in order to estimate the vehicle miles travelled, the fuel consumption and fuel tax revenues. This study concludes that the fuel tax revenue will decline by 29% in 2040 compared to 2010.

Jenn et al. (2015) explored how different vehicles could change the annual fee collected on a marginal basis and how alternative fuel vehicle adoption would affect the revenues at a state-by-state and national level. Their study focuses on light duty battery and plug-in hybrid EVs and is based on specific popular EV models (Toyota Camry, Honda Civic, Ford F-150, Nissan Leaf, Toyota Prius, Chevrolet Volt). The lifetime fees of these EV models are calculated, including use (fuel tax) and fixed (title, registration, inspection) fees. The authors use projected vehicle sales from the 2013 Annual Energy Outlook report of the Energy Information Administration (EIA, 2013) in order to calculate aggregate funding deficits. The study also attempts to estimate alternative policy options for EVs based on charging an annual registration fee, a use fee tax or a charging tax on electricity. The results suggest that the total annual revenue generation decreases by about $200 to $900 million by 2025, depending on the level of adoption of EVs. To overcome the decreases in revenue generation, the authors propose a flat annual registration fee at 0.6% of the vehicle's manufacturer suggested retail price or a 22¢/mile fee or a 4.5¢/kWh tax.

Schleith (2015) investigated the impact of light duty battery and plug-in hybrid EVs on federal and state highway revenue sources at a national scale. The authors assumed three scenarios of EV sales growth rates from 2016 (5%, 10%, and 15%) and used data on vehicle sales, annual average mileage and gasoline mileage to find the average gasoline tax paid per vehicle. Calculations for EV sales growth rates of 10% show that the revenue loss would account for drop in the gasoline tax of 1% in 6 years, 5% in 19 years, and 10% in 25 years. Although this report focuses on fuel tax revenue, it also discusses mechanisms such as replacing or adding to the fuel tax a vehicle mile traveled tax accounting for the vehicle type and weight as well as the location and time of its use or requiring additional highway usage tolls.

Vasudevan and Nambisan (2014) examined the impacts of Corporate Average Fuel Economy regulations as well as light duty hybrid and battery EVs and light truck fleet adoption on transportation funding at the U.S. national level. The New Sales Survivability model is applied and new vehicle sales data and vehicle survivability data from 1980 to 2005 were used to estimate the vehicle fleet, vehicle miles traveled by fleet mix and fuel-tax-based revenue projections for 2010–2025. Given that battery and hybrid EV sales increase by 20% annually from the base year (2009), the results project that the federal fuel tax revenues will decrease by 37% by 2025.

The Oregon Department of Transportation conducted studies to explore various funding ideas and examined potential implementation issues, including the case of "all-EVs." In Whitty (2007), the Oregon Mileage Fee Concept was examined. This program charges all automobiles approximately 1.8¢ per mile but approximately 40% of the revenue is paid to third party technology companies that facilitate the program and not to the state. The study did not calculate the impact of EVs on state revenue but mentioned options for all-EVs to pay a mileage-fee. The most viable option involves wirelessly uploading mileage-based fee data through electric utility meters for billing via the monthly electric bill. This system would have cost savings from integrating it onto an existing billing system and would be convenient for the user who can pay the electric bill as before with the addition of the mileage fees. Other less desirable or viable options included (1) cellular uploads of mileage fee data to centralized data and billing centers which is expensive or (2) uploading mileage data and collect the fees during vehicle registration which may be infeasible for broad scale implementation to all vehicles due to the infrequency of registrations and/or the avoidance of re-registrations. In Jones and Bock (2017), the results of the Oregon Road Usage Charge Program are presented. Among other options for conventional vehicles, this program also examined funding ideas for EVs, including flat fees, taxes on electricity for vehicle use, and fees based on distance traveled. The most important learning of their test program is that charging drivers by the mile is possible and can work. Certain implementation issues can occur though, including the difficulty of communication between mileage reporting devices and EVs.

These previous studies examined the revenue impacts of EV adoption either qualitatively or under various scenarios for light duty vehicles mostly. However, the reality is that (1) quantitative research is also essential to easily understand and describe the magnitude of a situation to decision-makers and (2) advancements in EV technology are not limited to light duty vehicles only. Several vehicle manufacturers have indicated plans to introduce medium and heavy duty commercial EVs to the market soon. These vehicles, like light duty EVs, are expected to have significant negative impacts on highway revenue generation due to the reduced use of diesel or gasoline fuel. Additionally, the majority of the past studies had focused mainly on policies related to fuel tax while transportation funding is also based on more sources besides this source, and most studies did not address all alternative mechanisms such as user fees for electricity use and/or vehicle miles travelled-based fees with the exception of Jenn et al. (2015) and Short and Crownover (2021) that provided quantitative information. Thus, the review of the literature shows the need to present well-documented and more realistic models to develop highway revenue estimates in support of policy making.

2.8 Summary

Different supply and demand aspects of EVs were discussed in this chapter to provide the groundwork for identifying any gaps in infrastructure and needs from the potential growth of EV demand. By examining the existing literature, knowledge was gained on the different types and typical ranges of EVs (hybrid, plug-in hybrid, and battery EVs) as well as on the different charging methods. In particular, there are five main charging methods: stationary plug-in charging, stationary wireless charging, dynamic conductive charging, dynamic wireless charging, and battery swapping, which all differ in terms of how the electricity is transferred, charging times, maturity level, applicable vehicles and installation costs. When choosing a charging method to deploy, it is also imperative to consider EV driver's value of travel time (VOTT) to charge a vehicle. High levels of variance to VOTT exist, spanning from $5/hr to $50/hr for private vehicle drivers while VOTT is estimated as the value lost from not driving for commercial drivers. Furthermore, this chapter presented studies on EV demand forecasting as well as available forecasting tools that can be used for an accurate prediction of EV demand. There is a wide range in the projections of EV demand, depending on the location, policies and availability of charging infrastructure and most projections refer to light duty vehicles. Additionally, most available forecasting tools consider global, regional, or national scales. Studies that explored the impact of inadequate EV charging stations were also reviewed and most of them only used scenarios in short-distance city level trips, one-way trips, and existing infrastructure within the city limit. Previous work on stakeholders' perspectives regarding electrification was discussed and as shown, it mainly includes international studies. Furthermore, existing research mainly focuses on examining the barriers to EV adoption; certain topics, such as the interrelationships among different stakeholder groups, the impact of EV adoption on highway revenue, and the impact on the grid are not adequately explored. Moreover, the large-scale adoption of EVs is expected to affect highway revenue and as shown from a review of existing studies, this issue has been mostly examined either qualitatively or under various adoption scenarios for light duty vehicles.

3. VEHICLE ELECTRIFICATION IN INDIANA

This chapter examines current trends on electrification and current electrification projects within the Indiana (Section 3.1) as well as the current state of Indiana's electric grid (Section 3.2). A summary of the chapter is provided in Section 3.3.

3.1 Current Trends and Statistics for EVs in Indiana

In Indiana, the total light duty EV market reached around 3% (including battery electric, hybrid electric and plug-in hybrid EVs) in 2019 (Alliance for Automotive Innovation, 2022). Figure 3.1 shows the battery and hybrid electric light duty market share in Indiana from 2013–2019. In particular, the total EV share in 2019 was 0.68% for battery electric and 2.39% for hybrid EVs. This share in 2019 is higher that the share of 2018 by 0.09% but still lower than that in 2013 by 0.81%. Additionally, the majority of EVs are hybrid followed by battery EVs, a trend that is similar for all the years. The vehicle registration counts of all EVs in Indiana was 3,030 vehicles in 2018 (U.S. Department of Energy, 2018). The electric commercial truck market is difficult to track. In general, the market share of commercial electric trucks has not kept pace with passenger vehicle market share and therefore, adoption related data in this industry is important. For long-haul trucking in particular, the use of greener technologies is still well at a nascent stage in the U.S. (Loudin, 2020).

There is limited information regarding future trends for EV market penetration in Indiana. A consulting firm conducted a study for Duke Energy and evaluated the benefits of increased penetration of plug-in EVs in the state of Indiana (M.J. Bradley & Associates, 2018). The analysis projects economic benefits of EVs for two different EV penetration levels between 2030 and 2050. These scenarios include a "business as usual" scenario of modest EV penetration that is based on the Energy Information Administration's current estimates of future EV sales (EIA), and a more aggressive scenario based on the EV penetration that would be required to get the state onto a trajectory to reduce light duty GHG emissions by 70%–80% from current levels by 2050 (80×50). According to these scenarios, EVs can reach 6% (for the moderate scenario) to 95% (for the aggressive scenario) of the registered vehicles in Indiana by 2050. If Indiana EV adoption follows the moderate EV penetration scenario, the net present value of cumulative net benefits from greater EV use in the state will exceed $3.7 billion state-wide by 2050. If Indiana EV adoption follows the aggressive penetration scenario, the net present value of cumulative net benefits from greater PEV use in Indiana could exceed $32.2 billion statewide by 2050. As noted in the study, the levels of PEV penetration in the aggressive scenario are unlikely to be achieved without aggressive policy action at the state and local level, to incentivize individuals to purchase PEVs, and to support the necessary roll-out of PEV charging infrastructure.

Indiana's EVs are served by the state's 325 public charging stations and 892 charging outlets available (U.S. Department of Energy, n.d.b). These charging stations include DC fast (52 stations) and Level 2 (273 stations). These numbers refer to charging stations with public access that can be federal or state government owned, jointly owned, local/municipal government owned, privately owned, or utility owned. The charging stations are either non-networked or networked with one of the following EV networks: ChargePoint, EV Connect, Blink, Greenlots, Tesla, Electrify America, SemaCharge, EVgo (U.S. Department of Energy, n.d.b). According to EVAdoption (2021), comparing the charging infrastructure of Indiana with the other midwest states, only Illinois performs better with 22 EVs to charger ports, while Indiana's performance is similar to Ohio's, Wisconsin's, and Minnesota's performance with values between 17 and 18 EVs to charger ports.

Several transportation infrastructure projects in Indiana involve the cooperation of national utilities and state agencies to accelerate the adoption of EVs and explore green transportation technologies.

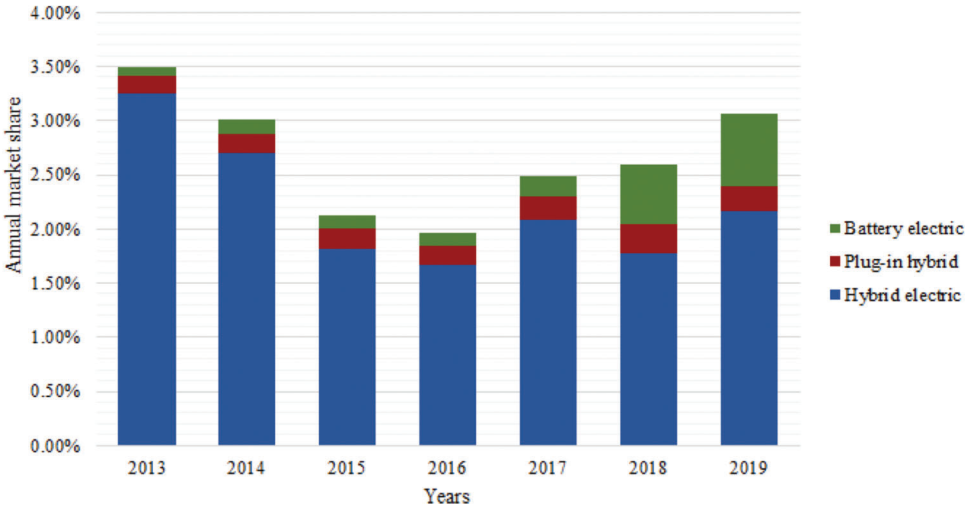


Figure 3.1 Market share of EV light duty vehicles (2013–2019) (Alliance for Automotive Innovation, 2022).

The Indiana Energy Association (IEA) has requested the maximum amount allowed under the Volkswagen settlement federal trust document to be allocated to invest in the EV infrastructure in the state (15% of the total $40.9 million in funds to Indiana, or $6.15 million (Indiana Energy Association, n.d.). IEA also proposed that Indiana invest 40% of the trust fund ($14.7 million) in projects that replace diesel with EVs and in charging infrastructure necessary to operate EVs. Investments in medium and heavy duty vehicles are also proposed to promote a cleaner environment, improve health and the state's economy by promoting the EV industry (Indiana Energy Association, n.d.). Additionally, Indiana has signed the *Regional EV Midwest Coalition Memorandum of Understanding (Regional Electric Vehicle Midwest Coalition, 2021*) which aims to accelerate medium and heavy duty fleet electrification (including cooperating with energy providers to ensure sufficient electricity supply and grid resilience), to elevate economic growth and industry leadership and to advance equity and clean environment.

Different local EV projects have been initiated. IndyGo has currently 31 electric buses that are running on its express Red Line and are manufactured by the BYD company (Associated Press, 2020). There was a plan for Indianapolis to switch to an entirely electric fleet of public buses by 2035 but this is in question due to problems with range. However, there are also discussions for the Purple Line and the potential of wireless charging capabilities. The Indianapolis Airport operates nine electric buses serving passengers between the ground transportation center and long-term parking. Buses can handle about 120 miles, which give an eight to 12-hour shift (Indianapolis International Airport, 2017). Their charging time is about 6 hours. This project is supported by federal grants ($3.6 million) under the Zero Emissions Airport Vehicle (ZEV) program. Bargersville police department is among the first to implement EVs into its fleet. The fleet includes a 2019 Tesla Model 3 car (May & Clark, 2021). It has been reported that the car will save the department more than $20K over the next 6 years. In early 2019, the city of Carmel's police department began switching its fleet of patrol cars from regular gasoline powered vehicles to ford hybrid interceptors (Carmel Indiana, 2019). This will provide annual savings of nearly $400K dollars once the entire 130-car fleet is replaced. There is also a plan for 41 hybrid police patrol vehicles to be added.

3.2 Energy Supply and Demand within Indiana

3.2.1 Past Energy Consumption

In 2018 (the last year of available data), the transportation sector consumed over 500 trillion BTU (146 million kWh) of energy (EIA, 2019a). This accounted for roughly 20.5% of all consumption in the state, behind only industrial uses. In fact, transportation has been the second highest energy-consumer in Indiana since the early 1980s (EIA, 2019a).

When considering the energy supply side, renewable sources have accounted for 6%–7% of all energy consumed in the state between 2015 and 2018. This primarily comes from a mix of wind, wood and waste, and fuel ethanol sources (EIA, 2019a). When only considering the energy that is generated within the state, renewables have accounted for about 6% of all energy generated over the same time span. Wind energy has accounted for significant majority of this share (EIA, 2019a). In 2018, wind energy comprised 85% of all renewable energy generated within the state. Additionally, it is important to note that renewable generation actually fell slightly from 2017 to 2018.

There do not appear to be statistics to display regarding the energy consumption of EVs in Indiana or what percent of EV energy comes from renewable sources. However, given that there were only 3,030 registered EVs in the state (U.S. Department of Energy, 2018) out of over 6 million total vehicle registrations (FHWA, 2021), it is fair to assume that these values are currently negligible.

3.2.2 Projected Future Energy Consumption

Supply and demand projections from utility companies as well as the State Utility Forecasting Group (SUFG) were reviewed for the next two decades. While an energy surplus currently exists in Indiana, the SUFG predicts that energy demand will outpace existing resources by 2024. This forecast predicts electricity usage to grow at a rate of 0.67% per year, and peak demand to grow at a base scenario of 0.60% (low scenario: 0.35%, high scenario: 0.92%) per year. Without the addition of new energy resources, electricity demand by 2037 is predicted to outpace supply by about 10,000 MW (Phillips et al., 2019).

This report divides this electricity sales growth into three use segments—residential, commercial, and industrial use. Residential usage is expected to grow 0.45% per year, industrial at 1.26% per year, and commercial use is expected to decrease by -0.1% per year. Additionally, the 2019 SUFG forecast provides projected inflation-adjusted electric prices through 2037. It predicts prices to rise 35% through 2026 before decreasing 8% from 2026–2037 (Phillips et al., 2019).

It is important to note that the SUFG report (nor any utility report) does not mention transportation-related electricity use in its projections. This reflects the current difficulty in performing real-world projections for the impact of EVs on electric grids. This difficulty is due to the need to accurately project EV diffusion rates in the area of interest and to predict the potential use of techniques to mitigate strain on the electric grid. These include methods such as coordinated charging, energy storage at charging stations, and bidirectional charging (as mentioned in the above section on charging techniques). While there is a significant level of research into such techniques, it is still quite uncertain which of these techniques may be implemented in the future, and how they would be designed. Due to these limitations, it may be expected that real-world energy grid projections cannot accurately project the effects of EV diffusion.

As the 2019 report projects demand to exceed generation resources in the coming decade, the SUFG released a follow-up report in 2020 performing a scenario analysis of potential generation additions to meet this increased demand (SUFG, 2020). The reference scenario for this report is based on the base scenario of the SUFG 2019 report to predict what types of generation will be added and what the overall generation mix will be by 2037. Other scenarios include preventions on coal plant retirements until 2025 and 2030, low renewable energy cost, high natural gas prices, and the inclusion of an increasing carbon price. The majority of scenarios indicate that natural gas (both combined cycle and combustion turbine) will be the primary additions, followed by wind generation. Solar generation is predicted to be minimal compared to gas and wind. The two exceptions to this trend are the high natural gas price scenario, which indicates primarily wind addition, and the low renewable cost scenario, which suggests primarily wind and solar additions (SUFG, 2020).

Ultimately, the analysis projects that by 2035, renewable generation will account for 13% of generation in the reference scenario, and up to 29% of generation in the low renewable cost scenario. Coal generation is projected to account for 23%–29% of generation in scenarios without a carbon cost, but only 6%–9% when there is a carbon cost. The percent of generation that is from natural gas is project to increase but then decrease over this period (SUFG, 2020).

This report also predicts energy prices for the various scenarios. The reference scenario is the same as the base price predictions as from (Phillips et al., 2019). Nearly all scenarios track the reference projections, though the high gas price scenario results in significantly higher price forecasts. The low renewable cost scenario yields the lowest projected energy prices after 2026 (SUFG, 2020).

The most recent Duke Energy IRP (Duke Energy Indiana, 2020) provides similar trends for its own projected energy generation mix within Indiana. However, it should be noted that the public version of this IRP heavily redacts the figures and analysis that was relied upon to create their projections. One important difference to note between the Duke and SUFG projections is that most Duke scenarios project a much higher percentage of solar use and lower rate of wind use than the SUFG projections do.

Additionally, the Duke reference projection includes a more aggressive carbon price than the SUFG carbon-price scenarios. This reference with carbon price projects 35% coal generation by 2035, which is higher than the SUFG projections without a carbon price. The Duke reference scenario without a carbon price predicts 56% coal generation in 2035 (Duke Energy Indiana, 2020). In general, the Duke scenarios project a more gradual phasing-out of coal than the SUFG scenarios.

However, the general trends of the Duke Energy scenarios are similar to the SUFG scenarios. Coal is expected to play a diminished role in generation while gas is expected to make up a greater part of the mix. Additionally, it is only in the most aggressive scenarios that renewables make up the majority of the generation mix. Again, it should be emphasized that the (SUFG, 2020) and (Duke Energy Indiana, 2020) reports, as well, do not account for increased EV penetration in their projections. Thus, it should be recognized that with increased EV diffusion, energy demands will most likely be greater than projected here, and this may affect the generation mix in ways not anticipated by these reports.

3.3 Summary

Current trend and statistics for EVs in Indiana were reported and it can be concluded that (1) there is limited information regarding future trends for EV market penetration, (2) there are different projects in the state that have started to explore green transportation technologies as well as programs with the goal to accelerate EV adoption, and (3) there is difficulty in performing real-world projections for the impact of EVs on electric grids.

4. SPATIAL ANALYSIS AND GUIDANCE FOR STRATEGIC DEPLOYMENT OF EV CHARGING INFRASTRUCTURE

This chapter describes the agent-based simulation for long-distance EV trips and the spatial analysis for high energy consumption areas for EV in Indiana. The scope of the simulation and analysis is the long-distance EV trips within Indiana. The agent-based simulations demonstrate the EV long distance trips, and energy demand to identify locations where EV driving can be impaired due to the EV driving range. In all, this chapter presents the work the team developed to conduct the spatial analysis upon the strategy of deploying potential EV charging stations. It mainly includes the following two parts: (1) the simulation model used to identify EV demand and frequency of charging (Section 4.1) and (2) the GIS-integrated spatial analysis for EV infrastructure deficit areas and potential EV charging stations deployment (Section 4.2).

4.1 Simulation Model of Electric Vehicle Trips in Indiana

A simulation model has been developed to derive the EV energy demand in daily trips. While most studies have focused on modeling short-distance city level trips (Chen et al., 2022; Santa-Eulalia et al., 2011; Zhang et al., 2018), the research team uses an agent-based simulation model to simulate daily long-distance trips and determine the locations of the failed trips where the EVs run out of energy using the existing state and interstate highway corridors of Indiana. Each EV trip is designed to be an independent agent in the simulation model with unique behavior patterns and circumstances. These studies show that the agent-based simulation model is suitable for handling the complexity of numerous factors, variables, inter-dependency in the actual driving conditions and existing infrastructure systems. In this section, the study gives a comprehensive demonstration of the simulation model's workflow in Figure 4.1.

AnyLogic is a widely used tool for modeling and simulation of discrete, system dynamics, multi-agent, and hybrid systems. Its application areas include logistics, pedestrian traffic simulation, pedestrian evacuation, urban planning and architectural design, urban development and GIS information, public policy, airports. The research team chose AnyLogic to develop the simulation model since its functions and libraries are suitable to the scope of this study.

4.1.1 Data

Observing the flowchart in Figure 4.1, the EV travel demand data is the essential foundation for the simulation. Correspondingly, the Indiana Statewide Travel Demand Model (ISTDM) is utilized in this study. The ISTDM is a projection model conducted by the INDOT to provide specialized planning services for statewide projects. This model supplies the projected number of daily trips traveling between different regions. In the ISTDM, those regions are named as the traffic analysis zones. An example of the daily trip table is shown in Figure 4.2.

Since the ISTDM model only provides the trip data for 2015 and 2045, the team performs a regression analysis (straight trendline) to get the projected long-distance Origin-Destination (O-D) trip data at other years. It is assumed that the increment of trips for each OD-pair is uniform throughout the time. Three significant timelines, 2025, 2030, and 2035, are selected to

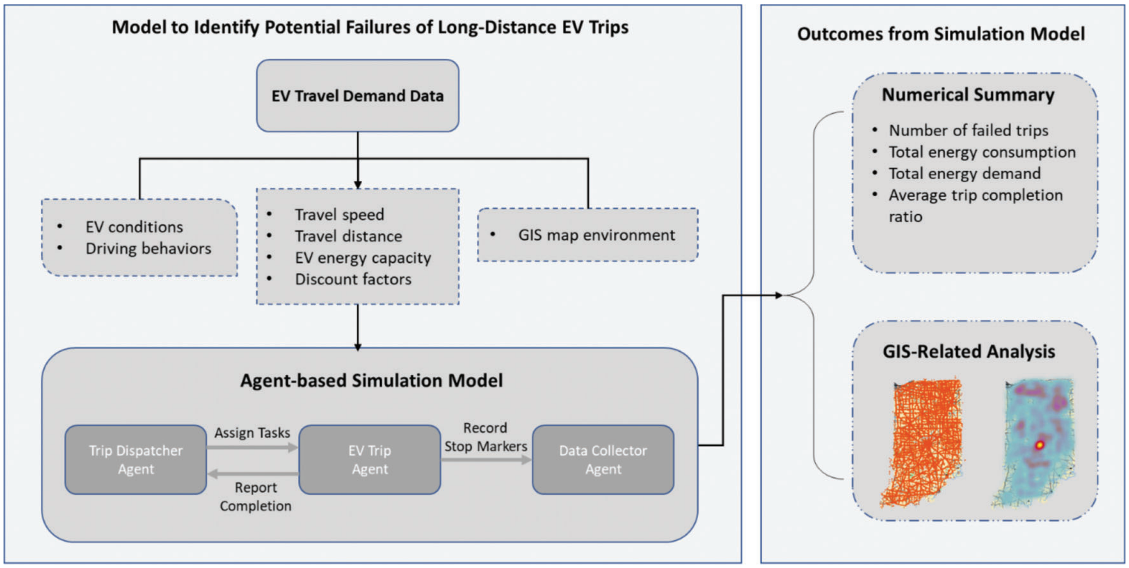
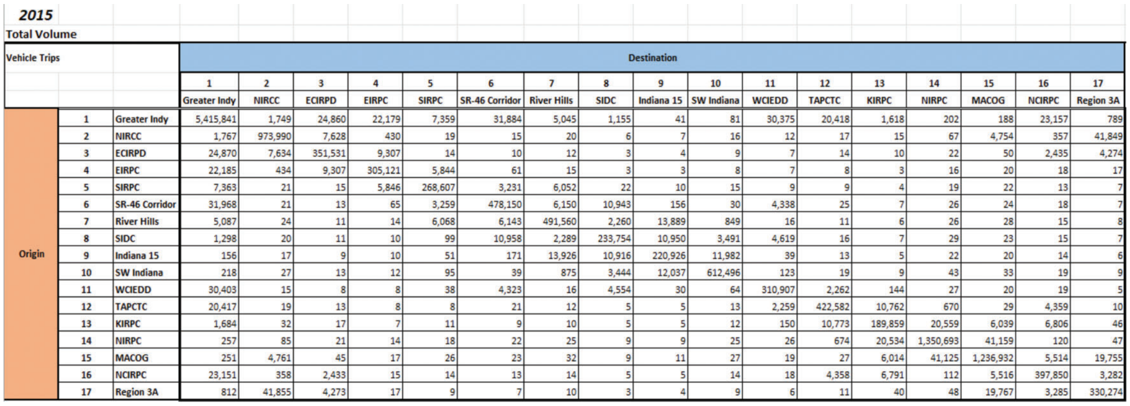


Figure 4.1 Overall flow of EV trip failure identification simulation model.



2015

Total Volume

Vehicle Trips			Destination																
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
			Greater Indy	NIRCC	ECIRPD	EIRPC	SIRPC	SR-46 Corridor	River Hills	SIDC	Indiana 15	SW Indiana	WCIEDD	TAPCTC	KIRPC	NIRPC	MACOG	NCIRPC	Region 3A
Origin	1	Greater Indy	5,415,841	1,749	24,860	22,179	7,359	31,884	5,045	1,155	41	81	30,375	20,418	1,618	202	188	23,157	789
	2	NIRCC	1,767	973,990	7,628	430	19	15	20	6	7	16	12	17	15	67	4,754	357	41,849
	3	ECIRPD	24,870	7,634	351,531	9,307	14	10	12	3	4	9	7	14	10	22	50	2,435	4,274
	4	EIRPC	22,185	434	9,307	305,121	5,844	61	15	3	3	8	7	8	3	16	20	18	17
	5	SIRPC	7,363	21	15	5,846	268,607	3,231	6,052	22	10	15	9	9	4	19	22	13	7
	6	SR-46 Corridor	31,968	21	13	65	3,259	478,150	6,150	10,943	156	30	4,338	25	7	26	24	18	7
	7	River Hills	5,087	24	11	14	6,068	6,143	491,560	2,260	13,889	849	16	11	6	26	28	15	8
	8	SIDC	1,298	20	11	10	99	10,958	2,289	233,754	10,950	3,491	4,619	16	7	29	23	15	7
	9	Indiana 15	156	17	9	10	51	171	13,926	10,916	220,926	11,982	39	13	5	22	20	14	6
	10	SW Indiana	218	27	13	12	95	39	875	3,444	12,037	612,496	123	19	9	43	33	19	9
	11	WCIEDD	30,403	15	8	8	38	4,323	16	4,554	30	64	310,907	2,262	144	27	20	19	5
	12	TAPCTC	20,417	19	13	8	8	21	12	5	5	13	2,259	422,582	10,762	670	29	4,359	10
	13	KIRPC	1,684	32	17	7	11	9	10	5	5	12	150	10,773	189,859	20,559	6,039	6,806	46
	14	NIRPC	257	85	21	14	18	22	25	9	9	25	26	674	20,534	1,350,693	41,159	120	47
	15	MACOG	251	4,761	45	17	26	23	32	9	11	27	19	27	6,014	41,125	1,236,932	5,514	19,755
	16	NCIRPC	23,151	358	2,433	15	14	13	14	5	5	14	18	4,358	6,791	112	5,516	397,850	3,282
	17	Region 3A	812	41,855	4,273	17	9	7	10	3	4	9	6	11	40	48	19,767	3,285	330,274

Figure 4.2 An example of the daily trip data from ISTDM in 2015.

reflect the major milestones of the U.S. electrification roadmap. Such three generated data are exactly contributed to simulate several different scenarios.

To keep the simulation consistent with the ISTDM trip data, the Indiana GIS map area in the simulation model is segmented into 17 regions, which is shown in Figure 4.3. Each colored region corresponds to a traffic analysis zone and consists of some adjacent counties. Since this study mainly focuses on long-distance trips, only the trips between different regions within Indiana are considered. For instance, average 5.4 million daily trips were made within in 2015, and these trips were excluded for the simulation model.

In addition, this study regards each trip as a round trip. The vehicle starts from the origin location, moves to the destination location, and then gets back to the origin place. For example, in Figure 4.2, given 1,749 trips from region #1 Greater Indy to region #2 NIRCC and 1,767 trips for the opposite direction per day, the smaller 1,749 is assumed as the number of daily round trips between the two regions. Thus, in the specific simulation process, 1,749 round trips between region #1 Greater Indy and region #2 NIRCC are traveled. The average daily long-distance round-trip number in 2025, 2030, and 2035 are shown in Figure 4.4.

4.1.2 Model Development

In this study, a multi-agent simulation model is developed, which includes the following three main agents: EV Trip, Trip Dispatcher, and Data Collector. These different agents are regarded as perceptive entities having the ability to react according to the current state of the simulation system. For example, the trip agent will stop if the energy is running out. Meanwhile, the message function plays a significant role in the communication process between different agents. In addition, the GIS is an essential component in designing the model. The main functions of the agents are described as below.

- The EV Trip agent is the core agent of the proposed model. It attempts to finish the trips dispatched by the Trip Dispatcher agent.

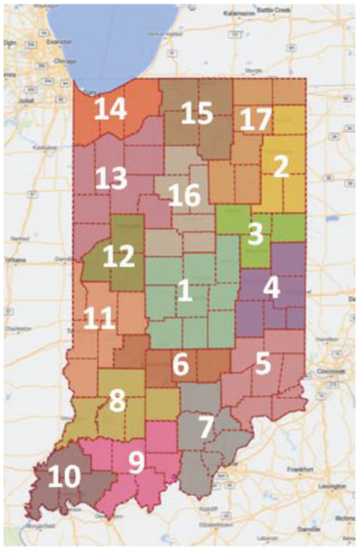
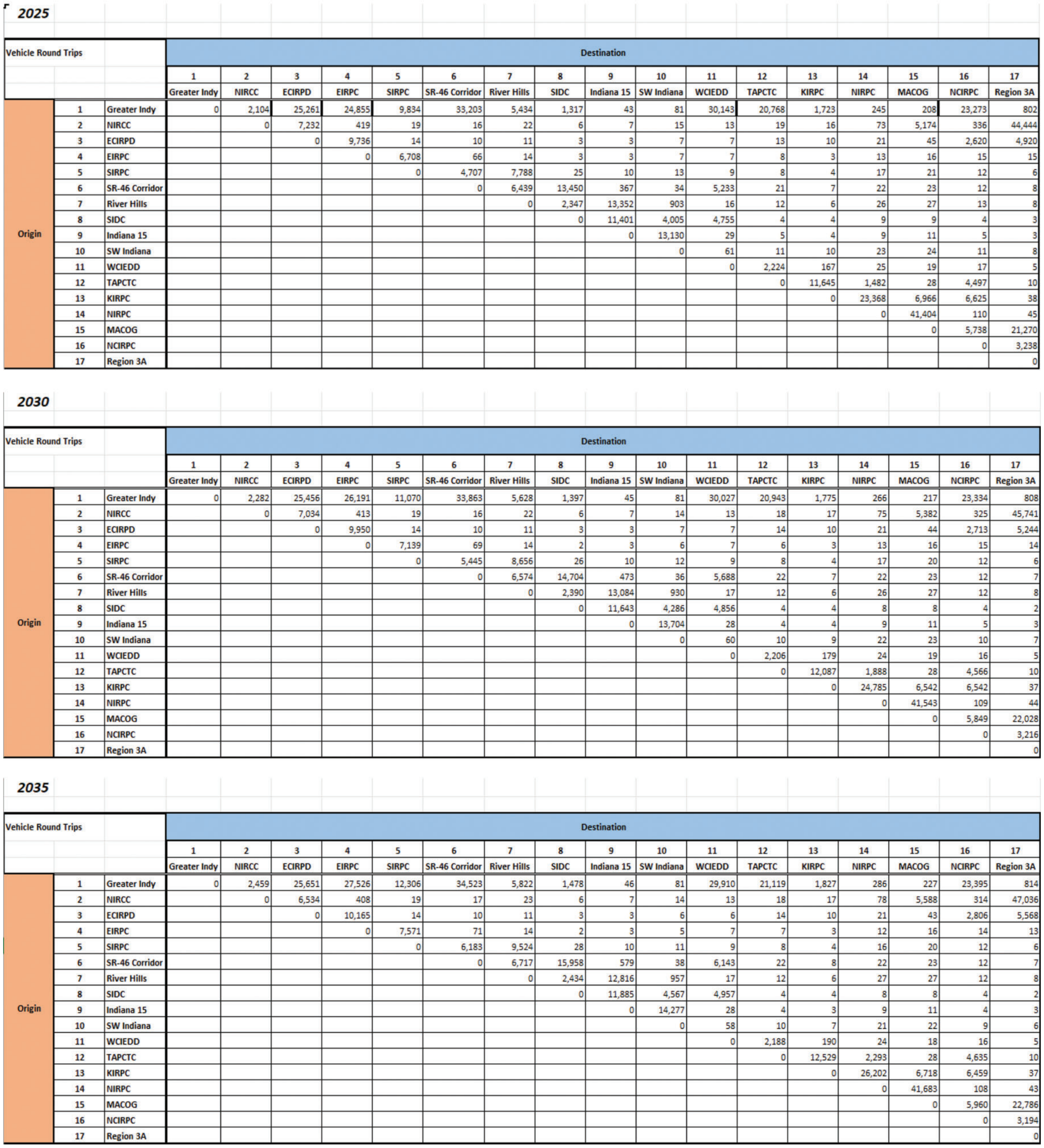


Figure 4.3 GIS map showing 17 regions that correspond to ISTDM.

- According to the trip data, the Trip Dispatcher agent is responsible for assigning trips for the EV Trip agent.
- The Data Collector agent acts as a receiver to handle and store all the information of failed trips.

Specifically, the concrete state transition charts of the three agents involved (Trip Dispatcher, EV Trip, and Data Collector agents) are shown in Figure 4.5. Note that these agents take their responsibilities and keep communicating with other agents. Some transition arrows are marked with the "mail" icon in the state charts, which means these paths can only be activated if receiving messages from other agents. For instance, the EV Trip agent will move from the idle state to the initial state when it obtains the trip information from the Trip Dispatcher agent. Then it starts to set up the trip parameters and then simulate the trips within the GIS map. A trigger function called "NoCharge" is utilized to monitor the status of every running trip, which is represented as a flash symbol. This function is invoked when the EV is running out the energy halfway, and the related information of the failure trip is sent to the Data Collector agent for the recording purpose.



2025

Vehicle Round Trips			Destination																
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
			Greater Indy	NIRCC	ECIRPD	EIRPC	SIRPC	SR-46 Corridor	River Hills	SIDC	Indiana 15	SW Indiana	WCIEDD	TAPCTC	KIRPC	NIRPC	MACOG	NCIRPC	Region 3A
Origin	1	Greater Indy	0	2,104	25,261	24,855	9,834	33,203	5,434	1,317	43	81	30,143	20,768	1,723	245	208	23,273	802
	2	NIRCC		0	7,232	419	19	16	22	6	7	15	13	19	16	73	5,174	336	44,444
	3	ECIRPD			0	9,736	14	10	11	3	3	7	7	13	10	21	45	2,620	4,920
	4	EIRPC				0	6,708	66	14	3	3	7	7	8	3	13	16	15	15
	5	SIRPC					0	4,707	7,788	25	10	13	9	8	4	17	21	12	6
	6	SR-46 Corridor						0	6,439	13,450	367	34	5,233	21	7	22	23	12	8
	7	River Hills							0	2,347	13,352	903	16	12	6	26	27	13	8
	8	SIDC								0	11,401	4,005	4,755	4	4	9	9	4	3
	9	Indiana 15									0	13,130	29	5	4	9	11	5	3
	10	SW Indiana										0	61	11	10	23	24	11	8
	11	WCIEDD											0	2,224	167	25	19	17	5
	12	TAPCTC												0	11,645	1,482	28	4,497	10
	13	KIRPC													0	23,368	6,966	6,625	38
	14	NIRPC														0	41,404	110	45
	15	MACOG															0	5,738	21,270
	16	NCIRPC																0	3,238
	17	Region 3A																	0

2030

Vehicle Round Trips			Destination																
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
			Greater Indy	NIRCC	ECIRPD	EIRPC	SIRPC	SR-46 Corridor	River Hills	SIDC	Indiana 15	SW Indiana	WCIEDD	TAPCTC	KIRPC	NIRPC	MACOG	NCIRPC	Region 3A
Origin	1	Greater Indy	0	2,282	25,456	26,191	11,070	33,863	5,628	1,397	45	81	30,027	20,943	1,775	266	217	23,334	808
	2	NIRCC		0	7,034	413	19	16	22	6	7	14	13	18	17	75	5,382	325	45,741
	3	ECIRPD			0	9,950	14	10	11	3	3	7	7	14	10	21	44	2,713	5,244
	4	EIRPC				0	7,139	69	14	2	3	6	7	6	3	13	16	15	14
	5	SIRPC					0	5,445	8,656	26	10	12	9	8	4	17	20	12	6
	6	SR-46 Corridor						0	6,574	14,704	473	36	5,688	22	7	22	23	12	7
	7	River Hills							0	2,390	13,084	930	17	12	6	26	27	12	8
	8	SIDC								0	11,643	4,286	4,856	4	4	8	8	4	2
	9	Indiana 15									0	13,704	28	4	4	9	11	5	3
	10	SW Indiana										0	60	10	9	22	23	10	7
	11	WCIEDD											0	2,206	179	24	19	16	5
	12	TAPCTC												0	12,087	1,888	28	4,566	10
	13	KIRPC													0	24,785	6,542	6,542	37
	14	NIRPC														0	41,543	109	44
	15	MACOG															0	5,849	22,028
	16	NCIRPC																0	3,216
	17	Region 3A																	0

2035

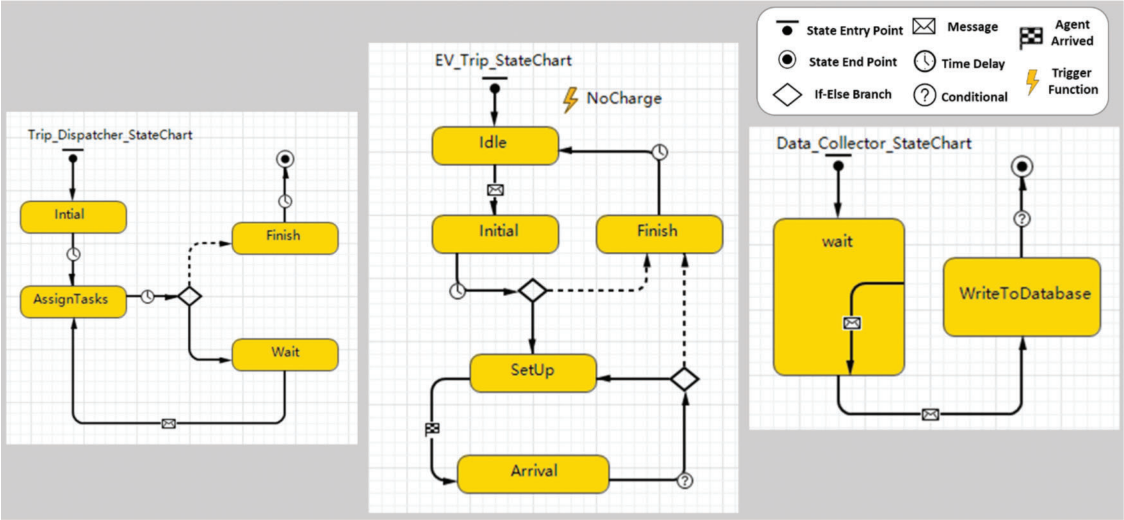
Vehicle Round Trips			Destination																
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
			Greater Indy	NIRCC	ECIRPD	EIRPC	SIRPC	SR-46 Corridor	River Hills	SIDC	Indiana 15	SW Indiana	WCIEDD	TAPCTC	KIRPC	NIRPC	MACOG	NCIRPC	Region 3A
Origin	1	Greater Indy	0	2,459	25,651	27,526	12,306	34,523	5,822	1,478	46	81	29,910	21,119	1,827	286	227	23,395	814
	2	NIRCC		0	6,534	408	19	17	23	6	7	14	13	18	17	78	5,588	314	47,036
	3	ECIRPD			0	10,165	14	10	11	3	3	6	6	14	10	21	43	2,806	5,568
	4	EIRPC				0	7,571	71	14	2	3	5	7	7	3	12	16	14	13
	5	SIRPC					0	6,183	9,524	28	10	11	9	8	4	16	20	12	6
	6	SR-46 Corridor						0	6,717	15,958	579	38	6,143	22	8	22	23	12	7
	7	River Hills							0	2,434	12,816	957	17	12	6	27	27	12	8
	8	SIDC								0	11,885	4,567	4,957	4	4	8	8	4	2
	9	Indiana 15									0	14,277	28	4	3	9	11	4	3
	10	SW Indiana										0	58	10	7	21	22	9	6
	11	WCIEDD											0	2,188	190	24	18	16	5
	12	TAPCTC												0	12,529	2,293	28	4,635	10
	13	KIRPC													0	26,202	6,718	6,459	37
	14	NIRPC														0	41,683	108	43
	15	MACOG															0	5,960	22,786
	16	NCIRPC																0	3,194
	17	Region 3A																	0

Figure 4.4 Average, daily, long-distance round-trip number for 2025, 2030, and 2035.

The algorithms for the internal logic flow of the agents are demonstrated in Tables 4.1, 4.2, and 4.3. Based on the EV trip data, the Trip Dispatcher agent first automatically classifies all the trips by the origin and destination regions. For each subgroup of trips, the Trip Dispatcher agent requests the EV Trip agent to finish the trips from the origin region to the destination region along the transportation network. The specific starting and ending locations are randomly selected within the regions to add more randomness to the model. The trips are processed one by one and travel through the fastest path. After finishing all the assigned trips, the EV Trip agent will trigger the Trip Dispatcher agent by the message function to conduct the next round of trip distribution. The Data Collector agent is always listening to the messages from the EV Trip agent to see if any trip fails halfway. Overall, the main outcome of this simulation model is a database composed of several failure trip info entries.

4.1.3 Model Parameters

Once the model's architecture is completed, the team applied 10 parameters to create various scenarios. Table 4.4 lists the parameters included in this model.



(a) Trip Dispatcher Agent (b) EV Trip Agent (c) Data Collector Agent

Figure 4.5 Internal state charts of the agents in the model.

TABLE 4.1
Algorithm of trip dispatcher agent

```
Classify all the trips based on the origin-destination pair
for all origin-destination pairs ($O_i$, $d_i$) in the trips do
    Get number of trips $n_i$ corresponding to ($O_i$, $d_i$)
    Package the trip information ($O_i$, $d_i$, $n_i$)
    Send trip information to EV Trip agent and request to handle the trips
    if receiving "finish" message from EV Trip then
        Go on to next origin-destination pair
    end if
end for
```

TABLE 4.2
Algorithm of EV trip agent

```
while receiving message from Trip Dispatcher agent do
    Extract the trip information ($O_i$, $d_i$, $n_i$) from the message
    Let $count = 0$
    while $count < n_i$ do
        Increment $count$ by 1
        Randomly pick starting and destination locations ($st$, $ed$) within regions ($O_i$, $d_i$)
        Compute the initial charging energy level and energy consumption rate
        Travel the agent from $st$ to $ed$ through the fastest path along the GIS map
        if energy is used up then
            Stop the agent
            Send both the trip information $\{O_i, d_i, st, ed, distance(st,ed)\}$ and the GIS coordinates of stop location ($lat$, $lng$) to Data Collector agent
        end if
    end while
    Send "finish" message to Trip Dispatcher agent
end while
```

TABLE 4.3
Algorithm of data collector agent

```
while receiving message from EV Trip agent do
    Extract the stop marker information $\{O_i, d_i, st, ed, distance(st,ed), lat, lng\}$ from the message
    Insert this information as a data entry into the database
    if receiving "display" message from Trip Dispatcher agent then
        break the while loop
    end if
end while
Transform the recorded database into standalone Excel file as the outcomes
```

TABLE 4.4
Input parameters for the simulation model

Input Parameters
Battery Capacity (kWh)
Energy Consumption Rate (kWh/100 miles)
EV Speed (miles/hour)
Simulation Year (2025, 2030, or 2035)
Adoption Rate (between 0%–100%)
Min Charging Ratio (between 0%–100%)
Max Charging Ratio (between 0%–100%)
User Defined Factor 1 (between 0%–1.0%)
User Defined Factor 2 (between 0%–1.0%)
User Defined Factor 3 (between 0%–1.0%)

In these parameters, battery capacity, energy consumption rate, and EV speed are the internal settings of the vehicle. In general, they will be kept static among a set of simulation cases. Refer to InsideEVs (Kane, 2022), the average battery capacity of the popular latest EV models is around 78 kWh and the average EPA

TABLE 4.5
Comparison of battery size and EPA range among EV models (Kane, 2022)

EV Model	Battery Size (kWh)	EPA Range (miles)
Audi e-tron (2021)	95	222
Chevrolet Bolt E.V. (2022)	65	259
Ford Mustang Mach-E (2021)	75.7	230
Hyundai Kona Electric (2021)	64	258
Jaguar I-PACE EV400 (2022)	90	234
Nissan LEAF e+ S (2022)	62	226
Porsche Taycan (2021)	79.2	199
Tesla Model 3 Standard Range Plus (2021)	60	263
Tesla Model S Plaid (2021)	100	390
Volvo C40 Recharge (2022)	82	260
Volkswagen ID.4 Pro (2021)	82	250
Average	77.7	253.7

TABLE 4.6
Comparison of MPGe among EV models (U.S. Department of Energy, n.d.)

EV Model	MPGe	Energy Consumption Rate (kWh/100 miles)
Audi e-tron (2021)	78	43.2
Chevrolet Bolt E.V. (2022)	118	28.6
Ford Mustang Mach-E (2021)	100	33.7
Hyundai Kona Electric (2021)	120	28.1
Jaguar I-PACE EV400 (2022)	90	37.4
Nissan LEAF e+ S (2022)	108	31.2
Porsche Taycan (2021)	78	43.2
Tesla Model 3 Standard Range Plus (2021)	142	23.7
Tesla Model S Plaid (2021)	100	33.7
Volvo C40 Recharge (2022)	79	42.7
Volkswagen ID.4 Pro (2021)	97	34.7
Average	100.1	34.6

range is about 254 miles, which can be referenced from Table 4.5. According to the information at U.S. Department of Energy (n.d.), the average Miles-per-Gallon-Equivalent (MPGe) of the popular EV models is around 100. Table 4.6 provides the details. The U.S. Environmental Protection Agency (EPA) states that it takes 33.7 kilowatt-hours (kWh) to generate the same amount of heat as burning one gallon of gasoline by way of electricity (EPA, 2019). Hence, the average energy consumption rate for EV can be calculated as 34.6 kWh/100 miles. Considering the average EV speed, the research team determined to set as 60 miles/hour, which is an appropriate value for the vehicle average speed on highway and state roads.

Regarding the other parameters, the simulation year can be chosen from three specific values, 2025, 2030, and 2035 as stated earlier. As the ISTDM only provides the trip data for general gasoline vehicles, an adoption rate (number of vehicles on the road) is needed to get the trip data for EVs. The adoption rate is based on the scenario and is directly multiplied with the trip number between various ISTDM regions to derive the required EV travel data.

Apart from exploring the impact of simulation year and EV adoption rate on the simulation results, this study also attempts to find how various driving and charging patterns affect the status of trips. Some drivers may experience range anxiety and try to keep the energy always almost full before their trip, while other drivers are not concerned about this. This causes the initial energy level for each trip to be different. To consider the diverse charging patterns, the simulation model defines two user-defined parameters: minimum charging ratio and max charging ratio. These two values are limited within a range [0, 100%] and the minimum charging ratio must be lower than the max one. The final energy level is computed via Equation 4.1.

$$Energy\ Level = Normal(Min\ Ratio,\ Max\ Ratio) \cdot Battery\ Capacity \qquad \text{(Equation 4.1)}$$

where Normal () refers to the truncated normal distribution function.

Similarly, the three user defined factors are employed to capture more complexity of the real driving situation. These factors can reflect any conditions, such as traffic delay, construction delay, battery degradation, use of in-vehicle facilities, etc. The user defined factors can be defined in the future to accommodate the specific conditions decreasing the optimum EV driving conditions. In the simulation model, the usage of the factors is expressed in Equation 4.2, where the Optimal Energy Consumption is the energy consumption rate documented by the manufactory.

$$Energy\ Consumption = \frac{Optimal\ Energy\ Consumption}{Factor\ 1 \cdot Factor\ 2 \cdot Factor\ 3} \quad \text{(Equation 4.2)}$$

Thus, users can utilize these three factors to generate diverse EV energy consumption rates for different cases. Figure 4.6 shows the layout of developed simulation model.

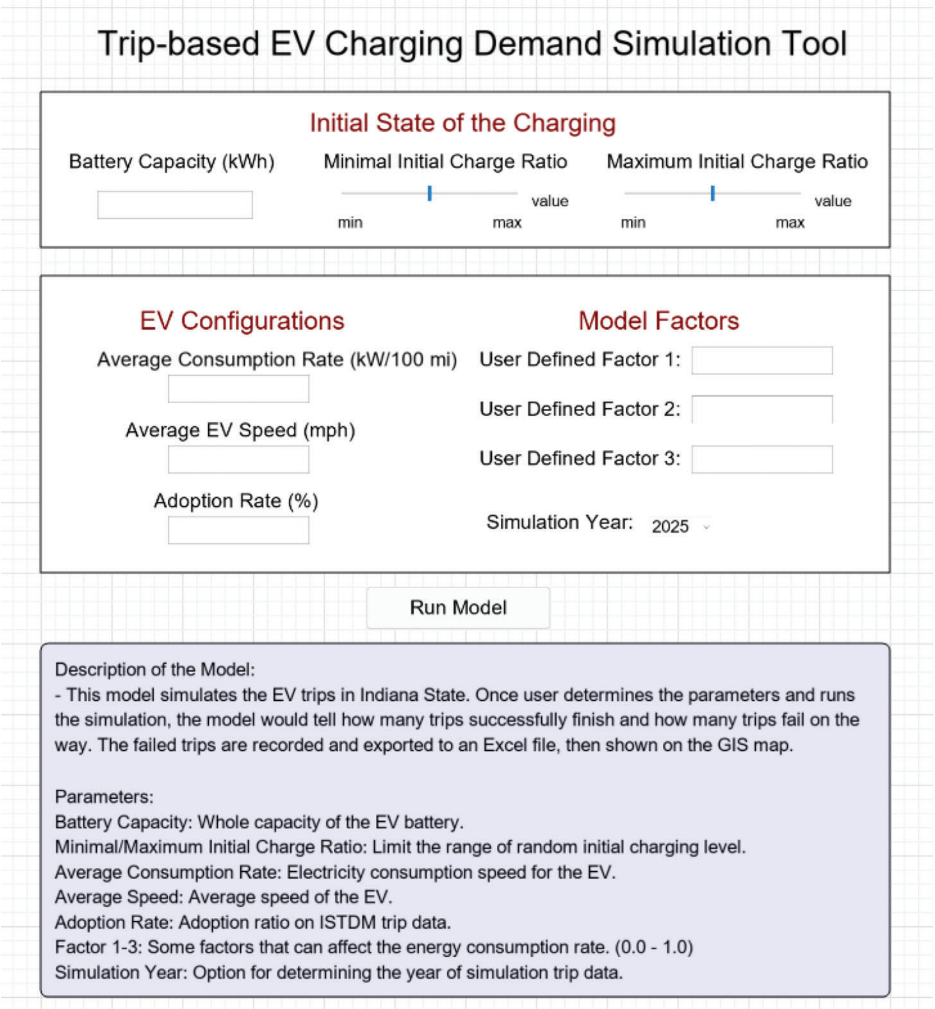
4.1.4 Simulation Scenarios

The team first established nine comparative simulation scenarios to mainly reflect the impacts of different travel demands and EV adoption levels over time. Specifically, the scenarios employ daily long-distance O-D trip data in the year 2025, 2030, and 2035. There are three different EV adoption rates in each year of the scenario. In these scenarios, the EV adoption percentages increase over time. The team defined three different increment speeds. Figure 4.7 shows the growth curve of the adoption rate over time. For the minimum and maximum initial charging ratios, the default setup interval is between 50% and 80%. Also, the random distribution function was applied to assign the initial energy level. The three user defined factors were all set as default 100% for this study.

Note the user defined factors are 100% in the above nine simulation scenarios, which may not reflect the actual EV driving conditions on the road. The team determined to perform an additional simulation (ID #10) applying the non-optimal factors. In specific, the year 2035 with a 50% EV adoption rate is chosen. The factors are determined as 0.8 (weather condition), 0.85 (traffic delay), and 0.95 (construction delay). The parameter configurations for these ten scenarios are listed in Table 4.7.

4.1.5 Simulation Data Analysis and Results

Based on the configured parameters, the model tracks the status of every trip agent during the simulation and records the essential information of every on-way failed



Simulation Year: 2025

Description of the Model:
- This model simulates the EV trips in Indiana State. Once user determines the parameters and runs the simulation, the model would tell how many trips successfully finish and how many trips fail on the way. The failed trips are recorded and exported to an Excel file, then shown on the GIS map.

Parameters:
Battery Capacity: Whole capacity of the EV battery.
Minimal/Maximum Initial Charge Ratio: Limit the range of random initial charging level.
Average Consumption Rate: Electricity consumption speed for the EV.
Average Speed: Average speed of the EV.
Adoption Rate: Adoption ratio on ISTDM trip data.
Factor 1-3: Some factors that can affect the energy consumption rate. (0.0 - 1.0)
Simulation Year: Option for determining the year of simulation trip data.

Figure 4.6 Configuration layout of simulation model in AnyLogic.

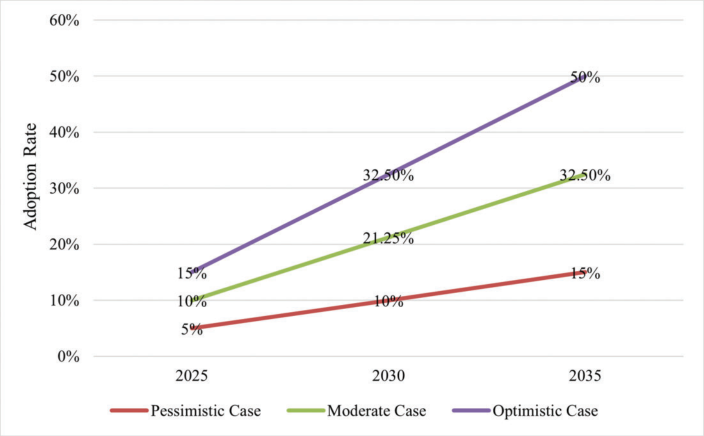


Figure 4.7 EV adoption rate variation chart over time (2025, 2030, and 2035).

TABLE 4.7
Summary of ten simulation scenarios configurations

ID	Year	EV Adoption Rate (%)	EV Battery Capacity (kWh)	EV Energy Consumption Rate (kWh/100 miles)	EV Speed (mph)	Thresholds of Initial Charging Level	User Defined Factors
1	2025	5	78.0	34.6	60.0	(50%, 80%)	1.0 for all three factors
2		10					
3		15					
4	2030	10					
5		21.25					
6		32.5					
7	2035	15					
8		32.5					
9		50					
10		50					0.8, 0.85, 0.95

trip, including the geospatial locations, energy consumption amount, etc. Table 4.8 provides a comprehensive summary of the simulation results. It is worthy to state the statistics shown in the table are all computed from failed trips. Through comparison of the first nine scenarios, it can be observed that they share a very similar pattern except the energy part, which means the trip data and EV adoption rate only influences the magnitude of failed trips. The energy gap column basically follows the trend as the number of failed trip column. The results of first nine scenarios also imply that an appropriate charging pattern can be developed to help accomplish most long-distance EV travel in the optimal driving conditions. However, it is challenging to maintain the desired conditions in daily trips. As a variant of Scenario #9, the Scenario #10 derives totally different outcomes, where the failure rate increases to 26.08% from 2.15%. It means the change of user defined factors has a significant effect on the trip accomplishment. Moreover, the 26.08% failure rate is a cause of concern in the context of EV charging facilities deployment at state highways.

4.2 Spatial Analysis for EV Energy Demand in Indiana

In addition to the statistical summary in the previous subsection, the GIS-based visualization and analysis of the simulation results are also conducted. Displaying the features as geospatial elements in the map layer is always essential and powerful. In this subsection, a demonstration of the GIS-based spatial analysis on the derived EV energy demand results in Indiana is exhibited. The main scope of the spatial analysis is to provide a visualization of the simulation outcomes from previous model and help the team explore more insights. The summary of the spatial analysis outcomes is shown in Figure 4.8.

4.2.1 Data

Since the geospatial location information (latitude and longitude) of the failed trips are also recorded in the simulation results, it is simple to draw the stop locations of the failed trips as the geospatial markers on the map. Here we call it stop marker. To feed the

TABLE 4.8
Result summary for ten simulation scenarios

ID	Number of Trips	Number of Failed Trips	Failure Rate (%)	Energy Consumption (kWh)	Energy Demand (kWh)	Energy Gap (kWh)	Average Energy Gap Per Failed Trip (kWh)
1	23,962	509	2.12	605,680.2	609,484.5	3,804.3	7.47
2	47,924	1,021	2.13	1,208,136.1	1,214,764.1	6,628	6.49
3	71,885	1,550	2.16	1,818,068.6	1,828,545.8	10,477.2	6.76
4	49,370	1,054	2.13	1,251,742.5	1,258,397.7	6,655.2	6.31
5	104,910	2,252	2.15	2,653,532.9	2,667,953.2	14,420.3	6.40
6	160,451	3,461	2.16	4,054,475.4	4,076,751.4	22,276	6.44
7	76,224	1,700	2.23	1,931,192.7	1,942,028.8	10,836.1	6.37
8	165,152	3,436	2.08	4,178,206.3	4,200,293.0	22,086.7	6.42
9	254,080	5,451	2.15	6,425,286.8	6,458,855.7	33,568.9	6.16
10	254,080	65,326	26.08	9,303,433.0	9,966,386.6	662,953.6	10.15

Note:
Energy consumption = energy consumed in simulated trips driven before failure.
Energy demand = total amount of energy required to finish all planned trips successfully.
Energy gap = energy demand – energy consumption.
Average energy gap per failed trip = energy gap/number of failed trips.

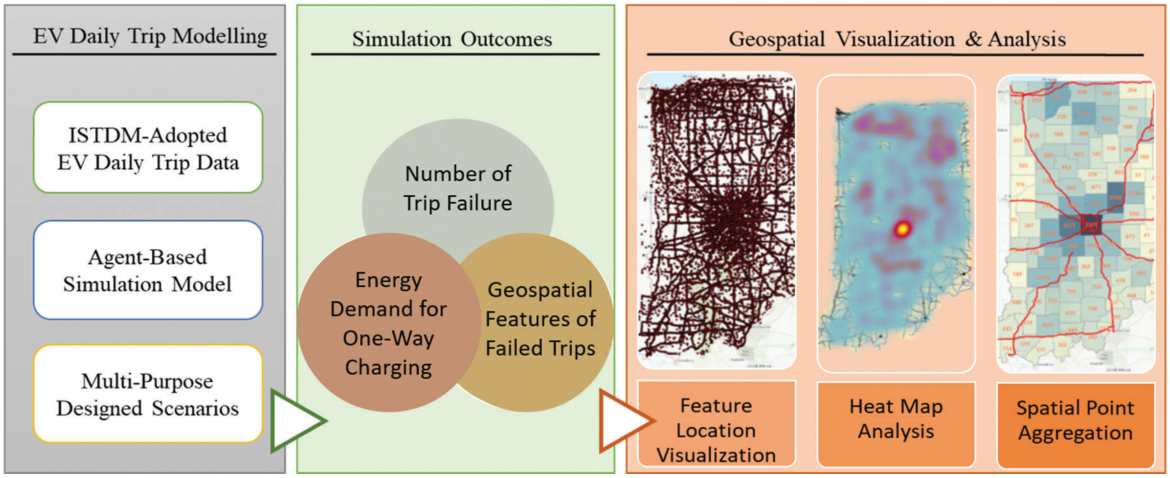


Figure 4.8 Summary of the performed spatial analysis flow.

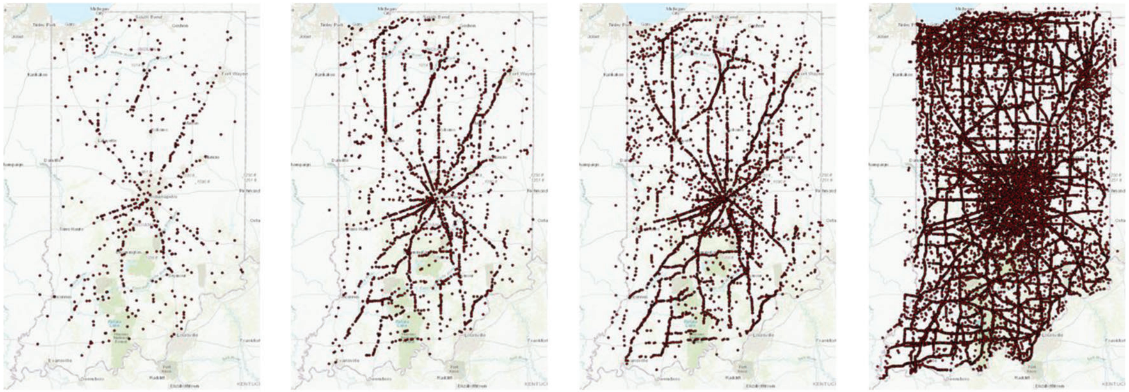
information of stop markers into the ArcGIS Pro, it requires some data transformation process. The ArcGIS Pro supports the import file formats of spreadsheets, such as MS Excel, CSV, etc. Thus, the team first filters out the useless features in the AnyLogic database and only keeps the geospatial information of the stop locations. Then the built-in function is employed to export the database into the supported MS Excel files.

Note that in the following subsections, the team chooses only four representative simulation scenarios to conduct the spatial analysis. The full list of figures and tables for all ten scenarios can be found in Appendix B. The four selected simulations are Scenarios #1, #5, #9, and #10. The first three scenarios correspond to three different level of fed trip data and the last one can be supplementary. The GIS map layers showing the stop markers (failed long distance trip locations) of these four scenarios are shown as Figure 4.9. It can be noticed the stop markers in Scenarios #1, #5, and #9 are mainly located along the primary state highway while it becomes less clear in Scenario #10.

Apart from the stop marker features above, the foundation map layer is another important element in the spatial analysis. As shown in Figure 4.9, the markers are displayed on the global topographic map, which is too general to enable discernment of specific patterns. Thus, the team considered two specific foundation map layers, Indiana County Boundary and ISTDM Traffic Analysis Region Segmentation. The two layers are included in Figure 4.10. Specifically, there are 92 counties and 17 ISTDM regions in Indiana.

4.2.2 Methodology

In general, large datasets create some unique challenges for spatial analysis. It can be difficult to interpret spatial patterns and gain an understanding of the data when the dataset contains thousands of unique features.



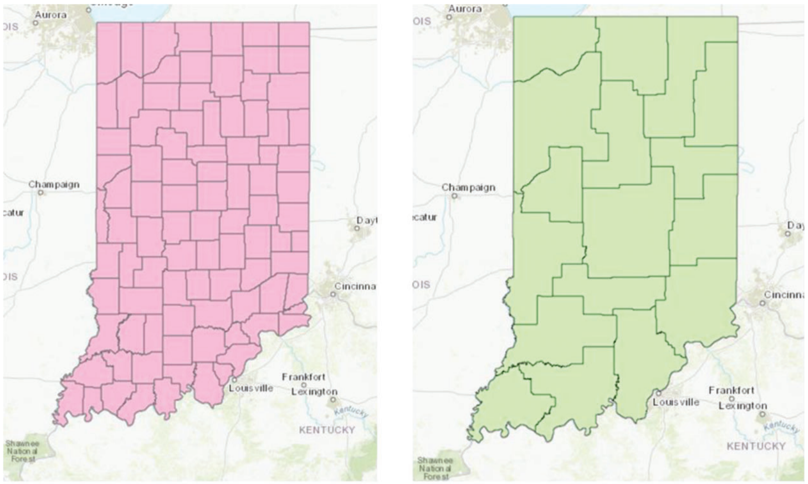
Scenario 1
2025 @ 5%

Scenario 5
2030 @ 21.25%

Scenario 9
2035 @ 50%

Scenario 10
2035 @ 50% w/ 80, 85, 95% factors

Figure 4.9 GIS map layer of EV stop markers at the failed trip locations.



Indiana County Boundary

ISTDM Traffic Analysis Region Segmentation

Figure 4.10 County boundary layer and ISTDM region layer of Indiana in ArcGIS.

Displaying the geospatial data as points is useful in a lot of situations, like for mapping the locations of hospitals in the city, or distribution centers in some regions. However, as the dataset gets larger, the ability to distinguish patterns is reduced.

For example, the stop markers of scenario #10 shown in Figure 4.9 almost covers the whole state. Obviously, the simple drawing of the markers can only provide a direct localization of the features but make it difficult to extract any regional modes. So, if such location map is not ideal, which visualization techniques can be applied? In ArcGIS Pro there are several options; here the team mainly focuses on heat map and spatial aggregation to explore the regional patterns.

A spatial point is a specific location while a geographic point is the element defined by a pair of latitude and longitude coordinates. A point is represented by a single dot or symbol on the map. While points are perfect for showing the exact location of features, they aren't always visually intuitive, especially when the amount is huge. Using smart mapping capabilities, the researchers can present the point data in more meaningful ways.

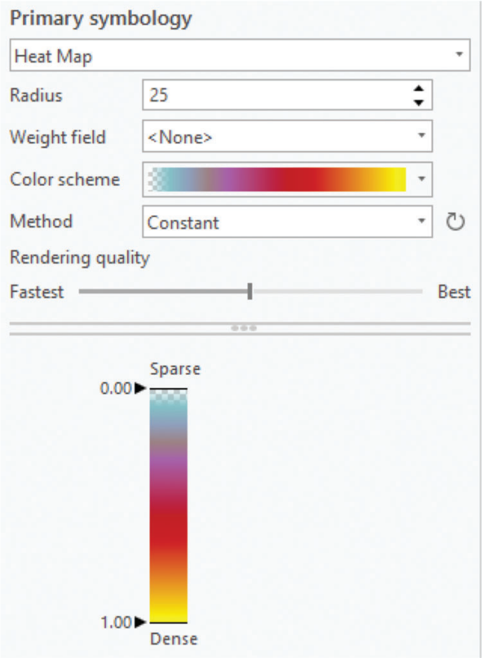
Smart mapping is a data-driven approach that lets the user choose from a variety of visualization methods. One of the available smart mapping styles for point features is heat map. Heat maps are especially effective when lots of points are to be displayed. The relative density of points on the map is calculated and rendered in a variety of color schemes to suit user needs. Typically, the color schemes range from cool colors indicating low density to hot colors indicating high density.

The following contents will provide a brief introduction on how to create the heat map of the feature dataset in ArcGIS Pro.

- Click the target feature layer in the Contents panel to reveal a set of contextual Feature Layer tabs, which is outlined in Figure 4.11. These tabs provide user the

In Beyond: <None>
Out Beyond: <None>
Transparency: 0.0%
Layer Blend: Normal
Feature Blend: Normal
Flicker: 500.0 ms
Field: No fields

Figure 4.11 Indication of feature layer tab sets on top panel in ArcGIS Pro.



Heat Map
Radius: 25
Weight field: <None>
Color scheme
Method: Constant

Figure 4.12 Parameter settings for heat map visualization.

capabilities to manipulate the properties of specific feature data.

- Click the drop-down menu of Symbology and select Heat Map from the available style options.
- Configure the parameters based on user needs. ArcGIS Pro provides six adjustable characteristics for heat maps which are shown in Figure 4.12.
- Radius is set to control the area searched when calculating the density of features.
- Weight field can be left as either None or an attribute field with numeric data to support weighted density calculation.
- Color schema specifies the color ramp that is used to display different densities.
- ArcGIS Pro provides two rendering methods, Constant and Dynamic. In the Constant method, the density is constant regardless of the map extent, which is suitable to compare density between different areas at the same map scale. Comparatively, the density is dynamically adapted to current visible features in Dynamic option.
- Rendering quality can be set to Fastest to speed up the drawing process or Best to maximize the map quality.
- Vertical color bar provides direct ways to restrict the color distribution, effectively making a “hotter” or “cooler” map.
- After finishing configuring the parameters, the heat map of selected point features will be automatically generated and displayed upon the map layer.

Another spatial analysis tool is the spatial aggregation method, which uses a layer of point features and a layer of polygon features to determine which points fall within each polygon’s area. After determining this point-in-polygon spatial relationship, statistics about all points in the polygon are calculated and assigned to the area. Figure 4.13 provides a brief description of the spatial aggregation approach.

Spatial aggregation calculates the count of features, or a statistic calculated with a specific field within specified boundaries and displays the count using graduated symbols such as different-sized shapes or different depths of colors. Spatial aggregation is most useful when the chosen boundaries have some significance to the analysis and warrant a comparison.

Compared to the heat map visualization, spatial point aggregation is more flexible. As mentioned above, a significant element in spatial aggregation is the boundary layer. Generally, it consists of a set of polygons designed based on the user requirement. Thus, when calculating the relative density of the point features, spatial point aggregation always strictly follows the regional division formed by the boundaries. In another word, the aggregation results are highly dependent on the boundary layer.

The most basic aggregation will calculate the basic statistics, including sum, minimal, maximum, average, and standard deviation, on numerical fields for each separate area. In addition, the statistical calculations can also be grouped upon a field with categorical values. In such application, the statistics are computed for both the whole area and the individual group. The outcome statistics can be viewed in the result layer’s pop-up windows for each division.

The following contents demonstrate how to finish the spatial point aggregation analysis with ArcGIS Pro.

- Click analysis>tools to open geoprocessing tools searching dialog.
- Search and select the aggregate points (GeoAnalytics Desktop Tools) to access the configuration of spatial point aggregation analysis tool. The configuration dialog is shown as Figure 4.14.
- Set the parameters based on user needs and click the run button to generate the aggregation result layer. The usage of each parameter is demonstrated below.
- Point layer refers to the primary point feature data to be analyzed.
- Output feature class defines the name of the aggregation result layer. Generally, this field is automatically generated according to the point layer.
- Polygon layer refers to the features assigning the boundaries for aggregation.

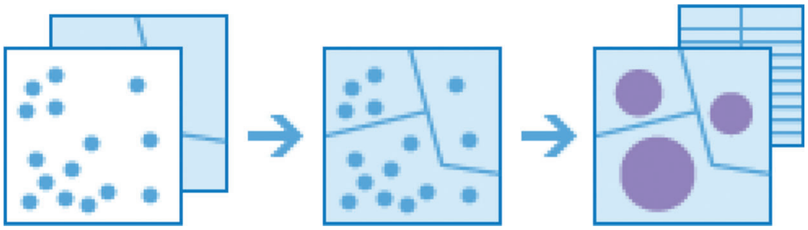


Figure 4.13 Process flow of spatial aggregation analysis.

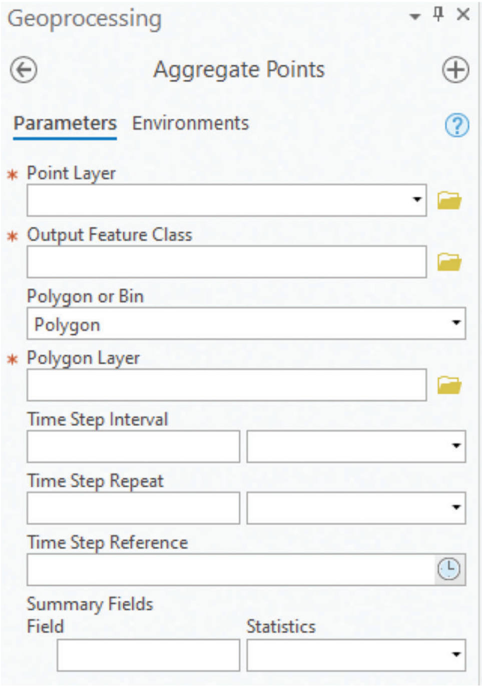


Figure 4.14 Configuration dialog of spatial point aggregation analysis tool.

- The settings for time step interval, time step repeat and time step reference are only valid when the input point layer is time enabled and represent an instant in time. These parameters can embed the temporal relationship extraction into the spatial analysis process.
- In the summary fields, users can complement any statistic calculation on the numerical or categorical fields within the input data. The added statistics would be calculated and presented in the output layer.

4.2.3 Analysis of Spatial Data and Results

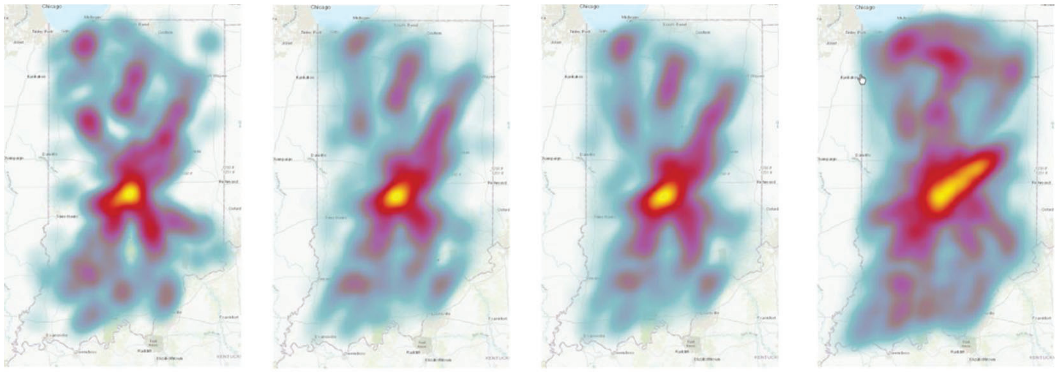
Figure 4.15 displays the heat map for stop markers among the four scenarios. All four scenarios indicate the center Indiana is most frequency area occurring the trip failure. The heat maps of first three scenarios share similar pattern of spectrum distribution while the last one spreads the high density to a bigger range.

Figures 4.16 and 4.17 show the spatial aggregation results of the four scenarios in terms of county boundary and ISTDM region segmentation, respectively. The numeric label tells the count of stop markers within each area, and the color represents the relative density of the stop markers. Compared to the heat maps, the spatial aggregation results can provide more organized outcomes corresponding to the boundaries. From the figures, the aggregated layers of first three scenarios are similar, which is consistent with the heat maps. By observing the aggregation results at county level division, the dense areas for failed trips are mainly along the interstate highway. In terms of ISTDM region level division, the Greater Indy region are much denser than other areas. Moreover, compared to Scenario #9, the Greater Indianapolis area becomes much denser than other areas in Scenario #10, which is the only potion possessing the blue color. It infers that in the more realistic situation, most failed EV trips stop near the central Indiana, which requires more attention on EV charging infrastructure deployment.

In addition, Tables 4.9 and 4.10 are made to list the top-10 counties and top-5 ISTDM regions containing the stop markers in the aggregation results for each scenario. In Table 4.9, each cell includes the county name as well as the number of stop markers included. Similarly, the cell in Table 4.10 implies the ISTDM region name and the corresponding amount of stop markers. From Table 4.9, it can be observed the Marion County and Hendricks County always occupy the top-2 places and the Morgan County, Madison County are basically in the top-5. It indicates these counties require more attention when planning the EV charging infrastructure deployment. Similarly, referring to Table 4.10, the Greater Indy Region, SIDC Region and SR-46 Corridor Region are the main EV energy deficit areas.

4.3 Discussion

The study in this section attempts to explore the potential EV charging station location analysis with a pilot simulation model and the GIS spatial analysis. Questions about where the EVs would request for charging can be answered by this model. However, it also has some limitations. As mentioned above that such model is a pilot version, it is developed based on some simple and ideal assumptions. For example, it is assumed that travelers charge their vehicles only at home before embarking on their trip, and that the existing charging stations are not integrated. Thus, the EV comes to a stop immediately after it runs out of energy. Regarding the complicated situation drivers may encounter during the trips, only three straightforward



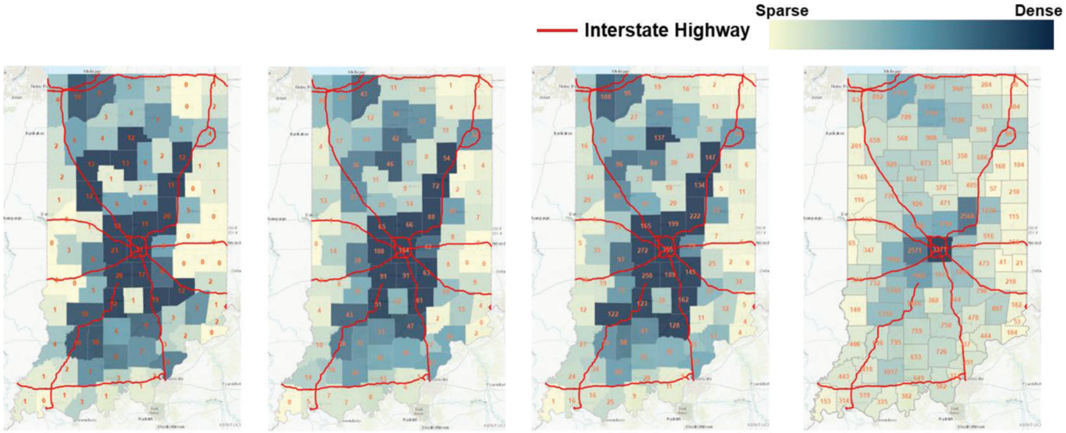
Scenario 1
2025 @ 5%

Scenario 5
2030 @ 21.25%

Scenario 9
2035 @ 50%

Scenario 10
2035 @ 50% w/ 80, 85, 95% factors

Figure 4.15 GIS map layer of the density distribution EV failed trip locations (heat map).



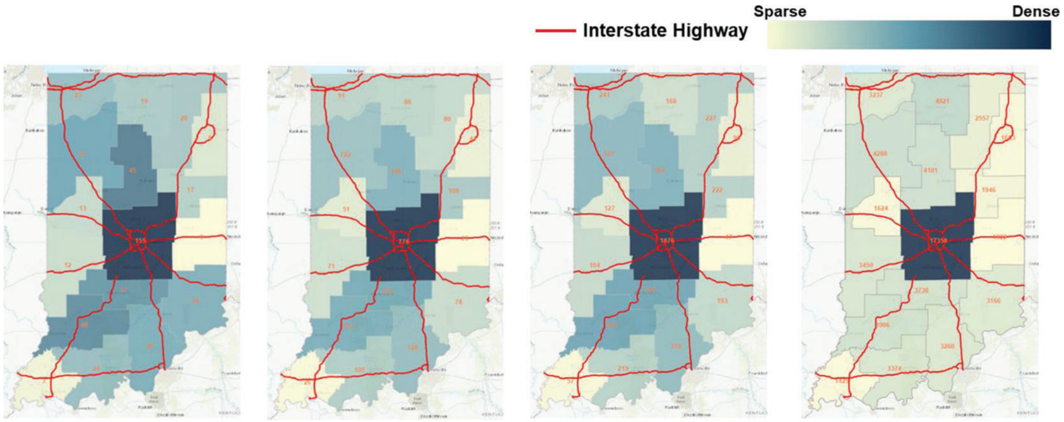
Scenario 1
2025 @ 5%

Scenario 5
2030 @ 21.25%

Scenario 9
2035 @ 50%

Scenario 10
2035 @ 50% w/ 80, 85, 95% factors

Figure 4.16 GIS map layer of the aggregation analysis of EV failed trip locations (county level).



Scenario 1
2025 @ 5%

Scenario 5
2030 @ 21.25%

Scenario 9
2035 @ 50%

Scenario 10
2035 @ 50% w/ 80, 85, 95% factors

Figure 4.17 GIS map layer of the aggregation analysis of EV failed trip locations (ISTDM region level).

TABLE 4.9
Top 10 counties for the number of stop markers for four scenarios

Rank	Scenario #1	Scenario #5	Scenario #9	Scenario #10
1	Marion (31)	Marion (164)	Marion (355)	Marion (3,371)
2	Hendricks (23)	Hendricks (108)	Hendricks (272)	Hendricks (2,571)
3	Morgan (20)	Johnson (91)	Morgan (250)	Madison (2,560)
4	Madison (20)	Morgan (91)	Madison (222)	Morgan (1,901)
5	Bartholomew (19)	Madison (88)	Hamilton (199)	Marshall (1,721)
6	Boone (18)	Grant (72)	Johnson (189)	LaPorte (1,714)
7	Johnson (17)	Hamilton (66)	Boone (165)	Hamilton (1,704)
8	Cass (13)	Boone (65)	Bartholomew (162)	Boone (1,599)
9	White (13)	Shelby (63)	Huntington (147)	Putnam (1,592)
10	Decatur (12)	Bartholomew (61)	Shelby (145)	Owen (1,340)

TABLE 4.10
Top 5 ISTDM regions for the number of stop markers for four scenarios

Rank	Scenario #1	Scenario #5	Scenario #9	Scenario #10
1	Greater Indy (155)	Greater Indy (778)	Greater Indy (1,876)	Greater Indy (17,358)
2	NCIRPC (45)	SR-46 Corridor (159)	SR-46 Corridor (395)	MACOG (4,821)
3	SIDC (40)	SIDC (155)	SIDC (394)	KIRPC (4,208)
4	SR-46 Corridor (37)	NCIRPC (148)	NCIRPC (354)	NCIRPC (4,101)
5	KIRPC (32)	River Hills (128)	KIRPC (327)	SIDC (3,906)

linear factors are applied. In consequence, lots of efforts could be made in the future studies to improve the model. As expected by the team, the developed simulation model can be used in other transportation networks, creating a roadmap for strategic deployment of EV charging infrastructure. For instance, the GIS spatial analysis in previous section presents the distribution as well as the hot spots of failure trips, which can support transportation staffs designing the EV charging station deployment layout. Therefore, a more extensive study can be carried out by the means of this model.

4.4 Summary

This chapter provides a framework for identifying EV infrastructure deficit areas and for analyzing the potential locations for EV charging station deployment. It mainly consists of two parts: (1) the agent-based simulation model developed to track EV demand and frequency of charging on the way, and (2) GIS-integrated spatial analysis to visualize the areas in the state that are characterized by inadequate EV charging infrastructure. The two parts form a logical flow, where the model simulates several scenarios and derives outcomes for the GIS application to finish spatial analysis. The important and most crucial outputs of this chapter were (1) a computerized model that can simulate EV travel patterns to identify charging deficit areas, (2) several scenario-based GIS feature layers which reveal the EV energy demand distribution and the EV infrastructure deficit areas, and (3) a practical workflow including designing and accomplishing simulation scenario and corresponding spatial analysis.

5. ASSESSMENT OF FUNDING NEEDS AND FEASIBILITY ANALYSIS OF NEW INCOME GENERATION STREAM MODELS

EV adoption is expected to increase in coming years. This development can potentially cause the revision of highway financing by changing the tax revenue base from one dominated by fuel taxes and vehicle fees. In Indiana, state and local transportation systems are funded primarily from state revenues though taxes and fees related to cars and commercial trucks (approximately 60% of the total revenue), and federal funds (nearly 40% of total revenue) (Cambridge Systematics, Inc. et al., 2015). The largest portion of state revenues consists of motor fuel taxes (57%). Vehicle fees account for 17% of the state revenues, toll proceeds contribute 17% and other miscellaneous fees constitute around 9% (Cambridge Systematics, Inc. et al., 2015). Additionally, EV owners in Indiana are currently charged an annual flat EV fee (Bureau of Motor Vehicles, 2022). Clearly, a large portion of state revenues are from motor fuel taxes; therefore, any large-scale adoption of EVs is expected to result in a significant decline in fuel tax revenue generated, under the existing highway taxation structure throughout the state. Thus, the objective of this task (Task 3) is to conduct a financial analysis to examine the funding needs and potential of prospective funding mechanisms/policies to recover the fuel tax revenue loss. The analysis is based on different

EV market penetration levels, indicating that there will be a transition period with a mix of electric and conventional vehicles and with taxation policies that should be in line with the new needs of highway financing. The methodology and data used (Sections 5.1 and 5.2) as well as the results of the analysis (Section 5.3) are presented in the following subsections. Lastly, the chapter concludes with a discussion section (Section 5.4) and a summary section (Section 5.5).

5.1 Methodology Overview

5.1.1 Impact on State Highway Revenue and Optimal EV Fee

The methodology for this objective is based on estimating an annual supplemental fee to be charged per EV to break-even the fuel tax revenue loss that is associated with the EV adoption ("recovery EV fee"). Figure 5.1 illustrates the approach followed to calculate the recovery EV fee. The first important research output is the revenue loss per vehicle class (revenue that would be generated from EVs if they were running on gasoline or diesel). To determine this revenue loss, the annual vehicle miles travelled (VMT) of EVs were estimated by multiplying the annual VMT per vehicle with EV registrations. The EV registrations were estimated by multiplying the EV market penetration by the vehicle registrations. Taking the ratio of the estimated annual VMT of EVs by the fuel efficiency per vehicle class produces the fuel gallons consumed or lost due to the growth of EVs in the market.

Next, the fuel revenue loss is estimated by multiplying the volume of fuel consumed by the fuel tax. The recovery EV fee that could make up the decrease in revenue generation is calculated by distributing the revenue loss to the EV registrations. The results are provided per vehicle class and from 2021 to 2035 following the analysis period of the latest INDOT revenue model (INDOTREV-2) (Agbelie et al., 2010). The vehicle classes considered are automobiles, light duty trucks, motorcycles, buses, single unit trucks, combination trucks. These six vehicle classes form the following two main vehicle groups: light duty vehicles (automobiles, light trucks and motorcycles) and medium and heavy duty vehicles (buses, single, unit trucks, and combination trucks).

The data needed to compute the loss in revenue on an annual basis (Figure 5.1) is described in more detail in the next section (Section 5.2). Projections for each future year are made based on available sources or predictive analysis from historical data (linear trend analysis, regression models, average flat line). Scenario development related to different levels of EV market penetration in 2035 was also conducted and the impact on highway revenue was estimated. The evolution of market penetration from 2021–2035 is estimated based on the assumption of a logistic S-curve. This methodology is in line with other studies, which used S-curves to predict market penetration of new technologies (e.g., Choi et al., 2013, Konstantinou, 2019, Trinko et al., 2022). The logistic curve is determined by specifying two coordinates (year, market penetration level) on the curve. The equation of the S-curve is as follows (Equation 5.1):

$$f(x) = \frac{1}{1+e^{-x}} \qquad \text{(Equation 5.1)}$$

This equation is transformed by adding two parameters (α and T_0) to reflect the growth of market penetration (Equation 5.2):

$$f(x) = \frac{1}{1+e^{-\alpha(t-T_0)}} \qquad \text{(Equation 5.2)}$$

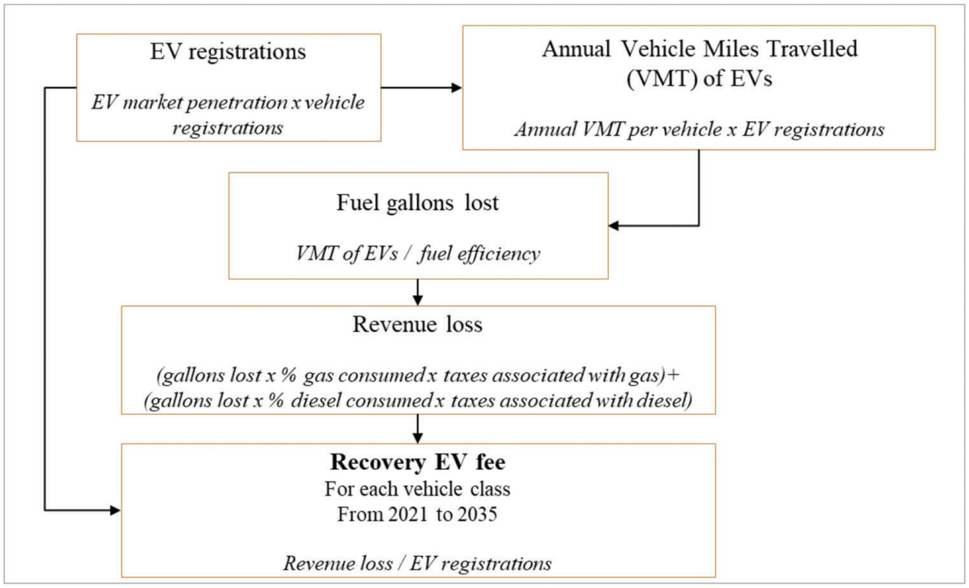


Figure 5.1 Methodology to calculate recovery EV fee.

where $f(x)$ indicates the market penetration value
t indicates the time (year)
α is a parameter that stretches or compresses time
T_0 is a parameter and shifts the timeline of the curve

For each scenario, the fuel tax revenue loss, recovery EV fee per vehicle class, fuel tax revenue, and revenue from vehicle registrations were calculated for each year of the analysis period. The fuel tax revenue loss and recovery EV fee were calculated as described in Figure 5.1. The fuel tax revenue was estimated by multiplying the volume of fuel consumed by the specific fuel type tax. The revenue expected from vehicle registrations is calculated as the product of the number of vehicles registered and the respective registration fees. Registration revenues from driving licenses and other registration-related items are also estimated as the product of the number for each registration-related item and the corresponding registration fee. The revenue from vehicle registrations is calculated based on both the existing/current registration fee for EVs and the recovery EV fee.

A conceptual figure or causal loop diagram (Figure 5.2) was also established to demonstrate the main parameters and outcomes of the process as well as their relationships (Labi, 2014). This diagram visualizes the behavior/structure of a system and provides insights regarding the system dynamics using causal links (Labi, 2014). In particular, this diagram uses arrows as links to show the causal relationships between each pair of parameters. The arrows are labeled as positive or negative, showing the direction of influence of one parameter (the start of the arrow) to the other parameter (the end of the arrow). For example, an increase in the gallons lost due to the popularity of EVs is accompanied by an increase in the revenue loss. For the purposes of this task, a linear pattern is presented, meaning that straight lines/arrows are used to depict the relationships across the system components since they are simple and easily understood (Labi, 2014).

Figure 5.2 describes the system dynamics that exist to calculate the recovery EV fee (final outcome). Besides the arrows and their labels, this figure uses colors to show the order of the calculations to estimate the final outcome. In particular, the first calculated parameter is the EV registrations that come from data on the EV market penetration levels and the total vehicle registrations. As the EV market penetration rate or vehicle registration increase, EV registrations increase as indicated by the positive sign of the specific arrow/link. When EV registrations increase, the VMT of EVs increase and the gallons consumed or lost also increase. As the gallons lost increase, revenue loss increases. Revenue loss is also influenced by the forces of fuel tax and the percentage of vehicles that belong to each fuel type (diesel or gas). As the revenue loss increases, the recovery EV fee per vehicle also increases to cover this loss.

It is expected that as EV registrations increase, revenue loss is distributed to more vehicles and thus the recovery EV fee decreases. It is also expected that as revenue loss increases, the recovery EV fee increases. However, due to system dynamics, the ratio of revenue loss to EV registrations stays always the same, even if different EV market penetration levels are applied. Hence, the net effect of all parameters on the recovery EV fee was found to be the same.

5.1.2 Impact on Revenue Distributed to INDOT

Following the methodology described above, the EV recovery fee and the impact on state highway revenue were estimated. This highway revenue is distributed to different accounts and funds according to the legisla-

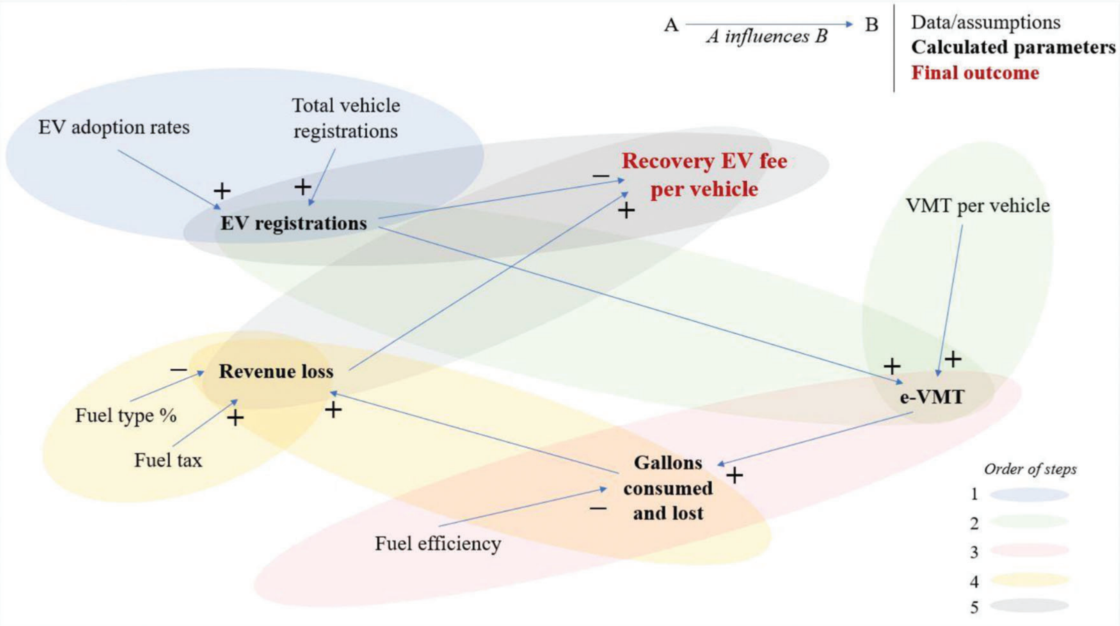


Figure 5.2 Causal loop diagram of system dynamics for calculating the recovery EV fee.

tively mandated ratios (Agbelie et al., 2010). Figure 5.3 illustrates the Indiana transportation funding chart for the fiscal year 2021, as adopted from INDOT. Following the flow of funds and accounts that lead to INDOT or State Highway Fund, the corresponding fuel tax revenue and revenue loss for INDOT were calculated. This includes losses in fuel taxes affected by EVs: the gasoline use tax, motor carrier fuel tax, special fuels tax and gasoline excise tax. In particular, the INDOT revenue loss is determined using Equation 5.3:

$$Loss_{INDOT} = (a\% \cdot GUT_{EV}) + (b\% \cdot MCFUT_{EV}) + (c\% \cdot d\% \cdot RAFD_{EV}) + (e\% \cdot x\% \cdot RAFD_{EV}) + (f\% \cdot x\% \cdot GUT_{EV}) \quad \text{(Equation 5.3)}$$

where a, b, c, d, e, f, and x the legislatively mandated ratios (percentages). x is the percentage of the total revenue from the Motor Vehicle Highway Account distributed to the State Highway Account (62%).

GUT_{EV} the revenue from gasoline use tax distributed directly to the State Highway Account (using a) and the Motor Vehicle Highway Account (using f).

$MCFUT_{EV}$ the revenue from motor carrier fuel use tax.

$RAFD_{EV}$ the remaining available revenue for distribution (generated from special fuels tax and gasoline excise tax) distributed to the Motor Vehicle Highway Account (using e) and Highway Road and Street Fund (using c).

$Loss_{INDOT}$ the fuel tax revenue loss for INDOT due to the emergence of EVs.

As can be seen from Figure 5.3, all revenue from "Electric/Hybrid fees" is distributed to the Local Road and Bridge Matching Grant Fund (Community Crossings) and not to the State Highway Fund or INDOT. According to INDOT, if the number of EVs increases, a portion of or all revenue from EV fees can then be distributed to the State Highway Fund. This introduces uncertainty in terms of (1) the conditions at which INDOT will start to collect revenue fully or partially from EV fees (EV market penetration level for EV revenue collection and year of EV revenue collection) and (2) the percentage of revenue that will be distributed to INDOT. To solve this problem, a scenario analysis was conducted to estimate the revenue loss and the revenue that is distributed to INDOT from EV fees. The scenarios were built for different years when INDOT starts to collect revenue from EV fees, for different EV market penetration levels at which INDOT starts to collect revenue and for different percentages of revenue distributed to INDOT. Note that even if the percentage of revenue collected from EV fees is 100%, x% is distributed to INDOT according to the legislatively mandated ratios (Figure 5.3). Equation 5.4 shows the calculation of the revenue from EV fees distributed to INDOT (Rev_{INDOT}):

$$Rev_{INDOT} = x\% \cdot y \cdot Rev_{total} \quad \text{(Equation 5.4)}$$

Where x is the legislatively mandated ratio associated with the account that first collects EV fees (62% in this case), y is the percentage of EV revenue distributed to INDOT/State Highway Fund and Rev_{total} is the total revenue from EV registrations (before distribution to the different accounts).

Table 5.1 shows a summary of the values used in the scenarios for each parameter (EV market penetration level, year of EV revenue collection, percentage of EV revenue collected by INDOT). S-curves were developed for each EV market penetration level. Different combinations of penetration levels for light duty vehicles versus medium and heavy duty vehicles were examined. For example, one scenario assumed 5% EV market penetration level for each vehicle class of the light duty vehicles (automobiles, motorcycles, light trucks) and 10% EV market penetration level for each vehicle class of medium and heavy duty vehicles (buses, single unit and combination trucks). Following the scenario development, the most likely scenario as well as the optimistic and pessimistic scenarios for INDOT were chosen to be reported in the results section (Section 5.3).

5.2 Data

In order to achieve the objective of this task, research is necessary to collect data related to electric and conventional vehicles in order to quantify the impact on revenue. The following paragraphs discuss the data sources and forecasts for each data type used.

5.2.1 VMT

To calculate the VMT of EVs, the VMT per vehicle is needed. The historical VMT per vehicle were obtained from the Highway Statistics Series from 2010 to 2019 (FHWA, 2021). Trend analysis was used to make projections until 2035. It was observed though that VMT per vehicle for all vehicle classes except for automobiles were decreasing over time which was not considered realistic. Thus, the average flat line was chosen to forecast future VMT per vehicle of light trucks, motorcycles, buses, single unit trucks, and combination trucks. The COVID-19 pandemic has caused various social and economic changes that could change the VMT prediction in the future. For this study, the impact of COVID-19 was not taken into account since it would constitute an outlier. Table 5.2 shows the VMT per vehicle class, from 2021 to 2035.

5.2.2 Fuel Taxes

The estimation of the fuel tax highway revenue was based on the following types of taxes: sales tax on gasoline/gasoline use tax, gasoline excise tax, special fuel tax, and motor carrier fuel use tax. The diesel surtax no longer exists. It was repealed in the 2018 Indiana General Assembly and in lieu of the surtax, the

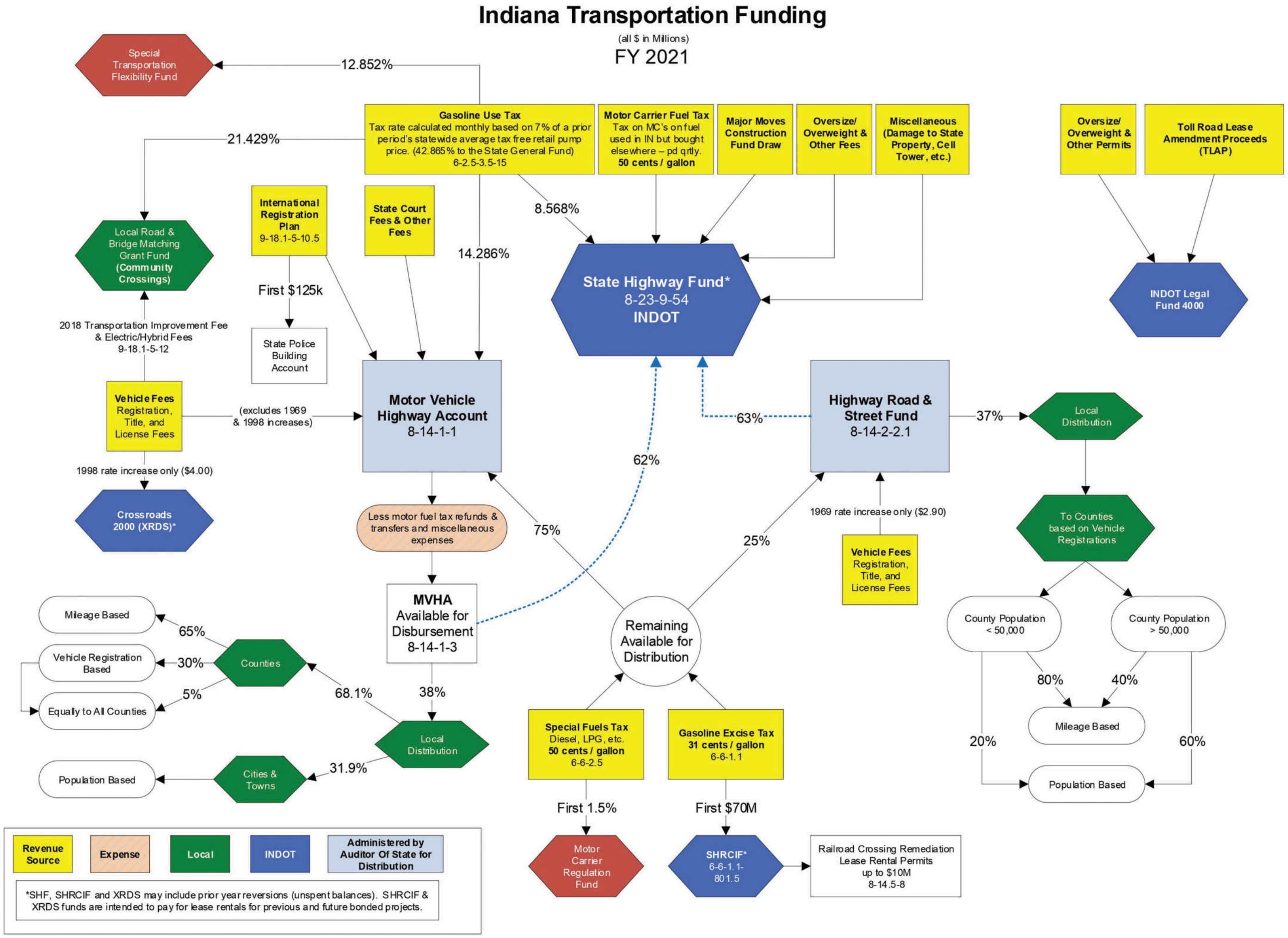


Figure 5.3 Indiana transportation funding chart obtained from INDOT (R. Abbott of INDOT Econometrics and Forecasting Division, personal communication, June 1, 2021).

TABLE 5.1
Scenario analysis to estimate the revenue distributed to INDOT

EV Market Penetration Levels for Each Vehicle Class	Year of EV Revenue Collection by INDOT		
	2025 (%)	2030 (%)	2035 (%)
Automobiles	5, 10, 20, 25	10, 20, 30, 50, 100	10, 20, 25, 50, 100
Motorcycles	5, 10, 20, 25	10, 20, 30, 50, 100	5, 10, 20, 25, 50, 100
Light Trucks	5, 10, 20, 25	10, 20, 30, 50, 100	10, 20, 25, 50, 100
Buses	5, 10, 20, 25	10, 20, 30, 50, 100	10, 20, 25, 50, 100
Single Unit Trucks	5, 10, 20, 25	10, 20, 30, 50, 100	5, 10, 20, 25, 50, 100
Combination Trucks	5, 10, 20, 25	10, 20, 30	5, 10, 20, 25, 50, 100
Percentage of Revenue Collected by INDOT		0, 25, 50, 75, 100	

TABLE 5.2
VMT (in thousands) per vehicle (2021–2035)

Year	Automobiles	Light Duty Trucks	Buses	Single Unit Trucks	Combination Trucks	Motorcycles
2021	11.88	12.39	18.12	12.81	64.73	2.34
2022	11.99	12.39	18.12	12.81	64.73	2.34
2023	12.09	12.39	18.12	12.81	64.73	2.34
2024	12.19	12.39	18.12	12.81	64.73	2.34
2025	12.29	12.39	18.12	12.81	64.73	2.34
2026	12.40	12.39	18.12	12.81	64.73	2.34
2027	12.50	12.39	18.12	12.81	64.73	2.34
2028	12.60	12.39	18.12	12.81	64.73	2.34
2029	12.71	12.39	18.12	12.81	64.73	2.34
2030	12.81	12.39	18.12	12.81	64.73	2.34
2031	12.91	12.39	18.12	12.81	64.73	2.34
2032	13.01	12.39	18.12	12.81	64.73	2.34
2033	13.12	12.39	18.12	12.81	64.73	2.34
2034	13.22	12.39	18.12	12.81	64.73	2.34
2035	13.32	12.39	18.12	12.81	64.73	2.34

special fuels tax was increased (Indiana Legislative Services Agency, 2018). To calculate the sales tax on gas, the gasoline price was multiplied by 7% (Agbelie et al., 2010). The EIA State Energy Data System (EIA, n.d.) was accessed to obtain the average annual gasoline prices for the transportation sector in Indiana from 1970 to 2018 in dollars per million British thermal units ($/MMBtu). These prices were converted to approximate dollars per gallon ($/gallon) using the heat contents provided in the petroleum consumption and fuel ethanol table (EIA, 2022). Historical data on the rates of gasoline and special fuel was collected from Indiana Legislative Services Agency (2018) that contained fuel tax rates for some years between 1943 to 2018. Trend analysis was used to forecast gasoline prices, gasoline and special fuel taxes. The motor carrier fuel use tax (tax on fuel consumed by trucks in Indiana but purchased in another state) is taxed the same as the special fuel tax since 1985 (Indiana Legislative Services Agency, 2018). Table 5.3 shows the gasoline prices, gasoline and special fuel taxes from 2021 to 2035.

5.2.3 Vehicle Registration Frequencies

Vehicle registrations were necessary to estimate the vehicle registration revenue and were obtained from different sources depending on data availability. Registration frequencies for automobiles, motorcycles, trucks, truck tractors, trailers and licensed drivers came from the Highway Statistics reports for 2010–2019 (FHWA, 2021). There were no direct historical data though for titles and other miscellaneous registration categories (e.g., recreational vehicles, special machinery, watercrafts etc.). For these registration categories, prediction models found in Agbelie et al. (2010) were used with updated data for their independent variables. In particular, the number of vehicle title registrations is a function of the driving age population which was obtained from the Highway Statistics reports from 2010–2019. Registrations of recreational vehicles, special machinery, recovery vehicles, watercrafts and other miscellaneous categories are influenced by GDP. Historical data on GDP was collected for 2010–2020 from the U.S. Bureau of Economic Analysis (2022). Trend analysis was used to forecast vehicle registration frequencies up to 2035. For the registration categories for which a downward trend was observed from the analysis (automobiles, buses, licensed drivers), the average flat line was used instead of trend analysis. To disaggregate the main registrations to the necessary registration categories such as the different weight classes for trucks, tractors, trailers and the types of

TABLE 5.3
Fuel tax rates (2021–2035)

Year	Gasoline Price ($/gallon)	Gasoline Fuel Tax (cents/gallon)	Special Fuel Fuel Tax (cents/gallon)	Special Fuel for MCFUT Fuel Tax (cents/gallon)
2021	$2.71	31.00¢	50.00¢	50.00¢
2022	$3.30	31.21¢	51.34¢	51.34¢
2023	$3.37	31.35¢	51.65¢	51.65¢
2024	$3.45	31.92¢	52.68¢	52.68¢
2025	$3.52	32.49¢	53.72¢	53.72¢
2026	$3.59	33.06¢	54.75¢	54.75¢
2027	$3.67	33.63¢	55.78¢	55.78¢
2028	$3.74	34.19¢	56.81¢	56.81¢
2029	$3.82	34.76¢	57.84¢	57.84¢
2030	$3.89	35.33¢	58.88¢	58.88¢
2031	$3.96	35.90¢	59.91¢	59.91¢
2032	$4.04	36.47¢	60.94¢	60.94¢
2033	$4.11	37.04¢	61.97¢	61.97¢
2034	$4.19	37.61¢	63.01¢	63.01¢
2035	$4.26	38.18¢	64.04¢	64.04¢

TABLE 5.4
Vehicle registration frequencies (in millions) (2021–2035)

Year	Automobiles	Buses	Trucks	Motorcycles	Truck Tractors	Trailers	Licensed Drivers	Titles	Miscellaneous
2021	3.31	0.02	3.89	0.27	0.32	1.07	4.67	5.15	42.29
2022	3.44	0.02	3.98	0.28	0.33	1.09	4.70	5.22	44.82
2023	3.57	0.02	4.07	0.29	0.34	1.12	4.73	5.29	47.34
2024	3.70	0.02	4.16	0.30	0.36	1.15	4.76	5.36	49.87
2025	3.84	0.02	4.24	0.30	0.37	1.17	4.79	5.43	52.39
2026	3.97	0.02	4.33	0.31	0.39	1.20	4.82	5.50	54.92
2027	4.10	0.02	4.42	0.32	0.40	1.23	4.86	5.58	57.45
2028	4.23	0.02	4.51	0.33	0.42	1.26	4.89	5.65	59.97
2029	4.36	0.02	4.60	0.33	0.43	1.28	4.92	5.72	62.50
2030	4.49	0.02	4.68	0.34	0.45	1.31	4.95	5.79	65.02
2031	4.62	0.02	4.77	0.35	0.46	1.34	4.98	5.86	67.55
2032	4.75	0.02	4.86	0.35	0.48	1.36	5.01	5.93	70.07
2033	4.88	0.02	4.95	0.36	0.49	1.39	5.04	6.00	72.60
2034	5.01	0.02	5.04	0.37	0.51	1.42	5.07	6.07	75.12
2035	5.14	0.02	5.12	0.38	0.52	1.44	5.10	6.14	77.65

buses, distribution factors were applied based on Agbelie et al. (2010). Table 5.4 presents the vehicle registration frequencies from 2021 to 2035.

5.2.4 Vehicle Registration Fees

Vehicle registration fees was obtained from the fee chart of Bureau of Motor Vehicles (BMV) (2022) and augmented with data from Agbelie et al. (2010) when this was necessary. Following the approach of the INDOT revenue model (Agbelie et al., 2010), the conventional vehicle registration fees remain the same across the years. As for EVs, EV owners pay a supplemental fee of $150 in Indiana (Bureau of Motor Vehicles, 2022; Indiana Legislative Services Agency, 2018). The fee is termed "registration" fee by the BMV, a term that could be described as a misnomer because it is intended to cover not only registration but also road use. Additionally, it was assumed that this EV supplemental "registration" fee follows the inflation rate. Historical data on inflation rate (12-month percent change in CPI) from 2010 to 2020 was collected from the U.S. Bureau of Labor Statistics (n.d.) and the average flat line was used to project to 2035 (Knoema, 2022). Note that the data on existing EV supplemental "registration" fees (Figure 5.4) was needed to compare the registration revenue generated by existing EV fees with the registration revenue generated by the recovery EV fee.

5.2.5 Fuel Efficiency

Historical data from 2010 to 2019 related to the fuel efficiency (miles per gallon) of automobiles ("light duty

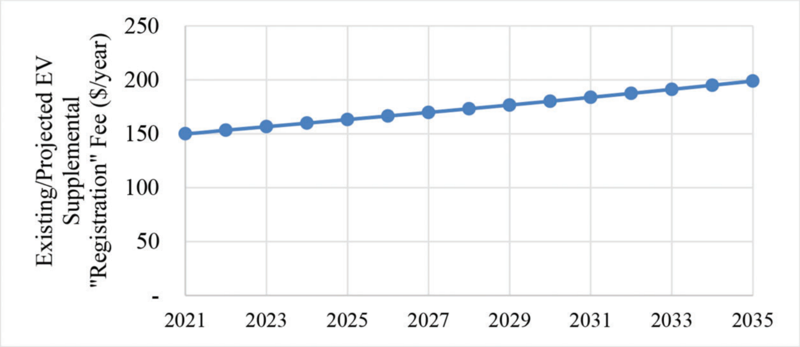


Figure 5.4 Existing/projected (battery) EV supplemental "registration" fees (2021–2035).

TABLE 5.5
Fuel efficiency (in miles per gallon) per vehicle class (2021–2035)

Year	Automobiles	Light Duty Trucks	Buses	Single Unit Trucks	Combination Trucks	Motorcycles
2021	24.59	17.99	7.42	6.61	5.36	44.22
2022	24.73	18.09	7.45	6.63	5.39	44.30
2023	24.86	18.18	7.47	6.66	5.41	44.37
2024	25.00	18.28	7.50	6.69	5.43	44.45
2025	25.14	18.37	7.53	6.72	5.45	44.53
2026	25.28	18.47	7.55	6.74	5.48	44.61
2027	25.41	18.56	7.58	6.77	5.50	44.69
2028	25.55	18.66	7.61	6.80	5.52	44.77
2029	25.69	18.75	7.64	6.83	5.54	44.84
2030	25.82	18.85	7.66	6.85	5.56	44.92
2031	25.96	18.94	7.69	6.88	5.59	45.00
2032	26.10	19.03	7.72	6.91	5.61	45.08
2033	26.23	19.13	7.74	6.93	5.63	45.16
2034	26.37	19.22	7.77	6.96	5.65	45.23
2035	26.51	19.32	7.80	6.99	5.67	45.31

short wheelbase"), light trucks ("light duty long wheelbase"), and single unit trucks ("heavy duty trucks") was found from EIA (2021b). To estimate the fuel efficiency for combination trucks, 2017 data from the U.S. Department of Energy (2017) was used. The ratio of the reported fuel efficiency of single unit trucks to the fuel efficiency of combination trucks in 2017 was estimated. This ratio was used to determine the fuel efficiency of combination trucks from 2010–2019 based on the Energy Information Administration data for single unit trucks. For motorcycles and buses, historical data for the same period was obtained from the table of vehicle miles of travel of Highway Statistics (FHWA, 2021) that also reported the average miles traveled per gallon of fuel consumed. Trend analysis was used to make projections to 2035. The results are presented in Table 5.5.

5.2.6 Fuel Consumption Percentages

Data on the percentages of fuel consumed by each vehicle type were from Agbelie et al. (2010). The fuel consumed by automobiles and motorcycles was considered to be 100% gasoline. Of the light and single unit trucks 95% and 5% of were considered to use gasoline and special fuel, respectively. The amount of fuel consumed by buses and combination trucks was considered 100% from special fuel. These percentages were assumed to remain the same during the analysis period. The motor carrier fuel use tax is imposed on fuel used in the state but bought elsewhere. Thus, this tax is also multiplied by a percentage of the (diesel) gallons consumed by motor carriers (combination trucks). This percentage was obtained for 2021–2035 from Agbelie et al. (2010).

5.2.7 EV Market Penetration

The EV market penetration was defined as a percentage of vehicle registrations. Different scenarios for the EV market penetration levels were examined. These scenarios were based on EV market penetration levels that were equal across the main vehicle groups (light, medium, and heavy-duty vehicles) or also EV market penetration levels that differ for certain vehicle types. As described in Section 4.1, s-curves were used to project the EV market penetration. For 2018, EV market penetration data was compiled from FHWA (2021) (total vehicle registrations) and the U.S. Department of Energy (2018) (EV registrations) to find an estimation of the EV market penetration in 2018 and use it in the s-curve. The data from the U.S. Department of Energy referred to light duty vehicles (around

TABLE 5.6
Data types and sources for financial analysis

Data Type	Data Source	Projection Method
Vehicle Miles Travelled (VMT)	Highway Statistics Series (FHWA, 2021)	Trend analysis (automobiles) Average flat line (light trucks, motorcycles, buses, single unit trucks, combination trucks)
Fuel taxes: Sales tax on gasoline Gasoline tax Special fuel tax Motor carrier fuel use tax	Agbelie et al. (2010) EIA (n.d., 2022) Indiana Legislative Services Agency (2018)	Trend analysis
Vehicle registration frequencies	Agbelie et al. (2010) Highway Statistics Series (FHWA, 2021) U.S. Bureau of Economic Analysis (2022)	Trend analysis (motorcycles, trucks, truck tractors, trailers) Average flat line (automobiles, buses, licensed drivers) Regression models (titles, and other miscellaneous categories)
Vehicle registration fees	Agbelie et al. (2010) Bureau of Motor Vehicles (BMV) (2022) Knoema, 2022 U.S. Bureau of Labor Statistics (n.d.)	Constant throughout the analysis period
Fuel efficiency (miles/gallon)	U.S. Department of Energy (2017) EIA (2021b) Highway Statistics Series (FHWA, 2021)	Trend analysis
Fuel consumption percentages	Agbelie et al. (2010)	Constant throughout the analysis period (for gas/diesel)
EV market penetration	U.S. Department of Energy (2018) FHWA (2021)	Scenario analysis S-curve

0.05% EV market penetration level in 2018). For medium and heavy duty vehicles, a 0% EV market penetration level was assumed for 2018. Table 5.1 of Section 5.1 shows the EV market penetration levels that were tested with different combinations for the vehicle types and the year at which this penetration level is achieved. Table 5.6 summarizes the main inputs of the analysis along with the data sources and projection methods.

5.3 Analysis of Data and Results

In this section, the findings for the recovery EV fee as well as the impact on the revenue from 2021 to 2035 are presented, assuming continuation of existing taxation structures.

5.3.1 Recovery EV Fee

The ratio of revenue loss to EV registrations produces the recovery EV fee that stays constant even for different scenarios due to system dynamics, as explained in Section 5.1. Figure 5.5 shows the annual recovery EV fee from 2021 to 2035 for each automobile, motorcycle, light duty truck and bus as well as the existing annual EV fee in Indiana for comparison. Figure 5.6 shows the annual recovery EV fee for each combination truck along with the existing EV fee in Indiana from 2021 to 2035.

The figures show the recovery EV fee in dollars per year that should be charged annually to each vehicle class to break even the fuel tax revenue loss. Since the fuel tax revenue loss will keep increasing over the years as the EV market penetration increases, the recovery EV fee follows the same trend. As expected, the existing annual EV fee is significantly lower to the proposed EV fee (the recovery EV fee), except for the vehicle class of motorcycles. To maintain the same tax revenue per vehicle, annual fees ranging from $241 (in 2021) to $342 (in 2035) for automobiles, $344 to $435 for light trucks, $1,246 to $1,488 for buses, $969 to $1,243 for single unit trucks, $6,192 to $7,321 for combination trucks and $26 to $35 for motorcycles would be needed over the analysis period.

As it can be observed, the recovery EV fee is high for heavier vehicles such as buses, single unit trucks and combination trucks. This high amount can be justified since each heavier vehicle pays additional taxes and contributes more to the fuel tax revenue due to its vehicle class characteristics. Hence, to break even the revenue that is lost, a high fee is necessary. Furthermore, this fee is an annual, direct, or one-time fee. The amount of money of this fee can be considered the same as the total amount that would be paid for fuel taxes for all the times these vehicles would fill their fuel tanks throughout the year. Also, it may be noted that the recovery EV fee for all EV classes is intended to

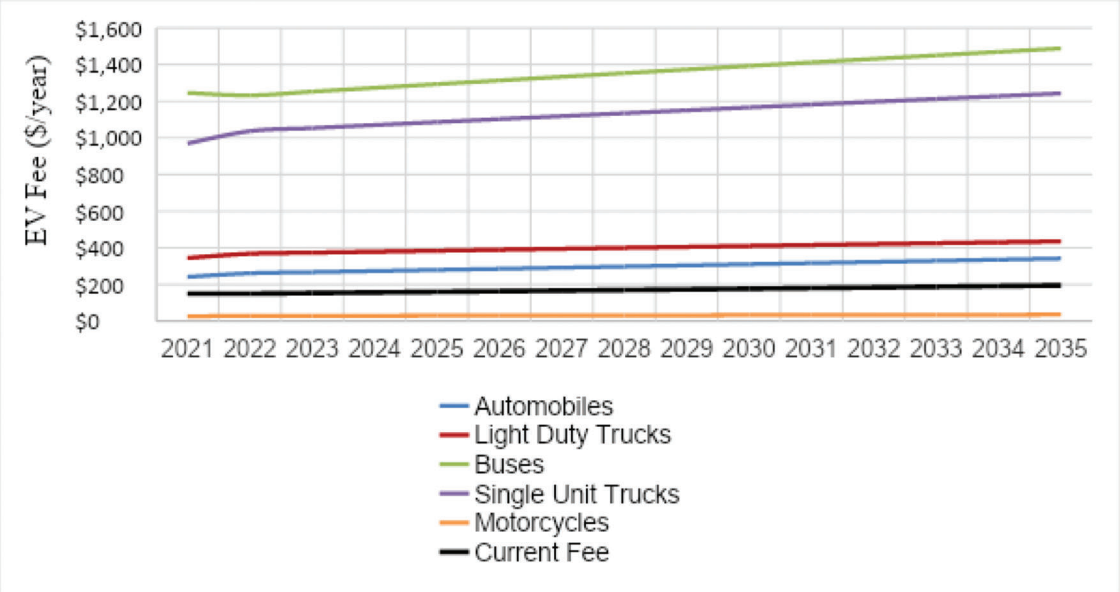


Figure 5.5 Recovery EV fee for automobiles, light duty trucks, buses, single unit trucks, and motorcycles.

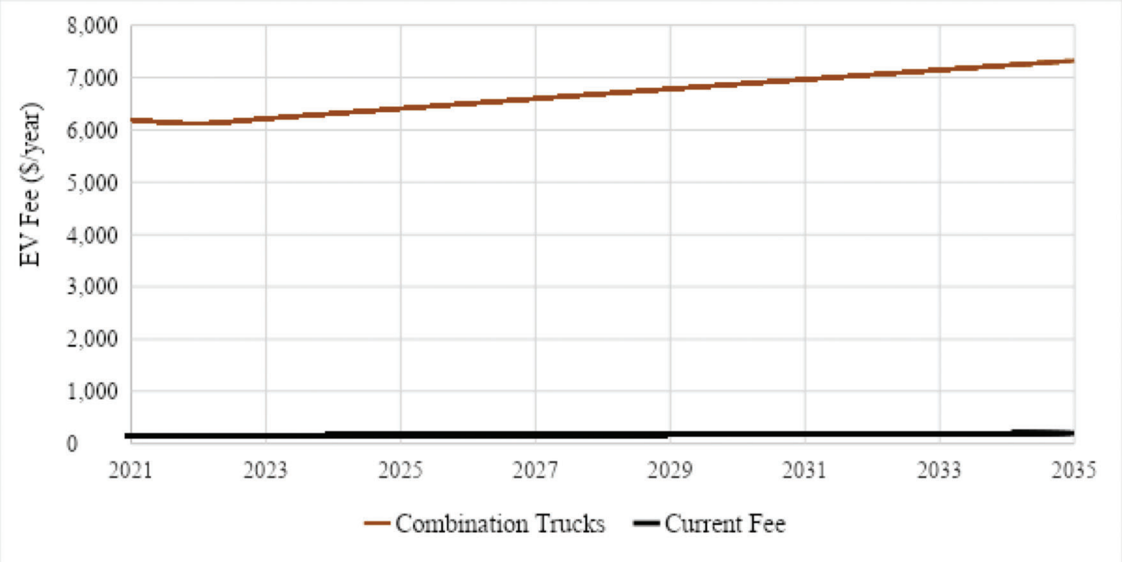


Figure 5.6 Recovery EV fee for combination trucks.

cover both registration and road use and therefore, it is much higher than the registration fee of a conventional vehicle.

5.3.2 Impact on Revenue

The impact of the adoption of EVs on the highway revenue was estimated before and after its distribution to the State Highway Fund or INDOT. Scenario analysis was conducted for different years when INDOT starts to collect the revenue from EV fees (fully, or partially with the locals), for different EV market penetration levels at which INDOT collects the EV revenue and for different percentages of EV revenue that is distributed to INDOT (refer to Table 5.1). In this section, the results are presented for the most likely scenario and an optimistic and pessimistic scenario from the perspective of INDOT, not the entire state.

(a) Most Likely Scenario

Literature review was conducted to find the combination of parameters (Table 5.1) that would form a baseline or more likely scenario for the future. This review focused on searching for realistic values for future EV market penetration levels for light duty versus medium and heavy duty vehicles as well as the year at which these market penetration levels will occur. Limited market data/projections about EVs exists to date for Indiana and thus the scale of the values found mainly refers to the U.S. The year of 2030 has been used as a target for various goals regarding alternative fuel vehicles. For example, an ambitious new target has been set requiring half of all new vehicles sold in the U.S. in 2030 to be zero-emissions vehicles, including battery electric, plug-in hybrid electric, or fuel cell vehicles (The White House, 2021). Major automakers endorse the specific target and plan for 50% of electric cars by 2030 (The White House, 2021). For the case of Indiana, information about market penetration rates of light duty vehicles in 2030 were obtained from M.J. Bradley & Associates (2018). According to their moderate scenario for EV market penetration in Indiana, a 5% market penetration level seems more likely to happen. This information was also validated though communications with INDOT Econometrics and Forecasting Division.

Additionally, a memorandum of understanding has been signed by a diverse mix of states that calls for 30% of new medium and heavy duty vehicle sales to be zero-emission by 2030 (NESCAUM, 2020). Furthermore, a stated preference survey of 200 truck fleet managers was conducted in the U.S. and solicited information related to trucking firm and fleet characteristics, and opinions on electric trucks. The survey was distributed during May 2021. Descriptive statistics of the survey data included the percentages of the medium and heavy duty fleet that truck fleet managers would electrify by 2030. The survey produced a pessimistic, average and optimistic scenario for the future adoption of electric medium and heavy duty vehicles according to the truck fleet managers' responses. The pessimistic scenario was chosen as the most likely scenario of this analysis. This is because the current EV share in Indiana is relatively low compared to the average EV share in the U.S. or compared to the EV share of top states such as California (Alliance for Automotive Innovation, 2022) and high adoption rates are unlikely to be reached without aggressive policy action (M.J. Bradley & Associates, 2018). The pessimistic scenario projects 30% electric medium- and heavy duty vehicle market penetration level in 2030.

Figure 5.7 shows the fuel tax revenue and revenue loss for all vehicle classes from 2021 to 2035 in Indiana. The fuel tax revenue (blue bars) refers to the revenue that would be generated from gasoline or diesel vehicles given the most likely EV market penetration levels. The graph also presents the fuel tax revenue loss due to EVs (red bars). For example, in 2035, the total fuel tax revenue will be around $3 billion due to the revenue loss associated with the emergence of EVs ($2.1 billion). If there was no revenue loss though, the total fuel tax revenue would be equal to around $5.1 billion. The average annual growth rate of the revenue loss is around 57% and reduces over the years. The fuel tax revenue decreases by around 21% from 2030 to 2035. Figure 5.8 focuses on the fuel tax revenue loss and breaks it down by vehicle class. As expected, the fuel tax revenue loss is higher for these vehicle classes that have higher EV market penetration levels (e.g., combination trucks).

Figures C.1 and C.2 of Appendix C illustrate the impact of the proposed recovery EV fee and the existing EV fee on the revenue that is generated by the total vehicle registrations from 2021 to 2035 in Indiana. This revenue is the summation of all vehicle registration fees with the recovery EV fee or the existing EV fee. These two graphs are based on the premise that the recovery EV fee will be implemented as a supplemental annual registration fee for each vehicle class.

Figure 5.7 showed the fuel tax revenue and revenue loss for the state due to the emergence of EVs. This revenue is distributed to different accounts and funds according to specific ratios, as described in Section 5.1. The corresponding fuel tax revenue and revenue loss for INDOT were calculated and are illustrated in Figure 5.9. As can be seen, the INDOT fuel tax revenue loss increases from around $1 million in 2021 to around $963 million in 2035. In 2035, INDOT will generate around $1.3 billion due to the revenue loss associated with EVs while approximately $2.3 billion would have been generated if all vehicles were running on gasoline or diesel.

As has been discussed in Section 5.1, scenarios were developed to estimate the portion of revenue from EV fees that is distributed to INDOT. This way, the potential of EV fees to cover the INDOT fuel tax revenue loss can be examined (without considering other revenue sources). Figures 5.10 and 5.11 show the revenue from EV registrations that is distributed to INDOT for different percentages of the share of EV-fee revenue

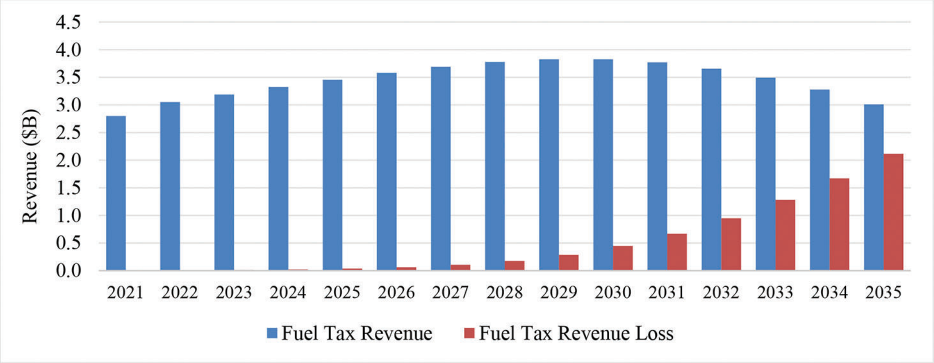


Figure 5.7 Projections of total fuel tax revenue and revenue loss in Indiana (for the most likely scenario).

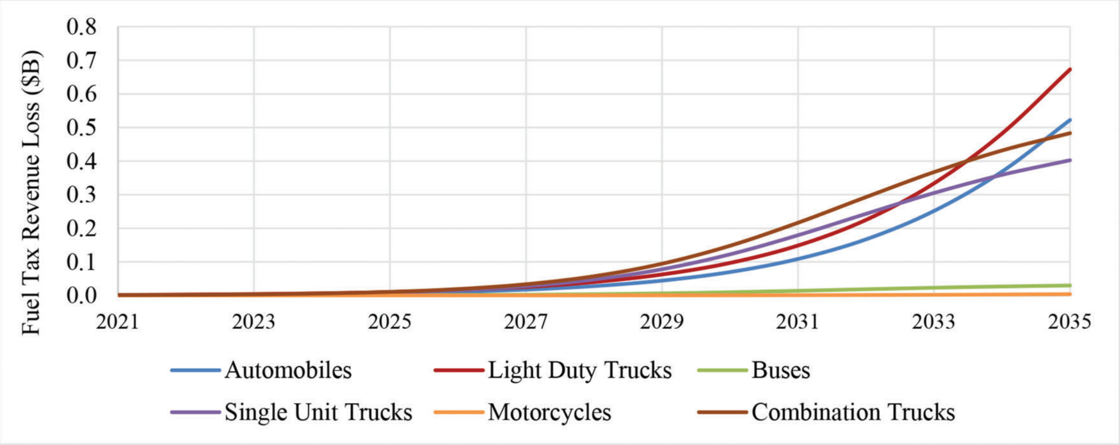


Figure 5.8 Projections of revenue loss by vehicle class in Indiana (for the most likely scenario).

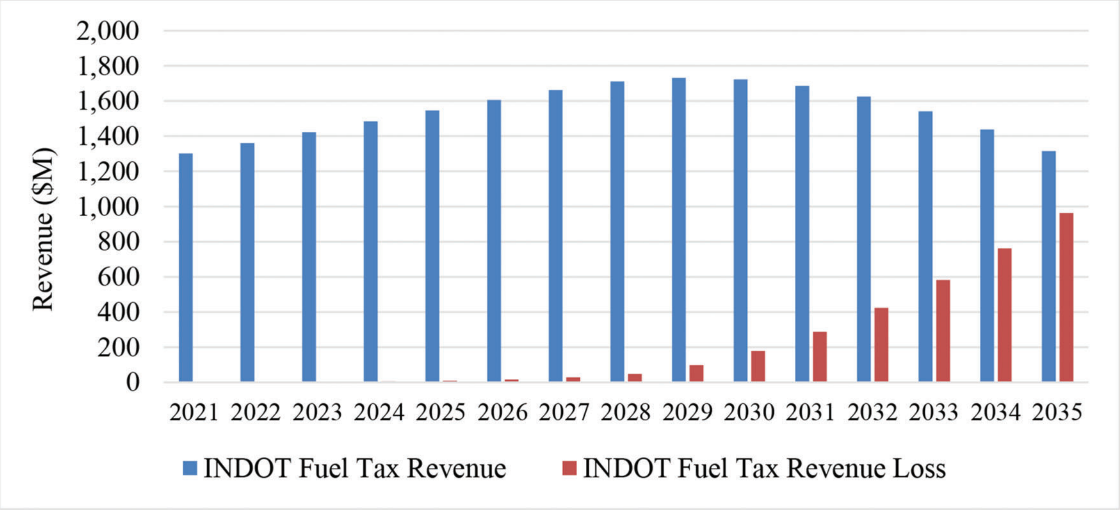


Figure 5.9 Projections of INDOT fuel tax revenue and revenue loss (for the most likely scenario).

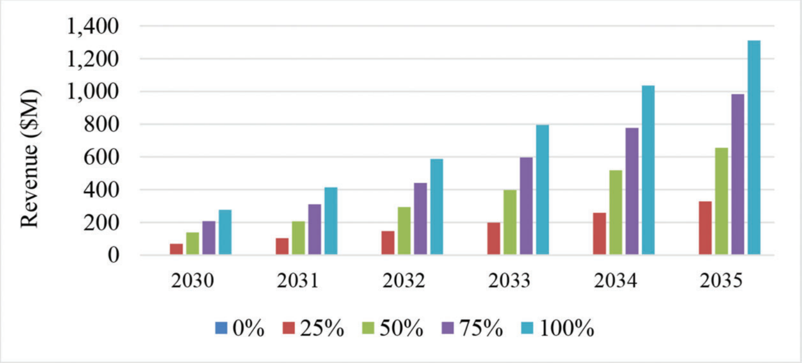


Figure 5.10 Projections of total INDOT revenue from EV registrations (recovery EV fee) for different percentages of EV revenue shares (for the most likely scenario).

(0%, 25%, 50%, 75%, and 100%) for both the proposed recovery EV fee (Figure 5.10) and the existing EV fee (Figure 5.11). INDOT will start to be given a share of the EV-fee revenues under the conditions of the most likely scenario (INDOT having a share of EV-fee revenue collection by INDOT starts in 2030 with 5% market penetration level for light duty vehicles and 30% market penetration level for medium and heavy duty vehicles). The results are presented from 2030 to 2035 since before 2030 the INDOT revenue from EV fees is zero.

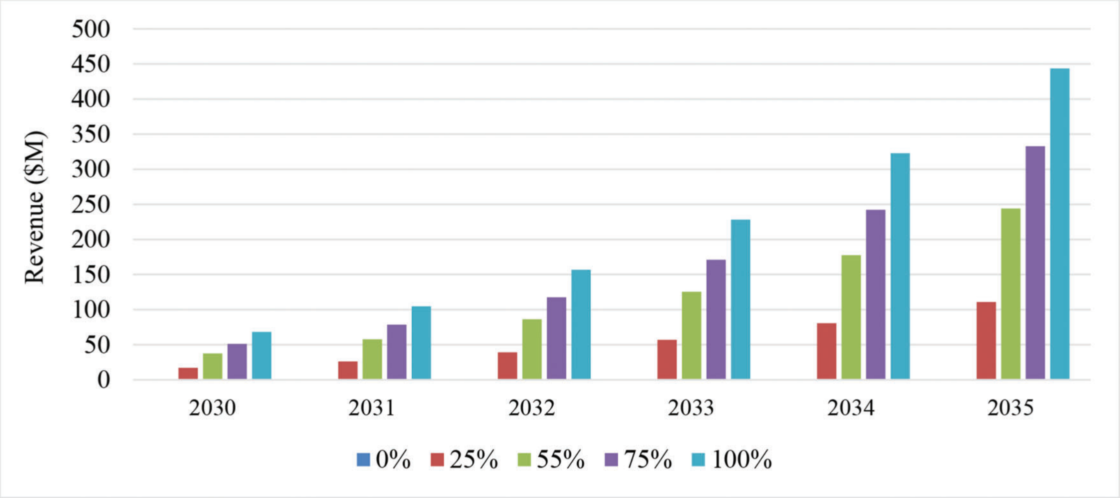


Figure 5.11 Projections of total INDOT revenue from EV registrations (current EV fee) for different percentages of revenue share (for the most likely scenario).

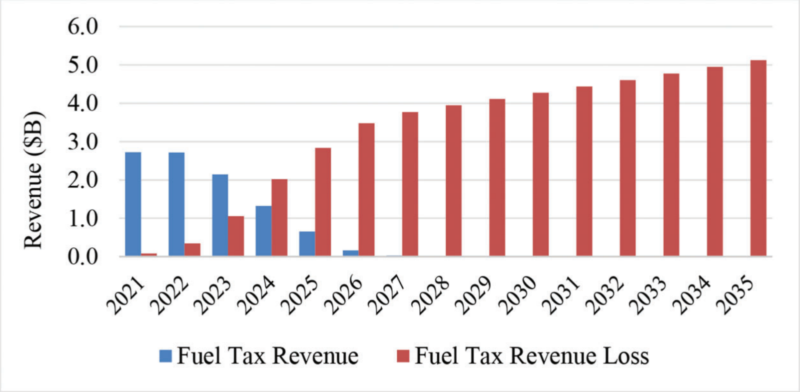


Figure 5.12 Projections of total fuel tax revenue and revenue loss in Indiana (for the optimistic and pessimistic scenarios).

Imposing the proposed recovery EV fee (Figure 5.10) can generate $69 million (given that 25% of the revenue from EV fees is received by INDOT) to $277 million (with 100% of the revenue being collected by INDOT) in 2030 and $328 to $1,311 million in 2035 for INDOT. For revenue collection of 75% and 100%, the revenue from recovery EV fees can cover the INDOT fuel tax revenue loss. With 75%, there is a cumulative revenue surplus of around $118 million from 2030 to 2035 and this surplus increases to $1,224 million if INDOT receives 100% of the EV-fee revenues. Figure 5.11 demonstrates that the revenue from existing EV fees cannot cover the fuel tax revenue loss for INDOT, even with 100% EV revenue share in 2030. The revenue deficit with 100% EV revenue received by INDOT, varies from about $111 million in 2030 to $963 million in 2035.

(b) Optimistic and Pessimistic Scenarios

The optimistic scenario, from the perspective of INDOT, is based on 100% EV market penetration level for all vehicle classes in 2030 and 100% EV revenue collection from EV revenues, leading to large revenue distributed to INDOT. Note that assuming 100% EV market penetration in 2025 would also be considered highly beneficial in terms of revenue generation but such a scenario seems impossible given the current EV market share both in Indiana and the U.S.; hence, it was not considered. On the other hand, assuming 100% EV market penetration level for all vehicle classes in 2030 and 0% collection of EV-fee revenue forms a pessimistic scenario from the perspective of INDOT.

These two scenarios share the same EV market penetration level and thus, the total revenue before the distribution to INDOT will be the same. Figure 5.12 shows the fuel tax revenue and revenue loss. For these scenarios, the cumulative revenue loss from 2021 to 2035 is around $50 billion which is approximately $42 billion higher than the cumulative revenue loss of the most likely scenario. As expected, the total fuel tax revenue in these scenarios would be zero from 2030–2035 due to the 100% EV market penetration level. Automobiles and light duty trucks constitute the two top vehicle classes that are associated with higher revenue loss compared to the other vehicle classes (Figure 5.13). Figures C.3 and C.4 of Appendix C show the impact of the proposed recovery EV fee and the existing EV fee on the revenue that is

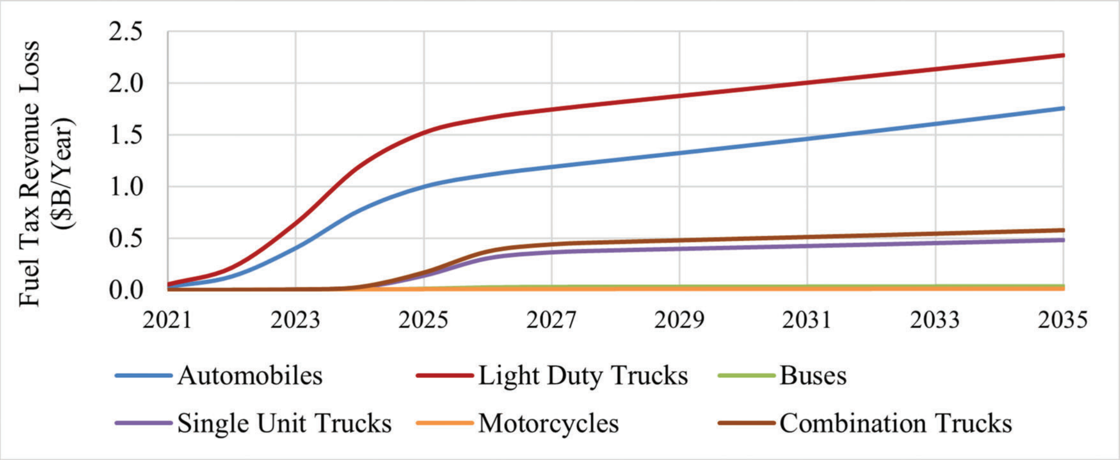


Figure 5.13 Projections of revenue loss by vehicle class in Indiana (for the optimistic and pessimistic scenarios).

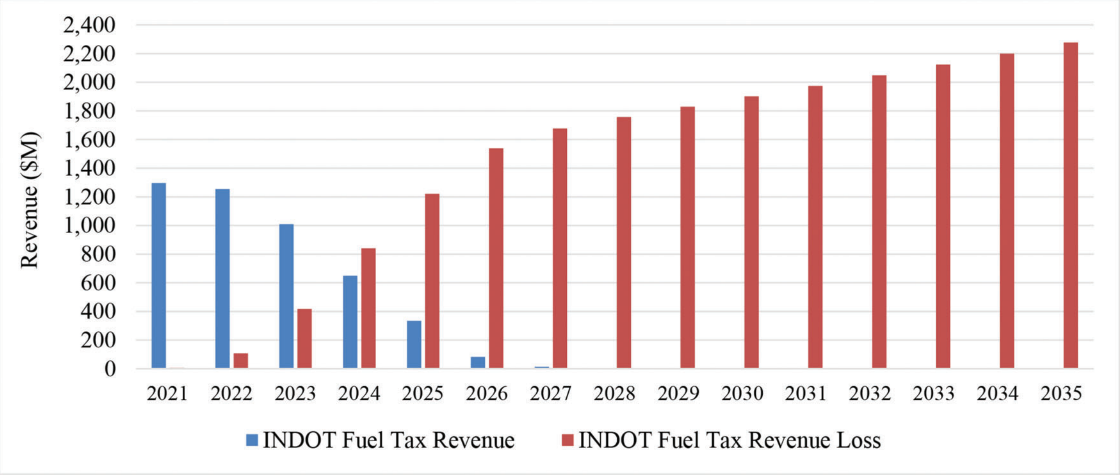


Figure 5.14 Projections of INDOT fuel tax revenue and revenue loss (for the optimistic and pessimistic scenarios).

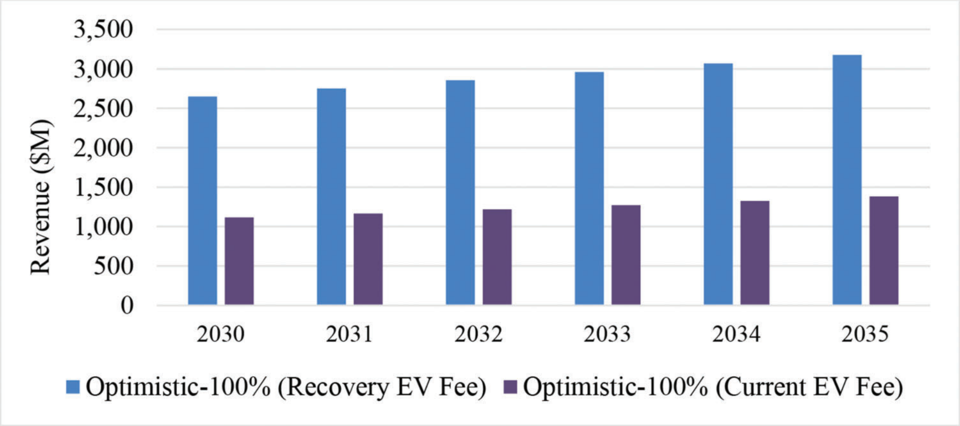


Figure 5.15 Projections of total INDOT revenue from EV registrations (current and recovery EV fee) for optimistic and pessimistic scenarios (pessimistic scenario: 0% or $0 distributed to INDOT).

generated by the total vehicle registrations from 2021 to 2035 in Indiana.

Figure 5.14 shows the fuel tax revenue and revenue loss for INDOT. As can be seen, INDOT has a significant revenue loss that reaches $2.3 billion in 2035, being 1,315 million higher than the corresponding revenue loss in the most likely scenario. Figure 5.15 shows the revenue from EV fees that is distributed to

INDOT. The pessimistic scenario assumes that 0% or $0 distributed to INDOT. In the optimistic scenario, the recovery EV fee can generate around $2,650 million in 2030 and $3,177 million in 2035. Thus, the recovery EV fee can cover the INDOT fuel tax revenue loss and offers a revenue surplus that reaches $899 million in 2035. Similar to the most likely scenario, the current EV fee leads to revenue deficit.

5.4 Discussion

5.4.1 Alternative Funding Mechanisms

Imposing additional annual fees for EVs to cover the revenue loss is considered a potential key initiative in the generation of transportation revenue but could negatively impact EV market penetration. The proposed recovery EV fees could be implemented as annual fees but may cause the opposition of the public due to their high rate, particularly for heavy vehicle classes. Thus, alternative ways to implement this recovery EV fee can be considered to ensure sufficient revenue as well as support EV adoption. A mix of alternative policy options to generate transportation revenues may include annual/monthly/quarterly EV fees, taxes on electricity, or mileage-based fees. In the context of fee taxes, the estimated recovery EV fee can be converted to a tax on electricity when charging an EV, measured in $/kWh, or to a user fee based on the mileage driven by the vehicle, measured in $/mile.

To calculate the VMT fee, the recovery EV fee was divided by the average VMT per vehicle (refer to Section 5.2 for the data sources). The estimation of the tax on electricity required data on VMT per vehicle as well as on each vehicle class's efficiency or energy consumption rate (kWh/mile) to calculate the EV consumption per vehicle class (total kWh). The recovery EV fee was divided by the total EV consumption, resulting in a tax on electricity or "pay-as-you-charge" fee. Note that here is still limited information and uncertainty about EV efficiency (kWh/miles), especially for heavier vehicles, and thus, average or indicative values from publicly available data sources were used in this study to provide an estimation. Table 5.7 shows the data sources used for each vehicle class. It was assumed that the EV efficiency decreases by 2% every year due to the EV technology improvement (Muratori et al., 2021). Figures 5.16 and 5.17 illustrate the results regarding the VMT and pay-as-you-charge fees per vehicle class and per year to break-even the fuel tax revenue loss. The calculated pay-as-you-charge fee represents the additional amount that should be charged on electricity consumed by EVs in the state to avoid the potential decrease in revenue due to EV adoption. As can be seen, combination trucks, single unit trucks and buses have higher VMT fees while motorcycles, single unit trucks and light duty trucks have a higher fee on a per kWh basis (compared to the rest of the vehicle classes). This shows that heavy vehicles pay more on a per mile basis, but this is not the case with the pay-as-you-charge fee. Hence, the trend (regarding which vehicle class will pay more or less) is not consistent across the alternative mechanisms nor is it always a reflection of vehicle weight trends, which indicates that a combination of alternative mechanisms could be applied. This combination may depend on different factors such as EV market share or vehicle class characteristics (e.g., weight) or other policy or operational criteria.

Similar to increase in fuel efficiency over time due to technology, EV efficiency values are expected to increase in future, and this will affect EV revenues. If that happens, the same revenue gap that has bedeviled gasoline fuel revenues, will be experienced for EVs too. The gap could be decreased by raising the electricity price; however, this will be difficult because transportation is not the only source of electricity and raising electricity prices to close the transportation revenue gap will affect the residential and industrial markets unduly.

Table 5.8 describes the alternative policy options to generate transportation revenues, including EV fees, taxes on electricity or mileage-based fees. The information shown in the table are based on the study results and highway funding literature (see Section 2.7).

5.4.2 User Costs

EV users may pay additional charges that can hinder the adoption of EVs; however, this is only one aspect of the user total cost of ownership, since EV users can still reap the benefits of lower fuel costs. To facilitate comparison between fuel tax and electricity tax rates and to address potential concerns for discouraging EV adoption due to the additional fees, Figures 5.18(a–f)

TABLE 5.7
Data for EV efficiency

Vehicle Class	Value (kWh/mile)	Data Source
Automobiles	0.346	Average of eleven latest models from EPA (2021)
Light Duty Trucks	0.421	Average of three Tesla Cybertruck models from Electric Vehicle Database (n.d.)
Buses	1.820	Number reported by Johnson et al. (2020)
Single Unit Trucks	0.940	Average of three models from CARB (2018) and Smith et al. (2019)
Combination Trucks	2.100	Average of six models from CARB (2018) and Smith et al. (2019)
Motorcycles	0.064	Number reported by Huang et al. (2018)

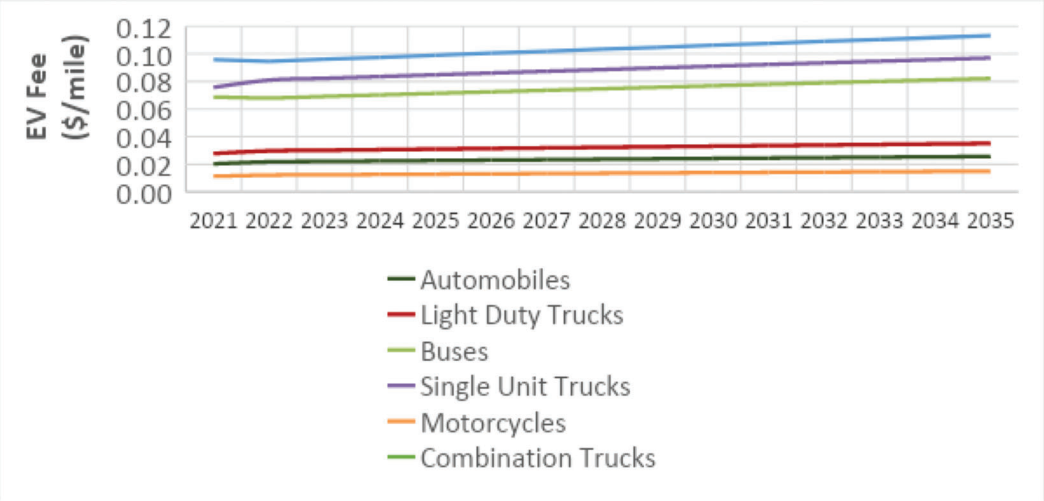


Figure 5.16 Projections of the recovery EV fee converted to a VMT fee in $/mile.

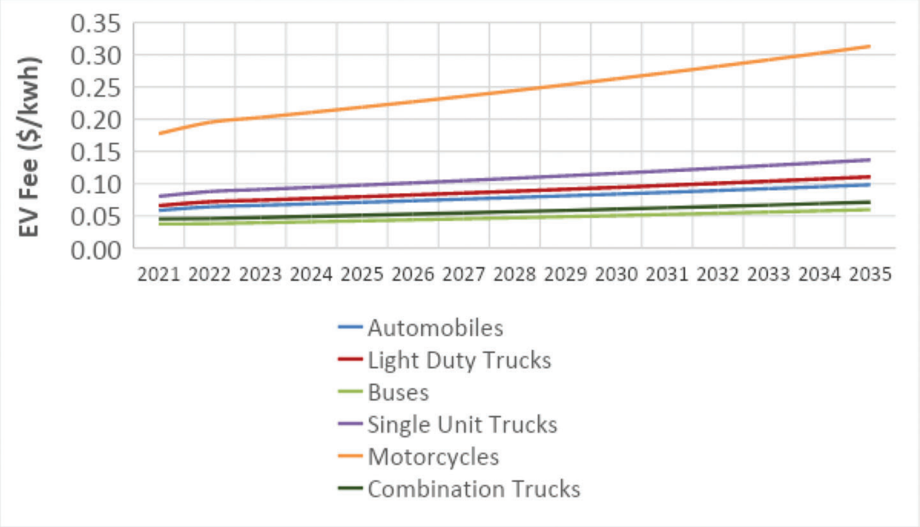


Figure 5.17 Projections of the recovery EV fee converted to a pay-as-you-charge fee in $/kWh.

were created. The figures show the total user costs in 2021 and 2035 when driving a gasoline or diesel vehicle and an EV. Each figure shows the fuel type (diesel or gas) that is dominant in the respective vehicle class, according to the fuel consumption percentages described in Section 5.2. These costs correspond to the average annual miles driven per vehicle in 2021 and 2035 (Section 5.2) and to fuel ($/gallon) or electricity ($/kWh) prices. In particular, the values and data sources for gasoline prices have been reported in Section 5.2. Historical data from 2015 to 2021 on Midwest diesel retail prices was obtained from EIA (2021a) (taking the average value for each year) and trend analysis was used to forecast the prices to 2035. The electricity prices considered were (1) the pay-as-you-charge fee that was found from this analysis and (2) the standard Midwest electricity price per kWh. Historical data on the latter was found for 2015–2021 from the U.S. Bureau of Labor Statistics (2021) and the prices were projected to 2,035 using trend analysis. Therefore, the cost to drive an EV per year was estimated by multiplying the total EV consumption (in kWh) by the summation of the aforementioned electricity prices. As can be seen from the figures, driving an EV is less expensive than driving a conventional vehicle, irrespective of the vehicle type. More specifically, the cost of driving an EV is half of the cost to drive a gasoline or diesel vehicle on average. Considering potential incentives and/or special rates that could be offered by utilities and local power providers, this fuel cost difference would be even higher.

5.5 Summary

The improvement of fuel efficiency of the vehicle fleet has influenced fuel tax revenue and thus, transportation agencies are facing pressures in their effort to operate and maintain transportation networks.

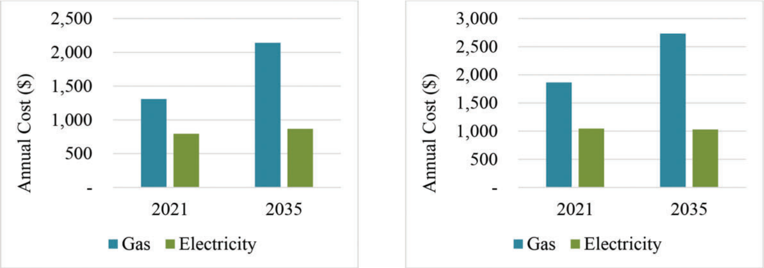
TABLE 5.8
Alternative mechanisms to implement the recovery EV fee (including the annual EV fee)

	Annual EV Fee	EV Fee Broken Into Periodic Payments	Pay-As-You-Charge Fee	VMT Fee
General Description	The total amount of EV recovery fee is paid once a year.	The amount of EV recovery fee is paid periodically (e.g., monthly or quarterly).	The EV recovery fee is converted to a tax on electricity when charging an EV, measured in $/kWh.	The EV recovery fee is converted to a use fee on the mileage driven by the vehicle, measured in $/mile.
Advantages	Fees are associated with vehicle ownership and thus, constitute a reliable source of revenue compared to use-based taxes (given that vehicle ownership will not significantly decline). This system is in line with the existing registration funding system and would therefore require less education, public outreach efforts, and would be lower in cost to implement.	Costs are spread out over time, alleviating the financial impact of one-time registration fees. Fees are associated with vehicle ownership and thus, are more reliable sources of revenue.	Costs are spread out over time. Fees are similar to the pay-at-the-pump nature of existing fuel taxes, facilitating their adoption by the public and implementation by the agencies. Fees have the potential to be efficiently collected through the use of a small number of transaction points.	Costs are spread out over time. Fees can be easily adjusted based on different parameters (e.g., road type, vehicle weight, time of day) to account for the actual cost caused to the transportation network. This mechanism may lead to more strategic/targeted investments in transportation infrastructure, since it can provide accurate information about which roads have high EV traffic.
Disadvantages	Fees are high to be paid upfront. Fees may hinder the promotion of EV adoption, especially from heavier vehicle classes that have higher costs. Fees do not consider mileage or usage Fees may become unsustainable in a future with shared mobility.	Fees may still hinder the promotion of EV adoption if the periodic payment is still high. Fees do not consider mileage or usage. Fees may become unsustainable in a future with shared mobility.	It is complex to accurately measure the location and time of EV charging to estimate the fee/tax. Most charging occurs at home and it would be difficult and costly to separate the EV electricity usage from the household usage. Fees may not be as accurate as a weight-based metric for assessing the impact of vehicles on the roads even though heavier vehicles will generally use more kWh per mile. Imposing fees on charging infrastructure could discourage its use and purchase of EVs. There may be privacy-related concerns if energy usage/charging location data are shared (with power companies or third-party data aggregators).	Fees do not consider usage and do not account fuel efficiency. Fees do not accurately capture the impact of each vehicle class on the transportation system. Fees may further discourage EV adoption for longer-distance trips and not receive uniform public acceptance from rural versus urban drivers. There may be privacy-related concerns due to the fact that the distances traveled are monitored. Administrative costs can be high since tracking technology, account management and transaction charges may be needed.

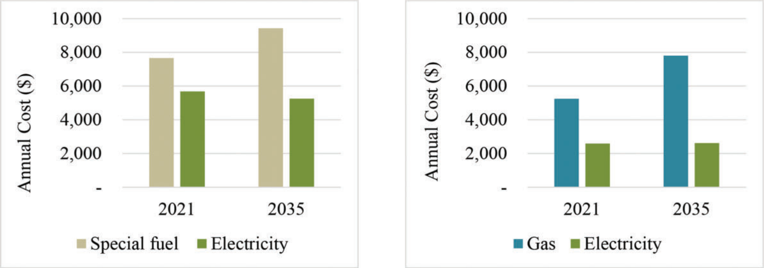
Continued

TABLE 5.8
(Continued)

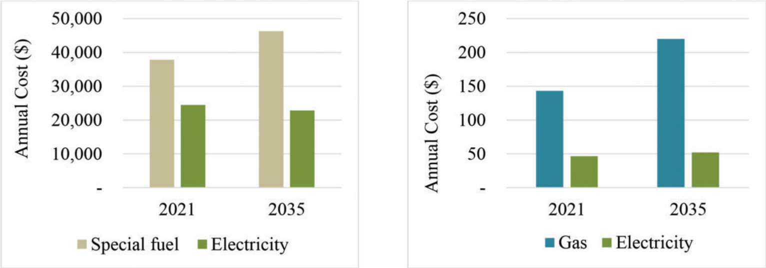
	Annual EV Fee	EV Fee Broken Into Periodic Payments	Pay-As-You-Charge Fee	VMT Fee
Policy Considerations	Additional design is needed to avoid potential disparity between EV miles driven and the amount paid for road usage. EV users with low mileage may be charged more per mile than EV users with higher mileage. Increased fees over time may work in opposition to purchase incentives for EVs given by state and federal governments. Fees can be combined with mileage-based or pay-as-you charge fees.	The EV fee broken into periodic payments may apply only to the case of vehicle classes whose annual EV fee is significantly high. The threshold for considering an EV fee high should be investigated	Their implementation may require both on-vehicle technology and submetering or smart chargers to measure the electricity consumption coming from EVs. Fees can be indexed for inflation to maintain the purchasing power of revenue generated by the fees. Utilities should build new tariff structures to reward certain charging behaviors (e.g., off-peak charging) to decrease user cost and thus, increase adoption. A connection between utilities, the state DOT and regulators should be developed (which is similar to the motor fuel industry) to effectively remit payments to revenue collection agencies, especially for the case of home charging.	Proper design is needed to account for the potential disparity between rural and urban EV users. This mechanism may need a specific design to encourage fuel efficiency. From a user perspective, EVs could be made to have lower VMT fees because EVs improve air quality. However, any EV fee should be adjusted appropriately to generate enough funding for transportation. The combination of this mechanism with weight-based fees would create a fairer rate structure that would also account for the impact of EVs on the road. Utilities can collect a portion of the fee to cover administrative costs. Their implementation may require multi-state implementation and agreements.



(a) Automobiles (b) Light Duty Trucks



(c) Buses (d) Single-Unit Trucks



(e) Combination Trucks (f) Motorcycles

Figure 5.18 Annual fuel costs for (a) automobiles, (b) light duty trucks, (c) buses, (d) single unit trucks, (e) combination trucks, and (f) motorcycles.

This study aimed to enhance the revenue structure by assessing the funding needs, finding the optimal EV fee by considering scenarios of EV market penetration levels and by evaluating the potential of funding mechanisms to recover the revenue loss. While past studies have focused on examining the revenue impacts of EV adoption under various scenarios for light duty vehicles mostly, this research quantifies (1) the revenue impact associated with all vehicle classes and (2) potential funding mechanisms to prevent the decline in revenues generated. The results can help state agencies better understand the impact of EVs on the highway revenue and serve as a reference to support decision-making on EV policies. The optimal annual EV fee per vehicle class (recovery EV fee) that is needed to recoup the fuel tax revenue loss was estimated. The recovery EV fee was converted to a VMT and pay-as-you-charge fee per vehicle class and per year through which revenue generation from EVs would breakeven the loss. Lastly, potential barriers to the implementations of these options and policy aspects were examined.

6. EVALUATION OF STRATEGIC PARTNERSHIPS AND GUIDANCE FOR EV PREPAREDNESS BASED ON STAKEHOLDERS' INTERVIEWS

There is limited literature regarding the existing market and business models for the provision of EV charging infrastructure, while charging infrastructure is critical for widespread EV diffusion. This chapter summarizes the outcomes of interviews conducted with stakeholders involved in the EV ecosystem. The objective of the interviews was to examine the strategic partnerships and business models for the provision of EV charging infrastructure as well as explore various impacts and aspects related to the adoption of EVs.

6.1 Data and Methods

This section provides details on the process and results of interviews conducted with multiple stakeholders for the evaluation of strategic partnerships and business models for the provision of EV infrastructure. The research team interviewed representative stakeholders from the EV ecosystem. The purpose of the interviews was to gather knowledge on the main factors related to the promotion of EVs and evaluate the strategic partnerships and business models for the provision of EV infrastructure. By reviewing the literature (see Section 2.6), the following main groups of stakeholders were identified: automotive industry/manufacturers, utilities/energy providers, government/policy makers, charging equipment/infrastructure providers, non-profit/non-governmental organizations, and other; representing a diversity of interests and organizations within the electrification ecosystem to explore a range of issues and needs. A purposive sample was used with the selection criteria being their relevant experience to the research questions and their key position in the target stakeholder groups (e.g., representatives from automotive industry, representatives from utilities etc.).

Stakeholders' contact details were obtained through the personal contacts of the research team. The research team contacted the prospective interviewees with an invitation email. The recruitment email indicated the purpose of the interview and its format (virtual), expressed the importance of the individual's participation and opinion, and also included the interview agenda. A follow up email was sent to the stakeholders that agreed to participate to schedule the interview and provide them with the specific discussion topics. Additionally, the email included the link to a survey that participants had to complete prior to the interview in order to (1) provide their consent to participate in the research study (using a consent form) and (2) to answer general questions related to their organization and role within your organization, their organization's experience within the broadly defined EV ecosystem, and their organization's perspectives about EVs. The goal of those questions was to help guide the discussion during the interview and to supplement the interviews with quantitative data. The survey took approximately 5–10 minutes to complete. A reminder email was sent to all confirmed participants two days before the interview to ensure maximum participation. The interview material was developed by the research team and refined following a pilot study based on a convenience sample. Note that all documents for the interviews (including all recruitment materials) were reviewed and approved by the Purdue Institutional Review Board (IRB-2021-1263). The interview material agenda and discussion guide are included in Appendix D.

The interviews were conducted virtually between October 11 and December 3, 2021, using a video conferencing service and each interview lasted approximately 40 minutes. A total of 23 individuals participated from 19 organizations/agencies. Table 6.1 shows the number of organizations/agencies and participants per stakeholder group.

The research approach consisted of semi-structured interviews which are based on asking open-ended questions while allowing participants to provide in-depth responses. Qualitative semi-structured interviews are one of the most widely applied methods of data collection within the social sciences (Bradford & Cullen, 2011). The semi-structured nature of the interviews enables participants to be more candid and freer to express their opinions for a broader spectrum of subjects (Gill et al., 2008). At the beginning of each interview, participants were reminded about the purpose of the interview, the main structure of the interview, the consent form they had to complete before the interview and the confidentiality of their responses. The participants that had not completed the pre-survey were sent a link to the consent form only (without the rest of the survey questions) to indicate their agreement to participate before moving on to the main part of the interview. Thus, although all participants completed the consent form, 19 out of 23 took the full survey. The research team also asked for permission to keep audio recordings of the interviews for research integrity reasons. The next part of the interview involved an open-ended discussion around the research topics guided by the research team (see Appendix D for the discussion topics).

After the completion of the interviews, the research team converted all the audio recordings into transcripts in order to perform the next step of the qualitative analysis, the content analysis. Krippendorff (2004) defined content analysis as "a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use" (p. 18). Content analysis is a systematic way of identi-

TABLE 6.1
Stakeholder groups, number of organizations/agencies, and participants

Stakeholder Group	Number of Organizations/Agencies	Number of Interviewees
Automotive industry/manufacturers	5	5
Utilities/energy providers	4	5
Government/policy makers	2	3
Charging equipment/infrastructure providers	2	2
Non-profit/non-governmental organizations (e.g., clean cities)	3	4
Other (engineering consulting firms, researchers, EV operators, etc.)	3	4

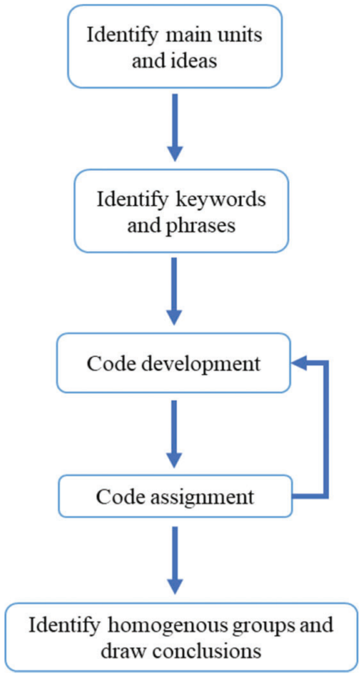


Figure 6.1 Visual description of the content analysis process (adapted from Bengtsson, 2016; Ward, 2021).

fying all the main concepts arising in the interviews, which afterwards would develop all the keywords and themes produced during the interviews (Bengtsson, 2016; Stemler, 2000). Although content analysis is one of the most common tools for conducting qualitative research, and especially for identifying main ideas and trends in given data source, it also poses some limitations based mainly on misconception of researchers and that use that method. The belief that content analysis is mainly a word frequency-based method for producing the main ideas is totally false and affects its credibility (Stemler, 2000).

The research team read all transcripts that were produced from the interviews in order to gain a first understanding of the context; during that process some first main ideas and trends emerged. This also enabled the subdivision of the text to smaller units and in turn, keyword, and code framing of the text (Erlingsson & Brysiewicz, 2017). The aforementioned procedure is continuous until the code and keyword framing is sufficient for the purpose of the study, and it was performed with the NVivo qualitative data analysis software. Figure 6.1 summarizes the content analysis procedure.

6.2 Content Analysis and Results

This section presents the key findings from the stakeholder interviews by discussion topic.

6.2.1 Stakeholder Groups Involved in the Provision of EV Charging Infrastructure

Identifying the stakeholder groups involved in the provision of EV charging infrastructure is a very challenging task, as it includes an immense ecosystem with multiple entities having a role to play. Despite this challenge, most of the stakeholders provided a fairly clear overview of the stakeholder groups involved in the provision of EV charging infrastructure. Interviewees identified the main stakeholder groups involved by categorizing them based on whether they are public and private contributors, fleet or private vehicle owners and based on the level of EV charging.

Firstly, public contributors consist of different levels, namely local (municipals, towns, and counties), state, regional (networks such as the REV Midwest–the Regional EV Midwest Coalition) and national levels with the federal government. According to the interviewees, the role of public agencies leans more towards the planning side as well as raising awareness and educating the industry and the general public. Private entities consist of a large group of non-governmental organizations, ranging from big firms to the individual EV owner. Table 6.2 describes a basic classification approach for the main stakeholder groups involved in the provision of EV charging infrastructure and their main role.

In an effort to identify the main stakeholders group involved based on the level of EV charging, Level 2 and fast charging are the two categories that dominated the discussion. For Level 2 charging projects, the main stakeholder involved is the individual who is going to host the charging infrastructure. For publicly available chargers, the municipality is the main stakeholder to host the charging infrastructure. There are also firms that choose to install chargers in their parking facilities for their customers. Finally, there are the individuals who own an EV and choose to install a charger in their parking lot. There was also the opinion that not all Level 2 charging stations require the utilities' involvement in hosting the charging infrastructure. In terms of fast charging, strategic partnerships between utilities and different entities such as the charging site host, the supplier of the hardware, the installer and designer of the site are needed to ensure a safe and resilient network to the general public. Table 6.3 gives a classification for the main stakeholder groups involved in the provision of EV charging infrastructure base on the given level of charging.

Despite the fact that Original Equipment Manufacturers (OEMs) and auto dealers do not typically own and operate chargers, their involvement is critical for the provision of charging infrastructure via demonstration events and a good sales experience for prospective EV owners. At the same time, charging network providers, companies that are the owners and operators of public accessible charging infrastructure, are critical

TABLE 6.2
Main stakeholder groups involved

	Public and Private Contributors	
	Public Sector	**Private Sector**
	Federal government Regional partnerships State governments County governments City governments Municipal governments	Non-governmental organizations, ranging from big firms to individual EV owners
Main Role	Planning side as well as raising awareness and educating the industry and the general public	Deployment and use of EV charging infrastructure

TABLE 6.3
Main stakeholder groups involved based on the level of charging

Stakeholder Groups Involved in the Provision of EV Charging Infrastructure	
Level of Charging	
Level 2 Charging	**Fast Charging**
Charging infrastructure site host	Charging infrastructure site host Utility companies Charging infrastructure equipment manufacturers Installers and designers of the charging infrastructure site

components of the electrification of transportation process. Lastly, many interviewees stressed out the importance of research institutions for conducting research on multiple adoption related issues of EVs.

6.2.2 Stakeholder Interrelationships

The complexity of the EV ecosystem was recognized by all the stakeholders. Working with multiple different vendors and stakeholders is very challenging and a critical point is that everyone involved should maintain the focus on the mission, which is the deployment of EV technology and the charging infrastructure development. As the transition to an electrified transportation system requires incredible amounts of capital and resources, competitive forces that exist between the various stakeholders should be blunted and exchanging knowledge for the advancement of electrification technologies is becoming a priority.

Another crucial point that interviewees pointed out is the lack of education and familiarity with EVs and charging technology. The two most experienced parties regarding charging infrastructure are typically the manufacturer of charging equipment and the utilities. The customer, the site host, and the electrician lack expertise though, and thus, there are opportunities for workforce development. The interrelationships between the different stakeholders also involve the collaboration between the charger manufacturers and the entity that owns the land where the charger is to be placed, as well as interactions with the OEMs. Lastly, the interactions between the electric utilities and the above-mentioned stakeholders are crucial for the power needed for the charging operations. So, those are the interactions typically on charging infrastructure facility side with the charging point operator also involved.

It was also supported that charging infrastructure owners are dependent on the fleet and the private vehicle owners for the charging demand. Hence, there should be a close coordination between these stakeholder groups in terms of understanding where the demand is, where the charging infrastructure is, and if policies are in place to help the growth of the network in a way that is as predictable as possible. In addition, EV users need the charging infrastructure and programs from the utilities to understand the pricing policy and its function. Furthermore, payment systems are an important aspect for EV users. So, there is a need to provide better transparency to understand the cost of energy as a lot of people outside the transportation electrification ecosystem face difficulties in understanding demand charges, time of use charges, or even their electricity bill. Multiple stakeholders proposed that education and coordination with utilities and public agencies is essential for this purpose. The extent to which a public policy framework is in place to provide, all the involved stakeholders, with relevant information and whether special rates or incentive program are available can significantly affect the customer value proposition. Figure 6.2 shows a diagram of the main stakeholder interrelationships and Table 6.4 provides more information about the specific interrelationships.

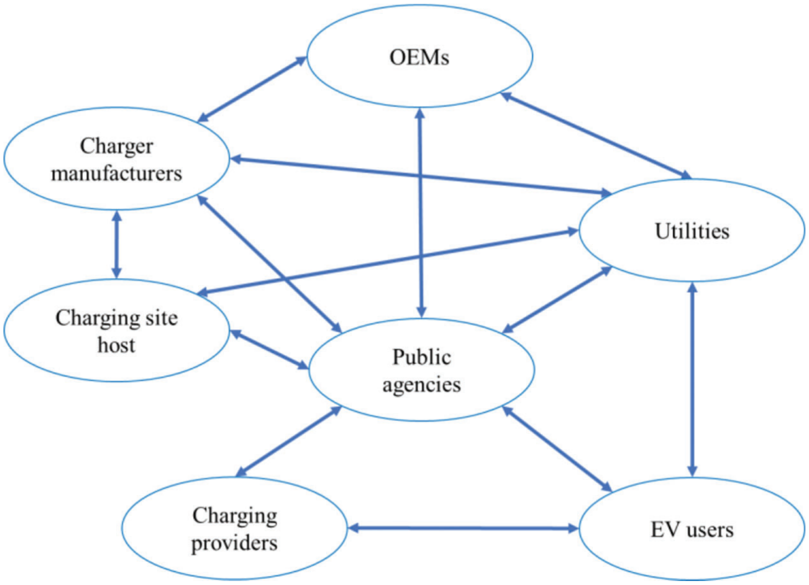


Figure 6.2 Main stakeholder interrelationships diagram.

TABLE 6.4
Main stakeholder interrelationships and interactions

Stakeholder Group	Interrelationship
Charger manufacturer and OEMs	Collaboration and knowledge exchange regarding EV charging and battery technology
Charger manufacturer and charging site host	Support and knowledge exchange on the installation and maintenance of EV charging equipment
Charging providers and EV users	Understanding of the demand, the location of charging infrastructure and existing policies that are in place
Utilities and EV users	Better transparency and understanding of the pricing policy and payment systems
Public agencies and EV eco-system stakeholders	Education and coordination for better communications of public policy frameworks, with relevant information for special electricity rates or incentives

6.2.3 *Business Models*

There is a range of business models that can be applied regarding the deployment of EV charging infrastructure, each suited to a different objective. When considering an EV charging business model, it is important to understand which models will be most effective for the type or class of vehicles served and the type of location where the charging station will be installed. The categorization approaches that the different stakeholders proposed were quite different, but the majority of them highlighted the different needs between local, interstate, home and parking lots charging, between Level 2 and fast charging and between commercial and privately-owned vehicles. Many of the aforementioned categorizations are overlapping and affect each other.

In an effort to propose suitable business models based on the location of the charging infrastructure, a distinction between local level and state or even interstate level is needed. For the local level, private's sector involvement is crucial, although there might be also public involvement. Level 2 charging is the most common at the local level and stakeholders stated that the Level 2 charging market is competitive already, with different options for consumers such as buying or leasing of charging infrastructure, or even paying a monthly amount in the electric bill for having a third party installing a charger. In addition, Level 2 charging infrastructure is not necessarily owned by utilities, but operational data is needed in order to inform their plans and offer a reliable grid at an optimal cost. On the other hand, fast charging business models are totally different. The return on investment for potential site hosts of fast charging infrastructure is not profitable while at the same time fast charging can drive EV adoption. The public sector, utilities and charging network providers are the main stakeholders involved in fast charging at a local level as well as at the state and interstate level with multiple locations such as rest areas or gas stations being candidate locations for placing fast charging infrastructure.

The distinction between commercial fleets and privately-owned vehicles is another important categorization that affects the business models and is also closely related with the distinction between publicly accessible and private charging infrastructure. In the commercial fleet space, multiple business models can be applied. In particular, there are truck fleets that only own tractors and do not own trailers or there are fleets that only own trailers; so, the complexity and the difficulty to propose an appropriate business model is high. As we move forward into transportation electrification, there are some companies that are implementing new business models where they buy the truck, and they take over the charging. However, uncertainties and the amount of investment needed are high, creating a challenging environment for electric heavy-duty vehicles. In addition to the aforementioned concerns, it is a very common practice for a commercial fleet to develop private charging infrastructure, without public access. In this case, the business model is straightforward, as those organizations buy or lease the equipment, or perhaps use charging as a service, which involves a monthly subscription fee for the use of charging infrastructure without paying all the upfront costs of equipment, installation, and permitting. For privately-owned vehicles, the appropriate business models are different of those mentioned for the commercial fleet space, as they need mainly a publicly accessible charging infrastructure network which is strategically located to provide services for short commuting trips as well as long distance traveling.

The funding of charging infrastructure was quite a controversial subject and although different perspectives were heard, almost all stakeholders believe that the public sector is not solely responsible for the provision of charging infrastructure. At the same time, public fast charging businesses may not be financially feasible at low utilization rates. As this consists of an enormous adoption barrier, government has definitely a role to play by providing direct incentives, that might not be a long-term sustainable solution, or by electrifying public's sector fleet, a strategy that would offer great adoption and economies of scale opportunities. Operation and deployment of charging infrastructure is not an industry that OEMs are willing to get involved. Nevertheless, OEMs can take part in managing home charging by making the battery an asset for the vehicle owner and the grid, something that would allow vehicle owners to understand when they should charge and when they should discharge.

In general, multiple stakeholders mentioned some advanced business models of interest that can be advantageous for the acceleration of EV adoption. A public private partnership is where the private sector sees potential revenue stream, as indicated both during the interviews and in the pre-survey by the 68% of participants and could be beneficial for the public that is using the charging infrastructure. Another innovative business model is the charging as a service through which the initial capital cost of the charging infrastructure and the purchase cost difference between an EV and an internal combustion vehicle can reduce. In addition, payments for the use of charging infrastructure based either on how often, or how long a fleet is using a given charging network, or a kilowatt hour basis or even a per mile basis are applicable business models. The regulatory environment within which the utilities operate is crucial for the feasibility and the applicability of business models, as legislation drives the adoption and the deployment of EVs.

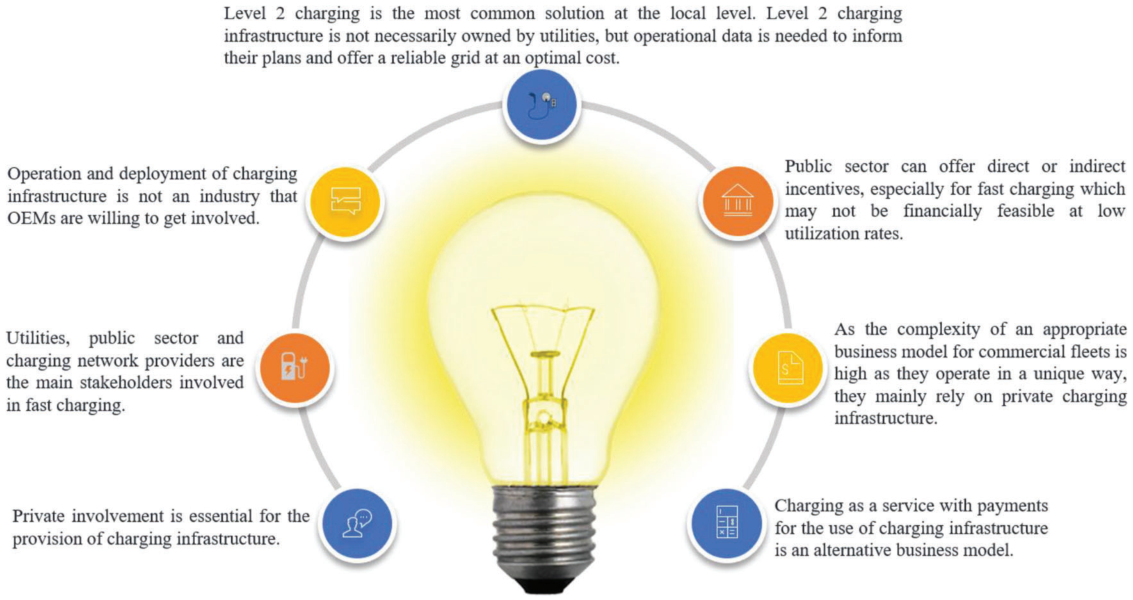
Finally, some important concerns were about the fairness among different paying systems for charging services. A kilowatt hour basis payment system is questionable, as battery's behavior and consumption are based on the environmental temperature, on the vehicle's model and on the utilities infrastructure and it can be an unfair business model for the end user. Additionally, most interviewees also mentioned the value of EV as a grid asset and highlighted that all business models have to take that into account and try to maximize those benefits. Figure 6.3 provides an overview of the main points discussed regarding business models.

6.2.4 Level of Charging Availability and Accessibility

Stakeholders' positions with respect to the level of charging availability and accessibility were controversial. While some of them pointed out that the current state of charging infrastructure availability and accessibility is limited, others supported that, with the current EV adoption rates, the available charging infrastructure is satisfactory, mainly referring to home/private charging.

It was supported that the charging availability and accessibility depends on the location of the area under review, as there are differences between urban and rural environments. In an urban setting, with the demand for charging being relatively high, the charging network most of the times is satisfactory and provides both fast charging as well as Level 2 charging, with the latter being the most common option. Indianapolis was used, multiple times, as a good case study of an urban environment within Indiana that has satisfactory charging coverage. In terms of home charging in urban environments, availability and accessibility issues may arise for apartments buildings or multi-unit residential complexes, as the adoption of EVs rises, and the development of guidelines and policy for those kinds of projects in order to promote charging infrastructure installation should be a priority. In addition, the importance of workplace charging infrastructure was stressed out as a driver of EV adoption.

For rural settings, publicly available charging infrastructure is very scarce and EVs' refueling is mainly supported by home charging. The level of charging availability and accessibility in rural areas also affects minor and principal arterials, where infrastructure is scarce. Interviewees mentioned that the majority of fast charging infrastructure within Indiana is currently located in urban areas, which poses barriers for long mileage and interstate trips. Range anxiety concerns of EV consumers cannot be overcome unless fast charging is not available along minor and principal arterials.



Level 2 charging is the most common solution at the local level. Level 2 charging infrastructure is not necessarily owned by utilities, but operational data is needed to inform their plans and offer a reliable grid at an optimal cost.

Operation and deployment of charging infrastructure is not an industry that OEMs are willing to get involved.

Public sector can offer direct or indirect incentives, especially for fast charging which may not be financially feasible at low utilization rates.

Utilities, public sector and charging network providers are the main stakeholders involved in fast charging.

As the complexity of an appropriate business model for commercial fleets is high as they operate in a unique way, they mainly rely on private charging infrastructure.

Private involvement is essential for the provision of charging infrastructure.

Charging as a service with payments for the use of charging infrastructure is an alternative business model.

Figure 6.3 Overview of main business models discussed.

Commercial fleets have different operational characteristics compared to privately-owned vehicles and the level of charging availability and accessibility for this type of vehicles has specific features. With the long-haul trucks, there is limited to non-existent charging infrastructure. This is not surprising as the technology of electric trucks is not in the maturity level of light duty vehicles. The level of charging availability and accessibility for systems such as transit buses or port operations is different compared to long-haul trucks that need infrastructure along the long routes that they cover. Hence, charging infrastructure for bus transit systems or port operations is directly connected with the availability of space where they could develop charging facilities for their fleets. The acquisition of land for those purposes as adoption rates increase is going to be a really challenging task in the near future, as expressed by multiple stakeholders.

To conclude, a high level of understanding of the charging network is critical together with studying the accessibility of charging locations. A robust dataset of charging infrastructure points is necessary for communication purposes and from a public policy standpoint. EV drivers and prospective buyers of EVs should have a good understanding of the location, type, and function of charging infrastructure, while public policy can be a central contributor by setting targets based on EV registrations and available charging infrastructure. Finally, some stakeholders mentioned the effectiveness of charging infrastructure to promote EV adoption and some equity concerns for charging infrastructure projects development. The spatial allocation and the population demographics of charging infrastructure projects sites were the main equity concerns mentioned by the stakeholders.

6.2.5 Vehicle Class or Type with Future High Adoption Rates

Stakeholders' statements regarding the vehicle class or type that can have the highest potential for electrification were homogeneous. In general, they recognized the fact that until today the development and the adoption of EV technology had mainly been concentrated on the light duty/privately-owned vehicles, and especially in the higher cost vehicles. Used car market could also directly affect future adoption rates of different vehicle types or classes with the way it will operate and the transition process to EVs. At the same time, there are some major opportunities for specific vehicles classes, and they formulated these patterns in a quite similar way. All the insights for the vehicles class or type with future high adoption rates were not related to the light duty/privately-owned vehicles, as they have passed the early adoption phase.

The most promising vehicle type for future high adoption rates is the transit bus. Most interviewees claimed that transit agency fleets are probably the most suitable and ready to pursue vehicle class as a result of both operational and financial attributes. From an operational standpoint, transit agencies network consists of predictable routes where ranging anxiety is not a barrier and where EV charging infrastructure is located in particular facilities, ensuring charging station reliability. From a financial standpoint, the subsidies and funding programs that are in place from the central government as well as the lower maintenance costs that battery EVs seem to have create a viable total cost of ownership. Except from transit buses, school buses and some terminal or port applications were also vehicle classes that have high potential for electrification for the same reasons.

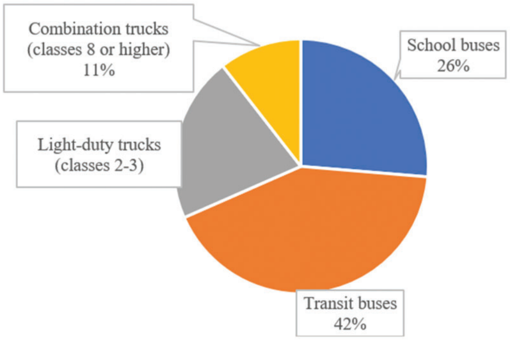


Figure 6.4 Vehicle class or type with high adoption rates in the future.

Transportation electrification in the commercial sector is still in its infancy but interviewees were optimistic that great progress will happen in the future. Small freight vehicles or delivery vans are going to be electrified sooner because their trips are characterized by predictable routes and high average idling which can be eliminated though electrification. As opposed to the aforementioned vehicles classes, there was intense skepticism around the heavy duty or long-haul applications and their abilities for viable electrification goals in the long run. Figure 6.4 summarizes stakeholders' perspectives regarding the vehicle class or type with high adoption rates in the future based on their responses in the pre-survey.

6.2.6 Transportation Funding Concerns

The majority of the stakeholders expressed major concerns about the impact of EV adoption on the fuel tax revenue. It was supported by a few stakeholders though that these concerns are not high yet because of the lower current EV adoption rates and thus, policy makers may have the time to adapt and develop. In general, the need for a recovery strategy of the lost fuel tax revenue was clear and the majority of interviewees recognized that EVs should pay their fair share for using the highway infrastructure.

First, imposing registration fees for EVs to cover the revenue loss is considered a common approach to generate revenue. Most stakeholders expressed that the registration fee for an EV is too high and certain adjustments may be necessary for the specific policy approach or even a new approach to promote equity.

More than one innovative alternative approaches were proposed as sources for a future transportation funding plan. The first revenue recovery method proposed is a motor fuel tax as a gasoline gallon equivalent that is based on a fee per kilowatt hour. Such approach provides a rate-based method that is consistent with how the fuel taxes are currently administered but it does require input data of the energy that is being used for charging, policy changes as well as the creation of new standards. Taxation during charging is viable but the multiples ways of charging create some difficulties. Home charging is really difficult to be tracked and the public may not be willing to pay a state tax for charging at home. Similarly, taxation during workplace charging would also be hard and given that charging is free at some work or public places and thus, there is not a real transaction, this approach becomes even more difficult. Except for the tracking challenges that this approach encloses, there are also privacy concerns and need for very expensive equipment installation. Finally, some major concerns were expressed by interviewees for the fairness of a fee per kilowatt hour, as different vehicles are consuming different amounts of electricity and electricity consumption also depends on the driving environment (e.g., urban and highway). The second revenue recovery method proposed was the VMT fee which does create an accurate tax based on vehicle usage. Although it was argued as the fairest approach, it requires a shift in public and policy thinking and new methods for measuring the VMT with privacy concerns again being a major barrier for its implementation. Figure 6.5 summarizes the potential of different tax/fee revenue structures to address the potential for decreasing tax revenue as the transportation system migrates toward EV technologies, based on the pre-survey data.

In conclusion, stakeholders highlighted the importance of a realistic and fair plan for the lost fuel tax revenue as the transportation system migrates toward EV technologies. Policy makers should be careful with the timeline of the alternative approaches since if owning an EV is more expensive than owning an internal combustion engine vehicle, the adoption curve will be negatively affected. Implementing an annual fee, a monthly fee, a VMT fee, or a pay-as-you-charge fee is crucial as today the gas purchase is spread over once a week or twice a week. More progressive approaches of making up for the fuel tax revenue loss such as increasing gas fuel taxes as EV adoption increases or implementing more expensive tolls for internal combustion vehicles were also heard.

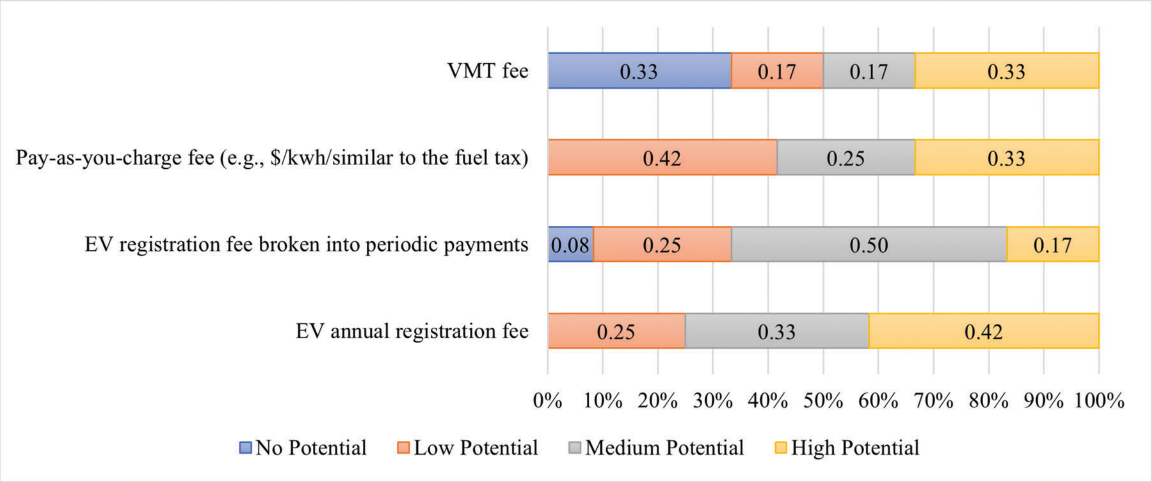


Figure 6.5 Potential revenue generation of different tax/fee structures.

6.2.7 Grid Impact and Renewable Energy Integration

Stakeholders recognized that the electrification of transportation will definitely affect the grid, but with the current adoption rates, there is no need for major grid updates. So, as adoption increases, the stress on the grid will become higher and grid innovation technologies will be developed. In this context, the importance of close collaboration between utility companies and the public sector was pointed out.

Commercial fleet electrification was the main area for which stakeholders expressed concerns regarding future needs on the grid level. When the demand for fleet charging emerges, utilities and policy makers should have plan ahead and be ready to provide services. Development and upgrades of the transmission and distribution network would be essential, as the reliability of the electrical grid would become one of the most important factors for the deployment of EVs. Charging reliability and resilience are critical from an operational standpoint because the whole transportation system operation is based on the electrical grid for refueling.

Grid management would also be of high priority as EV adoption increases. Supply and demand is expected to be shifted from today's patterns and it is possible to see high demand during traditionally off-peak hours. Technologies like vehicle to grid (V2G), on-site generation, on-site energy storage, would render the vehicle as a grid asset. Energy storage was reported as one of the most critical features that the grid should have for a successful electrification process since it can mitigate the impact to the grid. In addition, programs that shift the charging time and encourage customers to charge during periods of low demand (off-peak) are necessary to reduce grid stress.

Lastly, the shift of electricity production to renewable energy sources is fundamental. Utility companies are developing their integrated plans for renewable energy projects and increase the renewable energy of their mixes. Environmental concerns of public opinion have to be considered and develop a holistic approach where pollution is not just moved out of the cities to the electricity production areas. Finally, renewable energy sources are part of the overall reliability of the grid, and energy storage capabilities are again an integral part of the system.

6.3 Summary

The EV ecosystem involves a wide range of stakeholders involved in the electrification of transportation process and the understanding of their needs and perspectives is crucial for the provision of EV charging infrastructure. In this study, a content analysis was performed for the data collected by interviews and seven main ideas emerged from the analysis. Stakeholders used different categorization approaches for identifying the main stakeholder groups involved in the provision of EV charging infrastructure, for proposing business models, and for the level of charging availability and accessibility. Additionally, stakeholders specified the vehicle classes with future high adoption rates and identified concerns about the impact of EVs on the highway revenue and the electrical grid. Among other findings, it was noted that stakeholder partnerships and appropriate business models may depend on various factors including the type of charging (private vs. public or Level 2 vs. fast charging), the location (local, state, or regional level) and the vehicle type (commercial fleets vs. privately-owned vehicles).

7. CONCLUSIONS

7.1 Summary of Key Findings and Deliverables

The objective of this study was to identify opportunities for the strategic deployment of EV charging stations, to estimate the funding needs and revenue generation outcomes regarding EVs, and to examine major stakeholder perspectives on strategic partnerships towards EV preparedness. The study consisted of different tasks and sub-objectives; the study main findings are discussed in this section.

The research team developed an agent-based simulation model for long-distance EV trips and spatial analysis for high energy consumption areas in Indiana. This research focused only on long-distance EV trips in Indiana and demonstrated the EV long distance trips and energy demand to identify locations where INDOT can take next steps for further analysis. This study conducted the spatial analysis upon the strategy of deploying potential EV charging stations, and the analysis consisted of two parts: (1) developing a simulation model to identify EVs' demand and frequency of charging based on ten pre-determined scenarios and (2) GIS-integrated spatial analysis for EV infrastructure deficit areas and potential EV charging stations deployment. Marion and Hendricks Counties were identified as the top two counties where many EV long-distance trips may be interrupted due to running out of energy. Other areas include Morgan, Johnson, Madison, Bartholomew, Hamilton, Marshall, Boone, Grant, LaPorte, Cass, White, Shelby, Huntington, Putnam, Decatur, and Owen as potentially charging deserts in the future. The study outcomes also provide the geographical magnitude of the EV energy demand defined by the ISTDM regions. The Greater Indy area is potentially the most EV energy required region, followed by SR-46 Corridor, SIDC, and NCIRPC among the 17 ISTDM regions. The visualized results of EV energy demands based on EV long-distance trip failure analyses are provided in the appendices.

Next, the study aimed to enhance the revenue structure by assessing the funding needs, identifying the optimal EV fee based on scenarios of EV market penetration levels and by evaluating the potential of funding mechanisms to recover the revenue loss. The optimal annual EV fee per vehicle class (recovery EV fee) that is needed to recoup the fuel tax revenue loss was estimated. With the use of system dynamics, it was determined that the net effect of all parameters on the recovery EV fee is the same, even if different EV market penetration levels are applied, indicating that the fee will have the same value for every scenario. To maintain the same fuel tax revenue per vehicle, annual fees ranging from $241 (in 2021) to $342 (in 2035) for automobiles, $344 to $435 for light trucks, $1,246 to $1,488 for buses, $969 to $1,243 for single-unit trucks, $6,192 to $7,321 for combination trucks and $26 to $35 for motorcycles would be needed over the analysis period. The fuel tax revenue loss and impact of EV fees on revenue from vehicle registrations for Indiana and INDOT were estimated for the most likely, optimistic and pessimistic scenarios. In the most likely scenario (5% EV market penetration level for light duty vehicles in 2030, 30% for medium and heavy duty vehicles in 2030), the results project that the statewide fuel tax revenue will decrease by 21% and INDOT fuel tax revenue will decrease by 24% by 2035, relative to 2030. Assuming 100% EV market penetration level in 2030, the statewide cumulative fuel tax revenue loss from 2021 to 2035 is around $50 billion and this corresponds to around $22 billion cumulative fuel tax revenue loss for INDOT. The proposed EV recovery fee found for Indiana can extend revenues collected from INDOT beyond break-even to yield a surplus, if INDOT receives 75% and 100% of the EV-fee revenues (for all scenarios—most likely, optimistic/pessimistic). On the other hand, the existing EV fees yield a revenue deficit, even if the revenue distribution to INDOT is 100%. Alternative ways to implement the estimated recovery EV fees were also proposed. The recovery EV fee was converted to a VMT ($/mile) and pay-as-you-charge ($/kWh) fee per vehicle class and per year (Figures 5.16 and 5.17). Potential barriers to the implementations of these options (e.g., sustainability, costs, privacy concerns) and policy aspects (e.g., implementation process, partnerships, equity considerations) were examined (see Table 5.8). Lastly, although EV users may pay additional charges that can hinder the adoption of EVs, this is only one aspect of the user total cost of ownership, since EVs have lower fuel costs, as this study showed. The results of this task can help state agencies better understand the impact of EVs on the highway revenue and serve as a reference to support decision-making on EV policies.

Finally, this study attempted to gather knowledge on the main factors related to the promotion of EVs and evaluate the strategic partnerships and business models. To achieve these objectives, a pre-survey and semi-structured interviews were conducted online with 23 stakeholders representing the EV ecosystem. The interviewees included participants from utilities, policy makers, automotive industry/manufacturers, charging equipment/infrastructure providers, non-profit organizations, and other. From the content analysis that was performed, seven main ideas emerged. Stakeholders used different categorization approaches for identifying the main stakeholder groups involved in the provision of EV charging infrastructure, for proposing business models and for the level of charging availability and accessibility. Additionally, stakeholders specified the vehicle classes with future high adoption rates and identified concerns about the impact of EVs on the highway revenue and the electrical grid. Among other findings, it was noted that stakeholder partnerships and appropriate business models may depend on various factors including the type of charging (private vs. public or Level 2 vs. fast charging), the location (local, state, or regional level) and the vehicle type (commercial fleets vs. privately-owned vehicles). Most interviewees supported that the provision of charging infrastructure involves mainly private entities, while public sector provides a critical role by providing direct or indirect incentives to users, as well planning the charging infrastructure, raising awareness, and educating all stakeholders involved. Furthermore, the stakeholders identified transit buses having the highest potential for electrification, followed by followed by school buses and small freight vehicles or delivery vans. Equity concerns were raised related to the availability of charging infrastructure in rural areas as well as the various fees/taxes to be charged per EV to address the potential for decreasing fuel tax revenue. A VMT fee was argued as a fair approach to generating highway revenue, but privacy concerns were viewed as a major barrier for its implementation. Lastly, the need for grid management and renewable energy integration was pointed out as a high priority as EV adoption increases and especially, as commercial electric vehicle adoption increases.

7.2 Recommendations for Implementation and Benefits to INDOT

Based on the work performed, the following recommendations for implementation are provided.

- The agent-based simulation model of the study is developed for future long distance EV trip scenarios in Indiana and uses unique geographical information and model parameters for Indiana. This model enables INDOT to identify EV energy deficient areas for current and future energy charging demand scenarios and can support the state's strategic planning for the EV charging infrastructure development.
- The results of the revenue impact analysis can inform INDOT's revenue model and assist decision makers establish more reliable plans regarding preparedness for prospective EV operations in the coming future. The estimations of the recovery EV fee, the VMT fee and pay-as-you-charge fee can be used by INDOT in pilot programs to capture users' perspectives and willingness-to-pay and to estimate appropriate fee rates and structures such that both sufficient revenue is raised, and public acceptance is achieved.
- The study proposed an EV recovery fee to offset the revenue loss from gasoline fuel tax. It is anticipated that the revenues from the EV recovery fee will be split between the state and the local governments. A state share of 75% or higher can ensure that INDOT's revenues move beyond break-even to a surplus.
- Implementing the recovery EV fee as an annual flat fee for EVs may generate opposition from the public and road users, particularly, commercial vehicles. Therefore, to offset the gasoline revenue loss, a VMT ($/mile) or pay-as-you-charge ($/kWh) fee may be more appropriate and equitable. In particular, a VMT fee can be implemented, since it can be easily adjusted based on different parameters to consider the actual cost caused to the transportation network and lead to strategic investments in the transportation infrastructure. To enhance the fairness of this mechanism further, VMT fee can be adjusted or combined with weight-based fees and privacy concerns should be addressed. Additionally, given the air quality benefits of EVs, more VMT traveled by EVs should be associated with lower fees compared to conventional vehicles.
- The implementation of a pay-as-you charge fee can also be tested as part of a pilot program. A pay-as-you-charge fee is similar to the pay-at-the pump nature of existing fuel taxes facilitating its adoption. Nevertheless, it would be complex to separate the EV electricity usage from the household usage and partnerships between utilities and INDOT should be developed to effectively remit payments associated with EV charging at home.
- Extensive public outreach and education should be undertaken to inform users about the overall long-term cost savings associated with EV use. This can help earn public support. Further, the best of alternative policy options can be identified through pilot programs. This study highlights an opportunity to prepare INDOT for participating in pilot programs on a road usage charge, following the examples of other states.
- The insights obtained from the stakeholder interviews can be used to enhance preparedness for increasing EV adoption rates across vehicle classes and strengthen the engagement of different entities in the provision of charging infrastructure. The main stakeholder interrelationships that should be considered for the provision of EV charging infrastructure are the following.

    - Collaboration and knowledge exchange regarding EV charging and battery technology is essential between the charger manufacturers and the OEMs.
    - Interrelationships between charger manufacturers and charging site host involve the support and knowledge exchange on the installation and maintenance of EV charging equipment.
    - Coordination between charging providers and EV users is necessary to understand EV charging demand, the location of charging infrastructure and existing policies.
    - Better transparency and understanding of the pricing policy and payment systems are the core of the interrelationship between utilities and EV users.
    - Collaboration between utilities and policy makers is needed to plan for increasing EV demand (especially regarding commercial vehicles that have increased power requirements). The planning process may consider upgrades of the transmission and distribution network, grid management technologies such as V2G, integrated plans for renewable energy projects, new tariff structures to reward charging behaviors and investigation of the impacts of EV demand on the transportation system operation.
    - Public agencies' role focuses on planning, raising awareness and educating all stakeholders involved. There should be coordination among these stakeholders for better communication of public policy frameworks, with relevant information for special electricity rates or incentives.

- High level understanding of the charging network is critical together with studying the accessibility of charging locations. A robust dataset of charging infrastructure points is necessary for communication purposes and from a public policy standpoint. EV drivers and prospective buyers of EVs should have a good understanding of the location, type, and function of charging infrastructure, while public policy can be a central contributor by setting targets based on EV registrations and available charging infrastructure.
- Transit buses have the highest potential for electrification due to their operational and financial attributes, followed by school buses and small freight vehicles. Prioritizing planning (e.g., incentives, charging infrastructure) for the successful implementation of EV technology across the specific vehicle classes is crucial to handle the potential increased EV demand.

7.3 Limitations and Recommendations for Future Work

The agent-based simulation model of this study considered only long-distance trips only, the local traffic energy demand, and local existing charging stations are excluded. Additionally, the current model is based on the ISTDM trip data that may not be able to accurately reflect the actual EV trips in the future. Further research is needed to define the baseline data for the model. Data for the model parameters, such as energy consumption and discount factors, is insufficient or does not exist. Future research can work on filling the gaps in data collection, and validation for the key model parameters.

Regarding the revenue impact analysis, there are still certain limitations that could constitute research directions for future studies. The analysis focused on estimating the impacts of battery EVs and the following five main vehicle classes: automobiles, light trucks, buses, single-unit trucks, combination trucks and motorcycles. Future research could expand the analysis by disaggregating the results by weight class which would be especially interesting for trucks and by considering hybrid and/or other alternative fuel vehicles. Moreover, this analysis calculated the optimal recovery EV fee to break-even the fuel tax revenue loss without explicitly accounting for the equity of funding mechanisms across the different vehicle classes. Future research can work on developing effective metrics to capture this aspect and ascertain an equitable fee structure. Furthermore, the estimation of the pay-as-you-charge fee was based on data for the efficiency of EVs per vehicle class (kWh/mile) and on assumptions about the improvement of this efficiency. The energy consumption rate for heavier vehicles in real-world operations is still uncertain though. With more data in the future, studies can explore the sensitivity of the results to variations in the energy consumption rate parameter due to various factors such as weather or payload. The research framework used to estimate the impact of EV adoption on fuel tax revenue and to estimate the optimal EV fee can also be expanded and consider how transportation revenue sources can align with available funds and broader state emission and electrification goals. Moreover, the study results are considered preliminary. The actual implementation of the options proposed will need in-depth studies to examine both the user perspective and the necessary procedures for the implementation of EV fees such as their collection process, appropriate technologies, administrative costs, and more.

This study gathered knowledge on the main factors related to the promotion of EVs and evaluated the strategic partnerships and business models by interviewing representative stakeholders of the EV ecosystem. Future research can work on expanding this study by interviewing stakeholders from other organizations/agencies across the Midwest and nationwide as well as repeat this study to capture the change in stakeholders' perceptions over time.

Lastly, it is recommended that future research explores the synergies between the electrified, shared, automated, and connected mobility in the state. These revolutions in transportation may be combined in various ways and are expected to bring transitions in mobility and revenue losses under the tax structures that the states have developed. For instance, electric shared autonomous vehicles may render the fuel tax obsolete over time; cause induced travel demand and increase the damage caused on highway infrastructure; decrease vehicle ownership and registration fees; as well as eliminate other types of fees such as parking fees (Fox, 2020; Ha et al., 2020; Ratner, 2018). Additionally, it is recognized that connected and autonomous vehicles will be most likely to be propelled by electricity, and as such, additional EV infrastructure (charging stations and guideways) will be needed to support their operations.

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APPENDICES

Appendix A. Literature Review

Appendix B. Spatial Analysis and Guidance for Strategic Deployment of EV Charging Infrastructure

Appendix C. Assessment of Funding Needs and Feasibility Analysis of New Income Generation Stream Models

Appendix D. Evaluation of Strategic Partnerships and Guidance for EV Preparedness Based on Stakeholder Input

APPENDIX A. LITERATURE REVIEW

Table A.1 List of research studies focusing on EV demand forecasting

Reference	Study Area, (Study Year), Vehicle Type	Methodology & Years of Forecasting	Main Inputs	Main Data Sources	Key Takeaways
Barter et al., 2013	48 continental US states and the District of Columbia (2010) Light duty vehicles	• Four mathematical models (third-order Runge-Kutta algorithm with fixed step size): energy supply, fuel production, electricity grid, vehicle sub-model - These exchange price and demand points for energy supply stocks and fuels • Powertrains considered: conventional, hybrid, plug-in hybrid with 10 mile all-electric range (PHEV10) and PHEV40 variants of gasoline-fueled Spark Ignition, diesel-fueled Compression Ignition, and E85 flex-fuel • Vehicle sizes considered: compact, midsize, small SUV, large SUV, and light pickup trucks • Years of forecasting: 2010–2050	• Vehicle registration data • EV sales • Vehicle miles travelled • Vehicle fuel efficiency • Electricity use rates and base electric load • Federal and state-based subsidies and incentives • Vehicle costs • Battery capacities and recharging times • Growth trends of refueling infrastructure for alternative vehicles • Refueling station distribution • CO_2 equivalent GHG emissions • Fuel prices, taxes and fees	U.S. FHWA U.S. DOT Transportation Energy Data Book (2012) U.S. Census U.S. NHTSA National Highway Travel Survey U.S. EPA Argonne National Laboratory Oak Ridge National Laboratory U.S. DOE U.S. EIA Sandia National Laboratories	• Conventional powertrains and hybrid powertrains are nearly 60% of the fleet in 2050 • PHEV10s are more numerous than PHEV40s • EVs do not become more than 10% of the fleet until approximately 2030 • With subsidies, the model state predicts 2–3 times more EVs than would otherwise be on the road from 2015–2020 • Model projects a baseline reduction in GHG emissions per fleet mile of 50% by 2050
Cao & Mokhtarian, 2004	US (1993–2004) Light duty vehicles: Alternative fuel (E85, CNG, HEV)	• Bass diffusion model with varying market potential to estimate aggregated demand-S-curve statistical model based on past sales data • Initially approximate p, q, and m (innovation, imitation, and market potential coefficients) with ordinary least squares regression from vehicle sales	• Annual alternative fuel vehicle sales • Number of models available • Annual E85 and CNG vehicle conversions • Number of fueling stations available • Fuel prices • Range • Incremental vehicle cost	U.S. EIA U.S. DOE U.S. AFDC Polk Automotive Intelligence National Ethanol Vehicle Coalition	• Early example of using Bass Diffusion modeling to predict adoption trends for AFVs • Bass diffusion modeling is a well-known method for modeling the diffusion of innovations, but is extremely reliant on robust, accurate historical adoption data • Significantly overestimates the sales of all AFV classes for 2018

		• Perform nonlinear least squares to obtain more precise estimation of p, q, and m • As there are only 4 years of HEV data available, market potential is specified instead of estimated - Considered to be proportional to HEV awareness rate • Years of forecasting: 2005–2025		California Energy Commission	(last year of sales data available from the AFDC) • Indicates the difficulty of long-term sales forecasting, especially for relatively young innovations • Indicates the influence of future innovations (i.e., PHEVs and BEVs) when determining forecasts for current innovations (i.e., E85, CNG, and HEV vehicles)
Duan et al., 2014	Midwest Independent Transmission System Operator (MISO) area (13 US states in the Midwest area considered) (2012) Light duty vehicles	• Sales forecast model: multiple linear regression (variables: fuel cost, tax credits, price, number of EV models available) • EV recharging load forecasting model: convenience driven and cost driven models describing recharging behavior • Years of forecasting: 2012–2020	• Observed EV sales • Gasoline prices, Electric rates • Fuel efficiency • Miles driven • Vehicle prices • Tax credits • Supply side constraints • Number of EVs on the road	U.S. EIA U.S. EPA U.S. DOT MISO U.S. DOE	• EV sales in the east, central, and west regions of MISO: 6.5%, 6.6%, and 6.7% of total sales in the US., in 2012 • Forecast results of the cumulative EV sales curves in the US: 1M EVs by 2020 • EVs will not place an overwhelming burden to power systems until 2020, given smarter recharging infrastructures that can catch up with the growth of EV sales
Fluchs, 2020	Europe, Asia, North America 2010-2017 Light duty vehicles	• Epidemic Growth Model: - S-curve statistical model based on past sales data • Empirical analysis of financial and non-financial factors influencing EV diffusion rate • Considers market saturation levels of 50, 75, 100% • Excludes electric, gas, and diesel prices from model - Claims that other studies show these of low significance • Years of forecasting: 2020–2050	• EV sales data • EV purchase price (dis)advantage • EV tax exemptions • Non-financial EV incentives (use of HOV Lanes, etc.) • Percent population living in urban areas • Percent population living in houses	European alternative fuels observatory European automobile manufacturers' association International Energy Agency	• Purchase price advantage of EVs significantly increases diffusion rate • Tax exemptions and non-financial incentives for EVs have no significant impact • Increased population living in houses decreases diffusion rate (goes against standard hypothesis). Higher population in urban areas negatively impacts diffusion rate • There is not enough evidence to indicate that diffusion will naturally occur without policy incentives for EVs

Gnann, 2015	Germany (1994–2010, 2002, 2008, 2012) Light duty vehicles: private and commercial vehicles	• Joint simulation of PEV driving and use of public charging • Agent-based model: 1. Simulate agent driving profile 2. Calculate agent's utility w/ PEV vs. ICEV to determine optimal vehicle 3. Aggregate PEV stock 4. Determine optimal charging station number and charging cost 5. Repeat until equilibrium - Utility calculation also accounts for cost of charging stations, willingness to pay more for EV, and brand loyalty - PEV purchase decision modeled as utility maximization among vehicle alternatives • Years of forecasting: 2015–2030	• Real-world driving profiles • Utility factors: - Vehicle size - Vehicle price - Vehicle brand - Fuel consumption - Fuel type - Vehicle power - Emissions - Vehicle acceleration	Driver profile surveys: • MiD2002, • MiD2008, • MOP (1994–2010), • MOPS (2012) • KiD2002, • KiD2010	• Germany 2030 projection: -Best-case scenario: 99 M total EVs -Medium-case scenario: 4.8 M total EVs -Worst-case scenario: 1.5 M total EVs • "Framework conditions" (oil, energy, and battery price) are most important factors for EV diffusion • Commercial fleet vehicles have largest diffusion potential • Public slow charging has minimal diffusion impact • Domestic and commercial location charging are most important charge points, followed by workplace charging • Home charging significantly minimizes public charging need • Imperative to distinguish between charging location types and between BEVs and PHEVs
Guerrero de la Peña et al., 2020	Hypothetical network: set of line-haul highway corridors in the US Midwest, connecting Chicago, Indianapolis, St. Louis and Nashville and 2 distribution Centers (2018–2028) Heavy duty vehicles	• Model of a system of systems and regional freight transportation system for fleet vehicle purchasing behavior: -A mixed-integer linear program formulation: projecting adoption of emerging powertrains (natural gas, battery electric, and hydrogen fuel cells) -A simulation approach: capability to provide insights on how the introduction of emerging technologies to the line-haul market	• Operational, policy, and economic factors: • • Route characteristics (e.g., links, nodes) • Route restrictions • Vehicles on route (for 12 line-haul fleets) • Freight demand • Vehicle well to well emissions • Route speed • Energy consumption and efficiency • Purchasing and operating costs • Energy costs • Taxes and incentives/policies	U.S. DOE Transportation Research Board and National Research Council Federal Motor Carrier Safety Administration U.S. EIA U.S. EPA Other research environmental studies and studies related to purchase costs, efficiency, range and payload capacity	• Adoption rates from 0%–4% for natural gas, battery electric, and hydrogen fuel cells for the 2018–2028 period. Battery electric heavy-duty vehicles reach around 2% in 2028 • Incentives are the primary factor influencing adoption of EVs. On-road charging as the range-extending mode for electric vehicles appears to have a negative effect on battery EV vehicle adoption particularly when compared to the cases where battery swap stations are available • Decreasing the battery vehicle payload capacity from 25 tons to 22 tons-3 tons lower than the diesel

		will impact the utilization of freight vehicles and allocation over transportation routes (powertrain adoption scenario) - Sensitivity evaluation of projected adoption trends and resulting CO_2 emissions to variation of vehicle, policy, and infrastructure design parameters. - Years of forecasting: 2018–2028			vehicle payload capacity-causes a decrease of approximately 100 BEV purchases - Potential reduction of approximately 20% in cumulative emissions given a widespread adoption of natural gas, battery electric, and hydrogen fuel cell vehicles
Lee et al., 2019	California (2013–2018) Light duty vehicles	- Latent class model to classify EV buyers based on socio-demographic characteristics - Bass diffusion model using latent classes as inputs. Ordinary least squares method used to estimate the coefficient of imitation that best predicts the following years' actual sales - Years of forecasting: 2018–2030	- Respondents' sociodemographic characteristics - Latent classes (used as inputs in Bass diffusion model) - EV sales data - Market limits for different sociodemographic clusters	Multiple cross-sectional questionnaire surveys (data from EV buyers in California from 2013–2018) California Clean Vehicle Rebate Project National Household Travel Survey California add-on 2017 data	- Four heterogeneous clusters of early adopters of EVs: 49% are high income families, 26% mid/high income old families, 20% mid/high income young families, and about 5% are middle income renters - High income families decrease to 40.5% in 2017. Mid/high income old families remained between 22.7% in 2015 and 30.5% in 2017 Mid/high-income young families and middle-income renters reached around 24% and 9%, respectively, in 2017 - High-income families, Mid/high income old families, mid/high-income young families and middle-income renters reach around 97%,45%, 80% and 25% in 2030.
Ou et al., 2020	China Light duty vehicles	- New Energy and Oil Consumption Credits (NEOCC) - Uses nested logit function to calculate market shares of 18 vehicle types (ICEV, PHEV, BEV) purchased by personal vehicle drivers and public fleet drivers	- Vehicle weight - EV range - Vehicle price - Fuel consumption (ICEV and PHEV) - Electricity consumption (PHEV, BEV)	Chinese vehicle market info from the China Automotive Technology and Research Center	- Predicts 2020 PEV sales will be about 8.81% of passenger vehicle market - Finds that public charging has higher impact on vehicle diffusion in an emerging EV market than a mature market - EV commercial LDV fleet growth highly correlated to number of fast chargers

		• Uses a genetic algorithm to optimize a market dynamics function • Probability of choosing a vehicle depends on: - Total cost of ownership - Income (value of time) - personal consumer preference • Total cost of charging activities combines: - Electricity charging cost (at home, at workplace, at public chargers) - Charging inconvenience cost - Range anxiety cost • Allows a systematic assessment of charging infra impact on PEV ownership cost and market share • Year of forecasting: 2020			• More home parking spaces stimulates more PHEV sales than BEV - Authors note that this is most likely due to cultural and population density differences between the US and China; they expect the opposite would hold true in the US • Decreasing battery cost has a stronger effect on increasing sales than increasing public charging has on increasing sales for 2020
Santa-Eulalia et al., 2011	Germany (2009) Light duty vehicles: cars	• Model structure: Discrete choice model combined with Bass diffusion model to find buying probability estimation • Model parametrization: Conjoint experiment to find utility functions for each product attribute • Years of forecasting: 2009–2020	• Consumer preferences for 18 attributes that differentiate an EV from a conventional vehicle • Adopter categories • Utility functions	Interviews and semi-structured questionnaires	• Market for EVs accounts for 63% in 2009 • If no fast charging infrastructure is available, consumers are not willing to purchase the electric car • Restrictions imposed by limited charging possibilities and the long loading time led to a less than 0.1% market share • Fast charging leads to a market share of 14% in 15 years. If battery exchange stations are available, 18% of the potential market is achieved

Wolinetz & Axsen, 2016	British Columbia, Canada (2015) Light duty vehicles	• REspondent-based Preference and Constraint (REPAC) model: • Discrete choice model: probability that each respondent will choose each vehicle drivetrain type (conventional, hybrid, plug-in hybrid or battery EV) • Vehicle model: costs and characteristics of vehicles to be chosen (compact, sedan, small, and large SUV/Van/Truck) • Constraints model: three factors preventing the unconstrained demand of each respondent from being realized as sales: lack of familiarity with EVs, lack of EV supply and lack of home recharge access • 3 policy scenarios: no policy, demand-focused policies, supply-focused policies • Years of forecasting: 2015–2030	• Survey data: home charging access, EV familiarity, consumer preferences for vehicle attributes, weekly travel by respondent • EV battery and vehicle components costs • Gasoline and electricity prices	Canadian Plug-in Electric Vehicles Study U.S. DOE National Energy Board of Canada	• No-policy simulation for annual EV sales is 7% new market share by 2030 • Results are most sensitive to home charging, consumer learning and supply parameters • 2030 simulations range from 17 to 28% with strong demand-focused EV policies in place • Strong supply-focused policy is also required to achieve 2030 market shares over 30%

Table A.2 List of tools forecasting EV demand

Model name & Methodology	Developer & *References*	General description	Scale	Input	Output
ADOPT • Mixed multinomial logit	National Renewable Energy Laboratory *NREL (n.d.b.)* *Brooker et al. (2015)*	Automotive Deployment Options Projection Tool (ADOPT) is a light duty vehicle consumer choice and stock model. ADOPT estimates vehicle technology improvement impacts on future US light duty vehicle sales, energy use, and emissions.	State, county or zip code	• Technology improvements over time • Fueling station availability • Fuel prices over time • Vehicle purchase incentives over time • Vehicle attributes (price, fuel cost per mile, acceleration, size, range) • Consumers' income level • VMT • Penetration rates • Regulations and standards	• Vehicle sales by every model and powertrain
BEAM • Nested multinomial logit • Agent-based simulation	Lawrence Berkeley National Laboratory *Lawrence Berkeley National Laboratory (n.d.)* *Sheppard et al. (2017)*	BEAM Model stands for Behavior, Energy, Autonomy, and Mobility. It is an agent-based microsimulation model used to simulate plug-in EV mobility, energy consumption, and spatiotemporal charging demand.	Metropolitan region	• Mobility and charging data: • Population of area/number of agents • Traffic flows and travel times • EV ownership data • EV attributes (e.g., make/model year, battery capacity, state of charge etc.) • Spatial distribution and characteristics of charging infrastructure • Utility functions/stated preference data	• EV trip and charging demand and behavior • Behavior/trips by agents in different modes (car, public transit, walking, bike, or shared or networked mobility services) • Energy impacts of changing mobility trends/energy consumption
Caldera • Agent-based simulation: -Transportation network simulation -Electric grid distribution network simulation	Idaho National Lab *INL (n.d.)*	Electric Vehicle Charging Simulation Platform Caldera links grid and transportation network to optimize charging. It is used to develop strategies for managing charging and impacts on the electric grid. The foundation of the Caldera software platform is a library of high-fidelity EV charging models derived from	Regional/ Transportation and electric grid distribution network	• Vehicle module (vehicle travel demand forecasts, charging decision agent) • Infrastructure module (charging demand forecasts, infrastructure decision agent) • Charging model library (high fidelity charging models for AC level 1/2 and DC fast/extreme fast charging)	• Estimates of: -Charging power profiles - Efficiency and power factors for different vehicle types -Charging technologies -Grid impact of EV charging demand

		extensive charging and battery testing data.		• Charging control module (AC Level 2 smart charging strategies, extreme fast charging station control strategies)	
Compass • Data driven approach (Interactive tool)	LMC Automotive *LMC Automotive (n.d.)*	This model focuses on EV market analysis and outlook, including model activity and sales trends for electrification types (battery electric vehicle through fuel cell, plug-in hybrid to mild hybrid with 48V).	Global, regional and national	• Hybrid and Electric Vehicle sales and production data for different brands and models	• For over 30 OEMS and 70 brands for commercial vehicles and for 40 OEMs, 250 brands and 2,300 models for light duty vehicles: -Production volume forecasts -Sales forecasts -Powertrain forecasts (12 years forecast horizon for light duty vehicle sales and 7 years forecast horizon for commercial vehicle sales)
EV Hub • Data-driven (Interactive tool)	ATLAS Public Policy *EV Hub (n.d.)*	EV hub is an online platform that equips stakeholders with key information on the EV market. It provides access to data about the transportation electrification market (vehicle registrations, infrastructure deployment, public policies, research, public and private funding opportunities, and media coverage). It can consider light-, medium, heavy duty vehicles.	Global National State Local	• User inputs vary depending on the tool. • Tool for EV market forecast: • Report to derive data (e.g., Global Annual Outlook) • Vehicle type • Year (2020–2040) • Forecast country • Forecast entity	• EV sales forecast • EVs on the road • Forecast summary (report, publish date and source, link, and comments)
LAVE-Trans • Nested multinomial logit	Oak Ridge National Laboratory *Greene et al. (2014)* *Liu & Greene (2014)*	Light Duty Alternative Vehicle Energy Transitions (LAVE-Trans) model is a consumer choice model and transition costs/benefits analysis tool. Its objective is to better understand the role of vehicle technologies in the energy transition and to examine the barriers to and dynamics of transitions to advanced vehicle technologies and alternative fuels (hybrid, plug-in hybrid, battery	-States that have adopted the California vehicle standards -National	• Vehicle and fuel attributes • Infrastructure • Consumer behavior assumptions • Policies	• Vehicle market share, sales, energy use and emissions • Costs & benefits of the transition • Optimal transition • Strategies

	National Research Council (2013)	electric and fuel cell vehicles) under different policy scenarios.			
LVCFlex - Nested multinomial logit	Energetics Inc. *Birky (2015)* *TA Engineering, Inc. (2012)*	This model estimates future market penetration of advanced or alternative vehicle technologies based on vehicle and fuel attributes, including price. The model calculates market shares separately within five vehicle size classes at annual time steps from 2007 through 2050: small cars, large cars, small sport utility vehicles (SUVs), large SUVs, and pickups (battery electric, plug-in hybrid, hybrid, gasoline, turbo direct diesel, ethanol, compressed natural gas, hydrogen fuel cell).	National	- Vehicle Price - Vehicle sales specified by user for each size class (for base case) - Fuel cost per mile - Range - Battery Replacement cost - Acceleration - Home refueling capability - Maintenance cost - Luggage space - Fuel availability coefficient - Make/model Availability - Calibration coefficient	- Estimates of future sales shares (2007–2050) by drivetrain technology
MA3T - Nested multinomial logit	Oak Ridge National Laboratory *Lin et al. (n.d.)*	MA3T estimates future market shares and sales of 40 given powertrain technologies (gasoline, diesel, battery electric, hybrid, fuel cell and other subcategories), separately for passenger cars and light trucks and under user-defined scenarios of demand in response to changes in technologies, infrastructure, energy prices, consumer preferences, and policies.	National Census divisions	- Technology attributes - Consumer preferences - Infrastructure availability - Energy prices - Policies - Choice probabilities of each vehicle technology for each market segment	- Vehicle sales by powertrain type, consumer segment (Innovation Diffusion Theory), and year. - Vehicle population by powertrain type and year - Tailpipe and well to wheel GHG emissions by year - Consumption of gasoline, diesel, electricity, hydrogen and natural gas by year - Government expenditure on vehicle subsidies by year - Consumer surplus by year
National Energy Modeling System (NEMS) (Consumer Vehicle Choice Component Tool)	US Energy Information Administration *EIA (2019b)*	The transportation sector demand module is designed to achieve the following objectives: -Generate projections of transportation energy demand at	National Census divisions	- New car fuel economy - Vehicle price - Vehicle range - Fuel availability - Battery replacement cost - Vehicle performance - Home refueling capability - Maintenance costs	- Market shares for 14 alternative-fuel technologies as well as for conventional gasoline and diesel technologies.

• Nested multinomial logit		the national and the Census Division level. -Endogenously incorporate the effects of technological innovation, macroeconomic feedback, infrastructure constraints, and vehicle choice in making the projections.		• Luggage space • Make and model diversity or availability • Fuel price estimates	
ParaChoice • Nested multinomial logit	Sandia National Laboratories *Levinson & West (2015)* *Manley et al. (2015)*	ParaChoice model is a systems level economic analysis to model dynamic feedback between fuels, vehicles, and infrastructure up to 2050. Its main goals are to understand uncertainty in vehicle choice model and projections; understand changes to the light duty vehicle stock, fuel use, and emissions and determine the impact of additional EV infrastructure on EV adoption and use.	State	• Fuel cost • Vehicle sales • Range penalty: value of time times time spent refueling • Vehicle price, size, made, number • Policies • Driver demographic and travel characteristics	• Estimates of future sales shares by powertrains technology (battery electric, hybrid, bi-fuel, fuel cell and other subcategories of the previous) • Factors affecting sales (sensitivity to gasoline prices, refueling infrastructure, battery costs and other variables)
PEV Roadmap • Data driven approach (interactive tool)	Fosterra, LLC. *Fosterra (n.d.)*	PEV roadmap is an EV forecast tool intended to provide the latest data, insight, and program-related information to decision makers at local agencies and utilities.	City County Zipcode	• Years of forecasting • Zipcode • Growth rate • EV supply equipment to EV ratio	• Annually: • EV counts • EV growth projections • Projected outlets needed • Projected energy consumption • EV miles traveled • Avoided gasoline consumption and avoided CO_2 emissions
POLARIS • Agent-based simulation • Activity-based travel demand model • Simulation-based dynamic traffic assignment model	Argonne National Laboratory *Argonne National Laboratory (n.d.).*	Planning and Operations Language for Agent-based Regional Integrated Simulation (POLARIS) is a high-performance, open-source agent-based modeling and activity-based travel demand framework (a set of libraries) designed for simulating large-scale transportation systems. It is integrated with powertrain	Regional/ Transportation network	• Highway networks • Travel, transportation, or traffic analysis zones • Spatial data (land use/demographic/ socio-economic/GPS based travel surveys) • Urban transportation, safety, travel behavior, traffic monitoring, travel time and speed data	• Travel demand/Network load per hour or vehicle hours traveled for a new transportation system • Activity type distribution per unit of time • Energy use

	Auld et al. (2016)	simulator Autonomie to perform regional energy use analysis.			
SERA • Data driven-Sub-models: -Scenario generation -Vehicle choice -Vehicle stock -Infrastructure cost (cash flows) -Intra-regional refueling-station placement (optimization) -Inter-regional production and delivery optimization (simulated-annealing and greedy algorithms)	National Renewable Energy Laboratory *Bush et al. (2013)* *Bush et al. (2019)* *NREL (n.d.a)*	Scenario Evaluation and Regionalization Analysis (SERA) is an extensive systems analysis model that considers both market factors and technology factors to design transportation infrastructure from a city-scale up to a national road map. It can consider light-, medium- and heavy duty vehicles.	Regional State	• Total vehicle sales (new vehicles sold) • Market share (% of vehicles sold per year) • Vehicle use (miles driven annually per vehicle type) • Vehicle survival (% of vehicles surviving to the next year • Fuel split in each vehicle type • Fuel efficiency for each vehicle type	• Vehicle stock: total vehicles on the road by region, vehicle fuel type, and year • Early-adopter locations for alternative powertrain vehicles • Infrastructure costs and financing • Fuel consumption: total fuel used by region, vehicle type, and year. • Fuel economy: travel-weighted-average fuel economy by region, vehicle type, and year.

APPENDIX B. SPATIAL ANALYSIS AND GUIDANCE FOR STRATEGIC DEPLOYMENT OF EV CHARGING INFRASTRUCTURE

Table B.1 Count of stop markers in every county for all ten scenarios

County ID	County Name	Count of Stop Markers among Counties in All Scenarios									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	Blackford	0	0	1	2	2	6	0	5	5	57
2	Union	0	0	0	0	0	0	0	2	0	21
3	Ohio	2	1	0	1	0	1	1	1	4	53
4	Floyd	2	4	6	2	5	9	5	12	9	374
5	Fayette	0	0	0	0	0	2	0	1	2	41
6	Tipton	6	7	9	4	14	18	8	13	20	471
7	Steuben	1	1	0	0	2	1	2	2	1	60
8	Johnson	17	29	49	26	91	118	56	118	189	1,175
9	Brown	1	9	14	8	22	19	9	19	38	368
10	Switzerland	0	1	1	1	2	1	0	5	4	104
11	Hancock	6	12	21	12	42	56	19	60	79	1,181
12	Scott	3	9	11	6	17	27	13	30	45	337
13	Dekalb	2	0	2	1	4	2	3	8	9	404
14	Adams	1	1	4	0	4	4	2	2	6	104
15	Starke	3	9	12	9	12	21	11	21	27	709
16	Whitley	5	6	5	8	11	20	9	23	36	598
17	Decatur	12	11	11	9	20	30	20	32	52	798
18	Howard	2	2	7	2	9	16	4	6	18	378
19	Delaware	5	9	17	15	29	41	19	39	72	1,274
20	Jay	1	2	5	2	5	5	3	5	11	210
21	Lagrange	0	0	1	0	1	0	1	0	2	204
22	Hamilton	11	34	45	36	66	96	52	128	199	1,704
23	Huntington	12	27	43	33	54	100	33	88	147	686
24	Orange	8	9	18	13	25	32	8	36	55	653
25	Benton	2	5	4	5	7	14	5	13	24	165
26	Martin	10	14	21	13	31	57	25	55	88	795
27	Rush	0	4	10	2	8	10	4	8	25	473
28	Marion	31	66	119	75	164	233	126	224	355	3,371
29	Grant	11	37	42	26	72	107	49	106	134	405
30	Henry	0	1	2	2	8	4	1	10	7	516
31	Shelby	9	20	33	28	63	85	33	89	145	1,296
32	Clinton	6	14	19	11	20	52	19	36	61	926
33	Vanderburgh	0	1	1	4	5	5	6	6	16	314
34	Boone	18	27	47	35	65	96	52	102	165	1,599
35	Noble	0	0	6	6	4	9	3	6	13	651
36	Wayne	0	0	0	1	0	2	0	0	6	156
37	Pulaski	4	17	22	8	22	32	20	41	50	568
38	Marshall	4	11	20	7	34	52	17	45	74	1,721
39	Randolph	0	2	1	0	7	7	3	4	7	115
40	Franklin	2	3	8	9	9	15	8	21	34	210
41	Dearborn	1	0	2	2	4	7	7	8	5	182
42	Hendricks	23	71	70	51	108	161	88	164	272	2,571
43	Bartholomew	19	27	52	22	61	108	53	100	162	944
44	Wabash	2	5	6	4	8	10	9	16	28	358
45	Ripley	7	8	14	9	15	22	12	17	32	897
46	Elkhart	3	4	8	6	10	19	8	17	16	964
47	Lawrence	6	17	27	21	33	73	20	56	81	759

48	Carroll	1	4	14	6	11	27	14	27	33	862
49	Wells	1	1	2	0	1	9	4	11	14	168
50	Fountain	0	4	1	3	4	5	4	11	8	132
51	Owen	5	14	29	19	25	69	25	66	72	1,340
52	Warren	1	7	4	3	13	15	7	23	29	116
53	Morgan	20	54	70	54	91	158	89	176	250	1,901
54	Monroe	12	19	36	26	51	89	50	74	123	1,086
55	Tippecanoe	12	15	17	17	33	41	28	43	80	776
56	Montgomery	1	6	12	11	14	24	10	26	39	716
57	Madison	20	45	56	41	88	118	60	157	222	2,560
58	Fulton	12	25	53	18	42	94	39	86	137	908
59	Miami	6	6	7	6	17	18	13	16	30	545
60	Dubois	7	18	23	8	30	30	21	30	68	1,017
61	Newton	2	1	2	6	4	9	4	8	16	201
62	Cass	13	10	33	18	46	60	29	54	88	873
63	Clay	0	3	4	10	8	12	2	10	19	732
64	Vigo	0	5	9	4	7	21	4	7	16	574
65	Jennings	3	3	4	2	2	9	4	6	11	478
66	Parke	3	5	6	5	14	11	8	15	35	347
67	Greene	10	26	33	22	43	75	41	79	122	1310
68	Putnam	8	23	30	12	38	54	28	60	97	1,592
69	St Joseph	5	6	6	4	11	16	6	18	19	950
70	Vermillion	0	1	1	1	0	3	4	5	5	65
71	Kosciusko	7	13	19	22	33	44	19	34	59	1,186
72	Warrick	1	2	4	2	7	16	4	14	16	519
73	Sullivan	1	1	3	1	4	5	1	6	12	140
74	Allen	4	21	19	17	32	40	20	40	69	987
75	Clark	8	13	16	16	27	40	32	46	61	491
76	Jefferson	2	5	8	11	26	22	17	24	51	444
77	Porter	10	14	24	22	28	47	31	50	108	892
78	Pike	2	3	12	9	18	14	9	11	34	418
79	White	13	18	33	19	36	57	26	62	96	929
80	Jasper	6	8	11	7	17	33	15	34	52	658
81	Lake	4	9	12	7	20	20	15	21	38	631
82	LaPorte	9	9	22	13	43	70	29	53	95	1,714
83	Crawford	3	3	6	9	13	12	15	8	28	649
84	Perry	1	2	6	1	8	8	4	9	9	302
85	Washington	7	5	14	9	26	52	13	25	56	726
86	Spencer	3	2	5	5	7	19	8	16	25	335
87	Harrison	1	2	4	2	6	10	13	9	11	582
88	Jackson	9	22	31	21	47	82	41	75	128	750
89	Daviess	10	14	18	18	38	51	28	51	76	636
90	Posey	1	0	1	0	0	5	2	2	1	153
91	Gibson	1	7	7	6	14	15	10	21	24	443
92	Knox	4	5	4	4	10	22	6	11	27	406

Table B.2 Count of stop markers in every ISTDM region for all ten scenarios

Region ID	**Region Name**	**Count of Stop Markers among Regions in All Scenarios**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	Greater Indy	155	358	510	358	778	1,121	575	1,218	1,876	17,358
2	NIRCC	8	23	27	18	41	55	29	61	98	1,663
3	ECIRPD	17	48	65	45	108	159	71	155	222	1,946
4	EIRPC	0	7	13	5	23	25	8	25	47	1,322
5	SIRPC	29	32	48	44	78	107	69	114	193	3,166
6	SR-46 Corridor	37	69	131	75	159	285	137	259	395	3,738
7	River Hills	30	55	82	56	128	220	117	197	310	3,260
8	SIDC	40	76	103	78	155	278	120	252	394	3,906
9	Indiana 15	24	37	70	45	101	115	65	110	219	3,374
10	SW Indiana	3	10	13	12	26	41	22	43	57	1,429
11	WCIEDD	12	38	53	33	71	106	47	103	184	3,450
12	TAPCTC	13	25	30	31	51	70	42	80	127	1,624
13	KIRPC	32	69	102	63	122	208	102	229	327	4,208
14	NIRPC	23	32	58	42	91	137	75	124	241	3,237
15	MACOG	19	34	53	39	88	131	50	114	168	4,821
16	NCIRPC	45	64	128	59	148	258	112	211	354	4,101
17	Region 3A	20	39	61	51	80	140	57	135	227	2,557

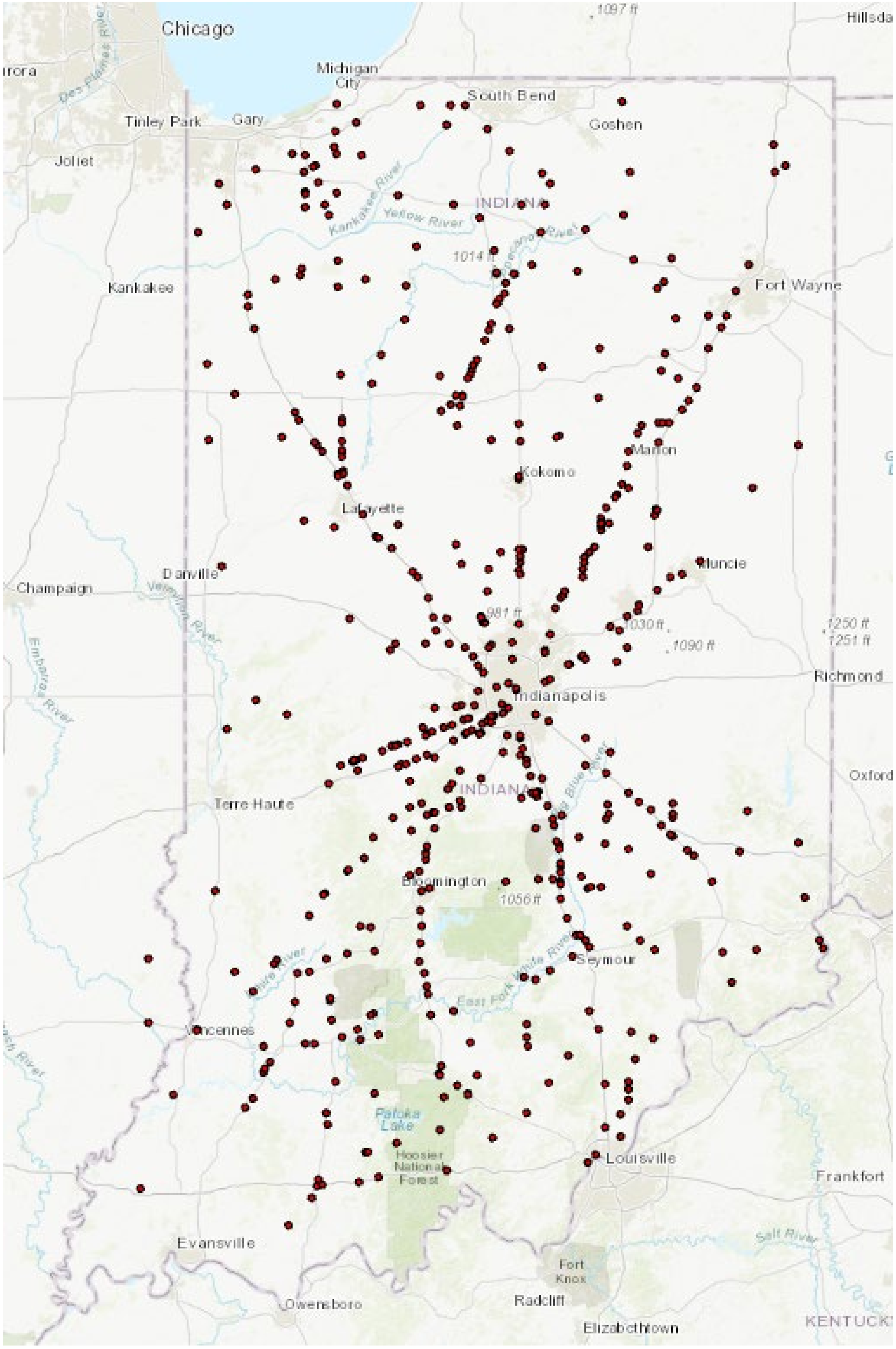

Figure B.1 Distribution map of stop markers for scenario #1.

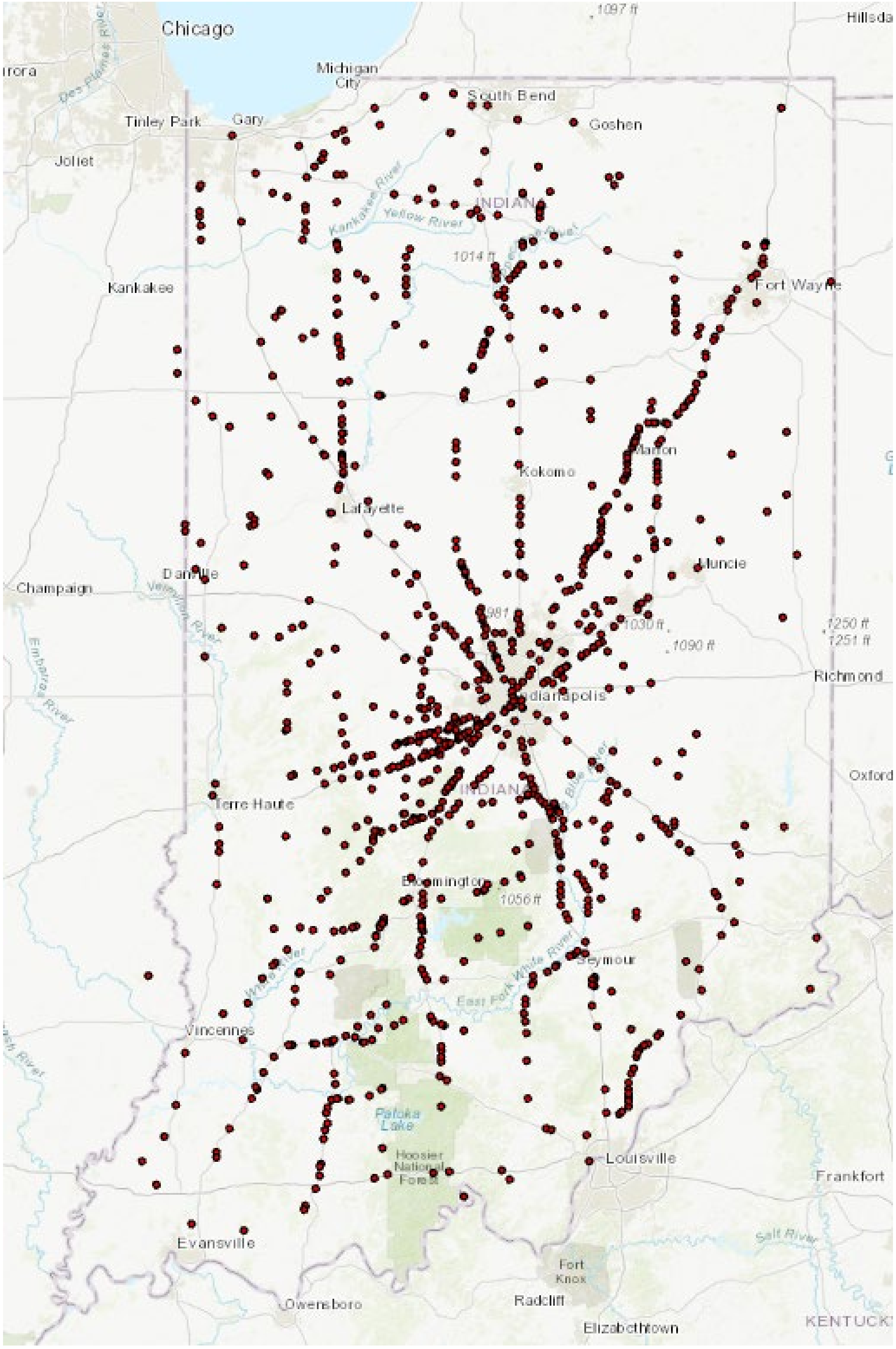

Figure B.2 Distribution map of stop markers for scenario #2.

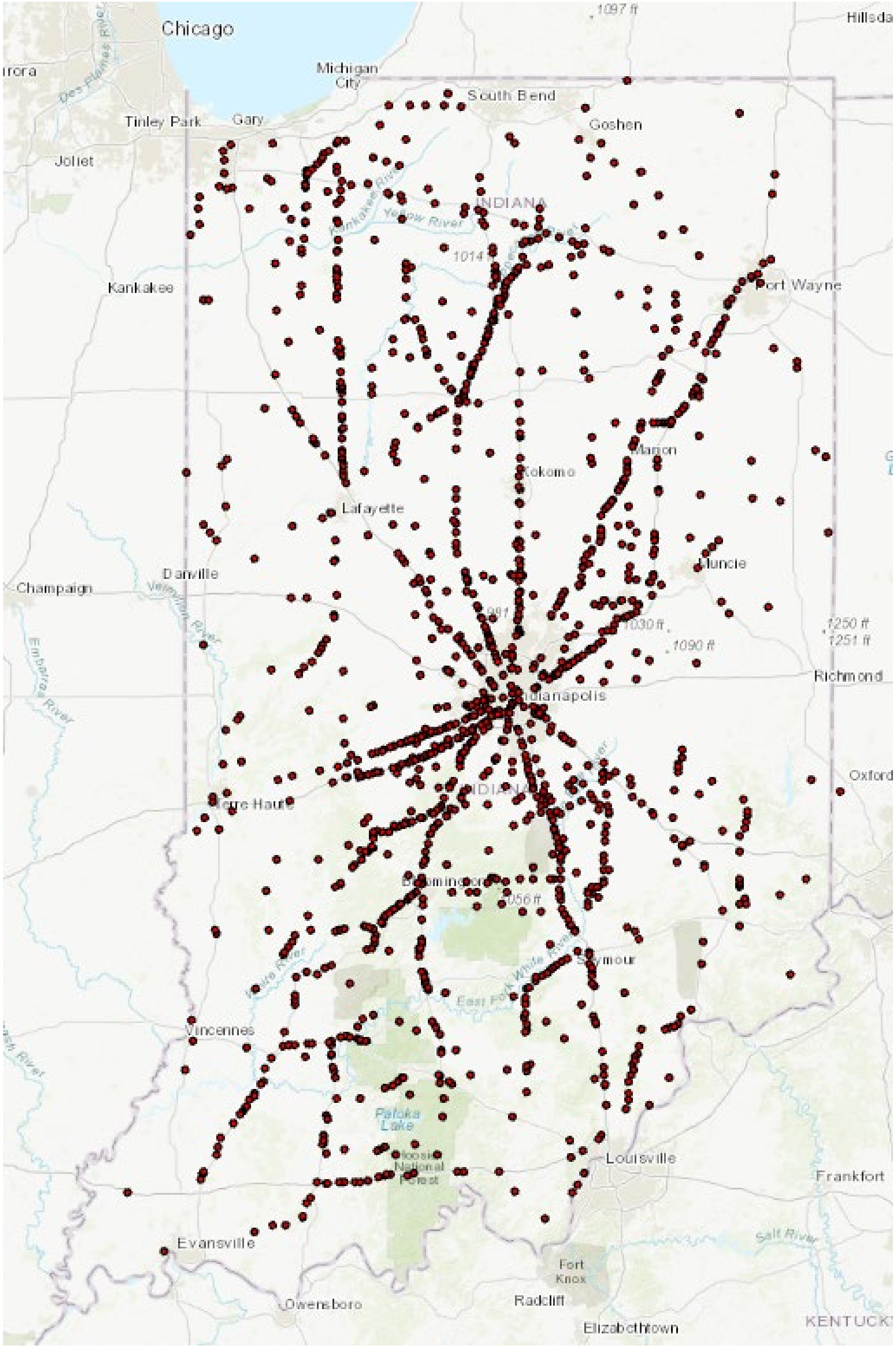

Figure B.3 Distribution map of stop markers for scenario #3.

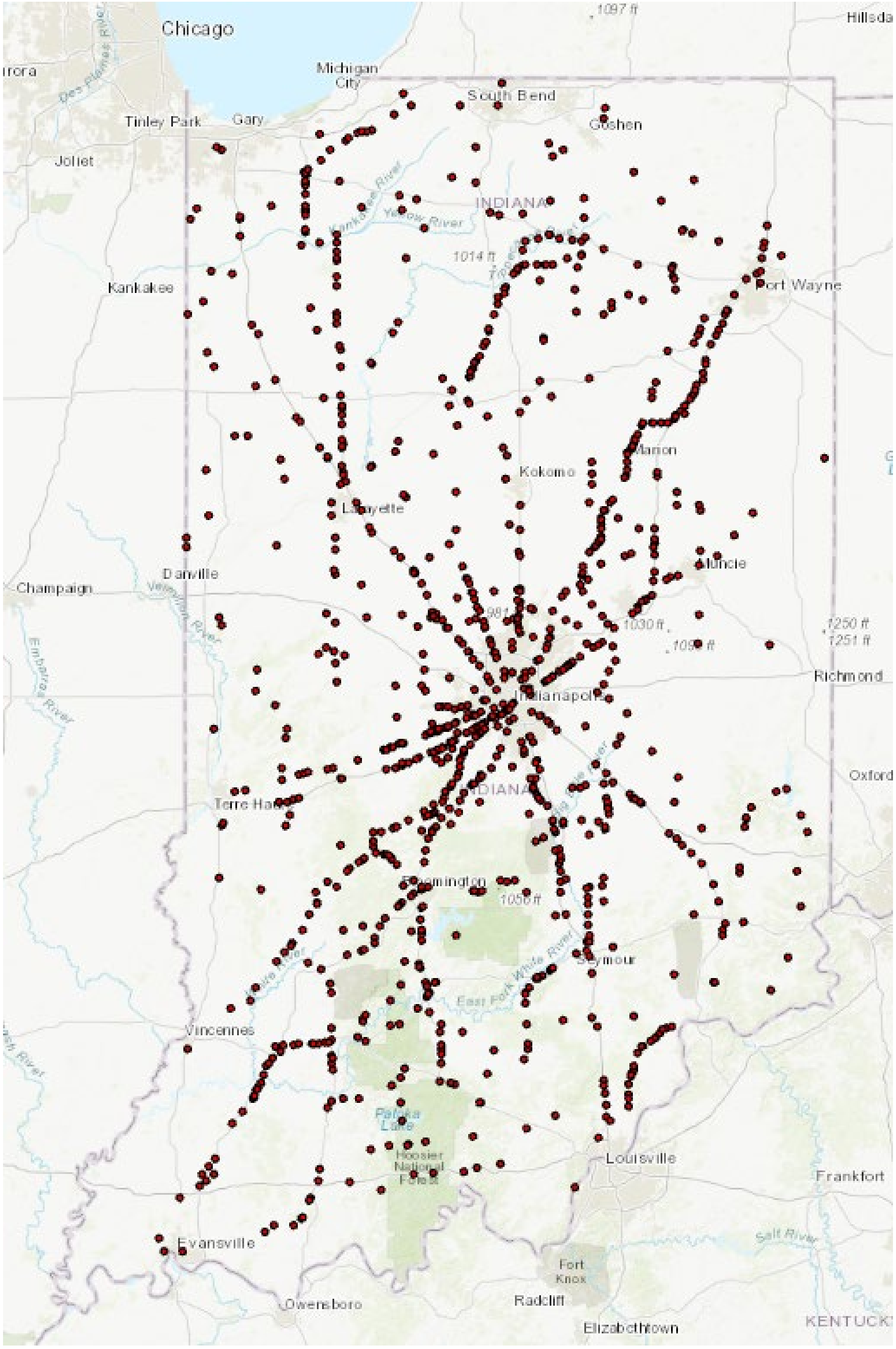

Figure B.4 Distribution map of stop markers for scenario #4.

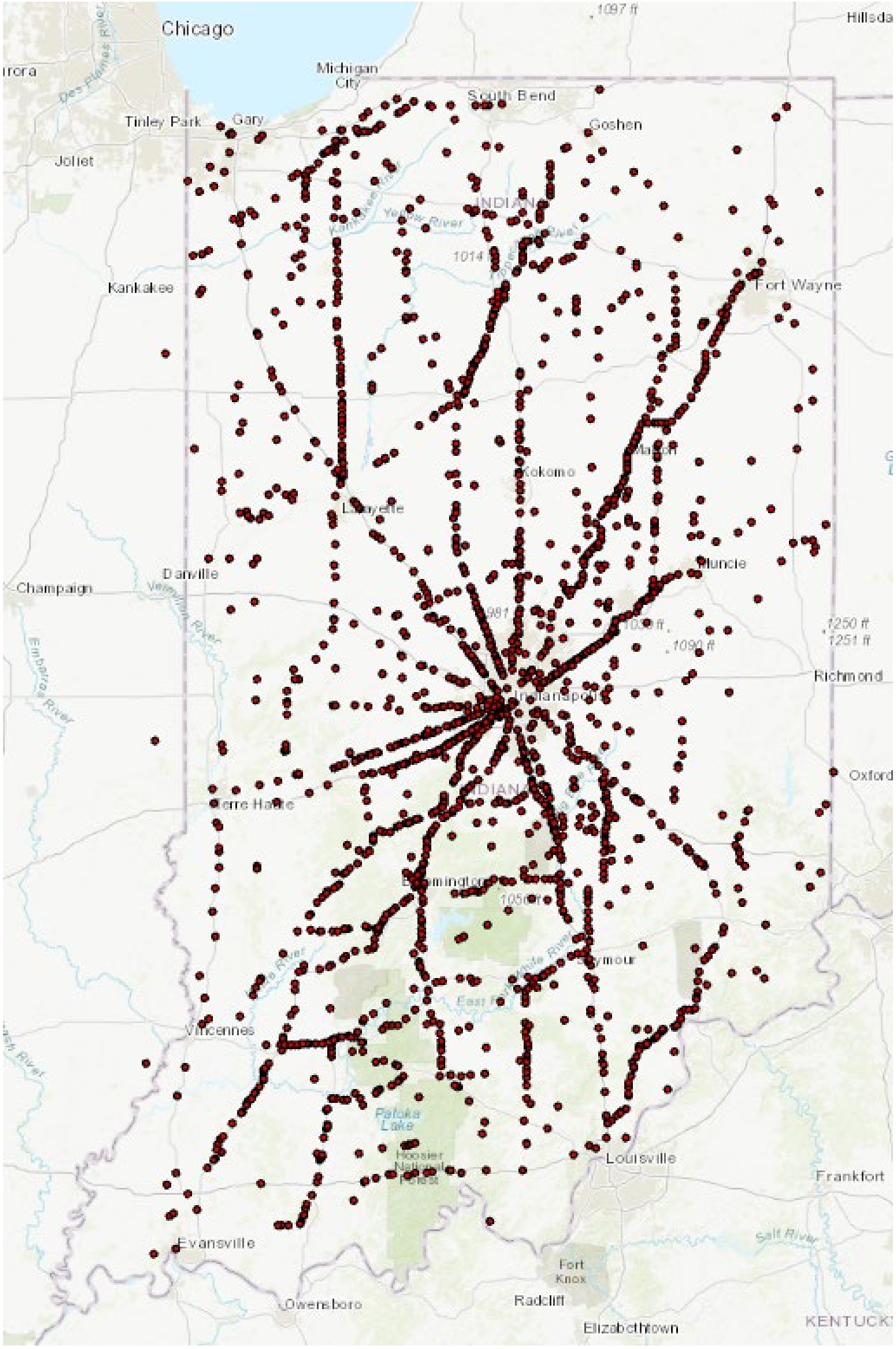

Figure B.5 Distribution map of stop markers for scenario #5.

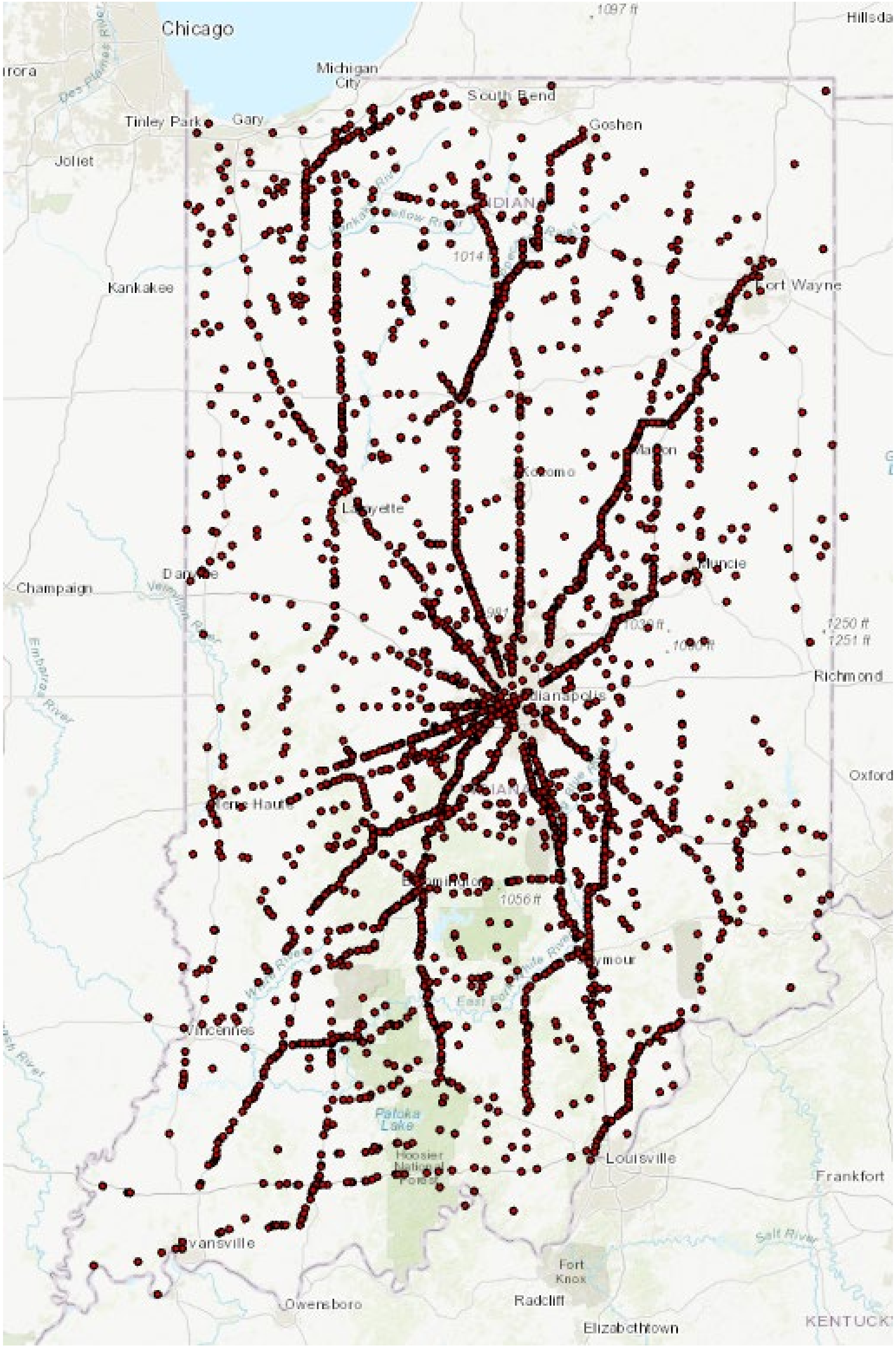

Figure B.6 Distribution map of stop markers for scenario #6.

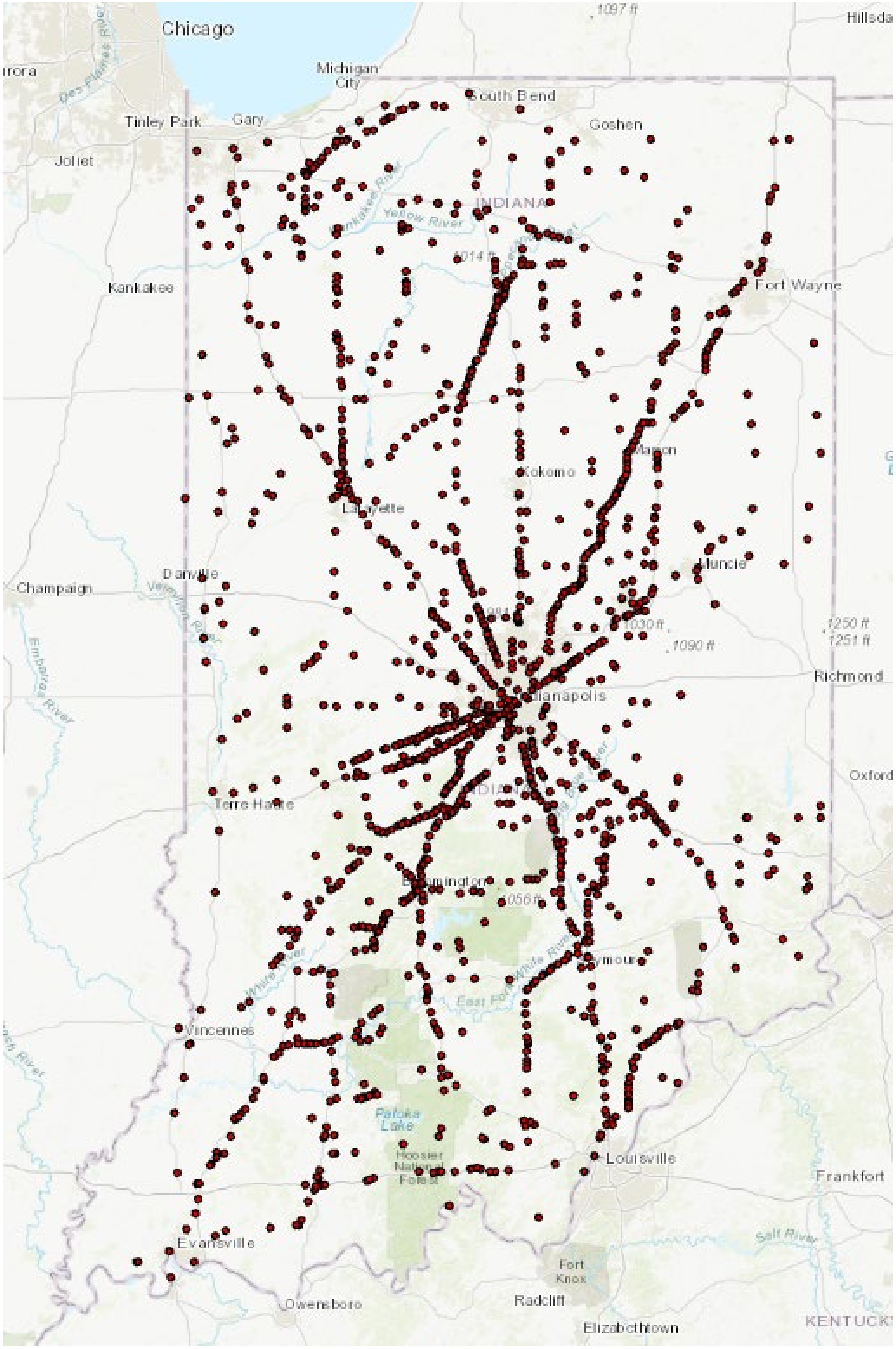

Figure B.7 Distribution map of stop markers for scenario #7.

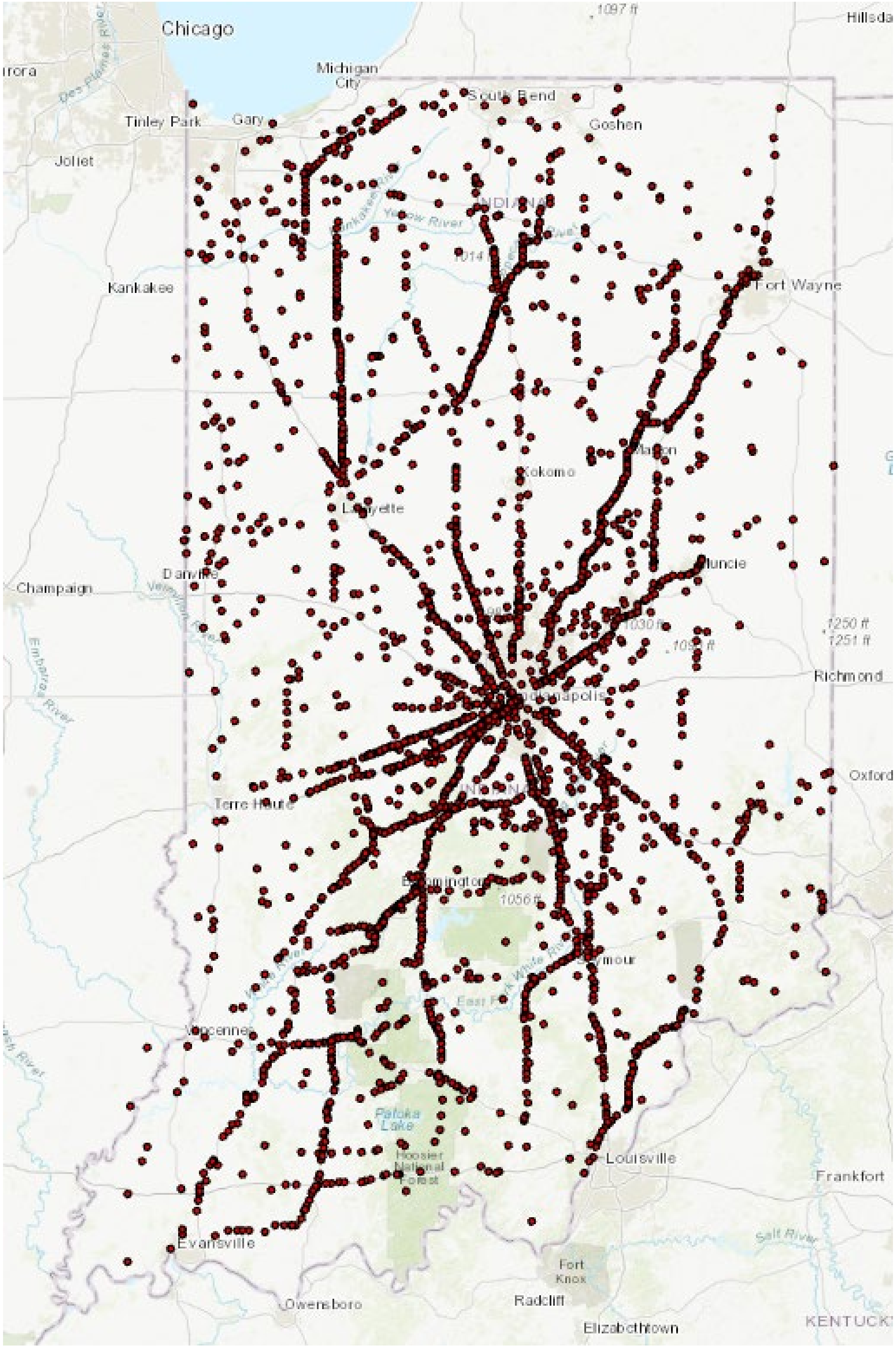

Figure B.8 Distribution map of stop markers for scenario #8.

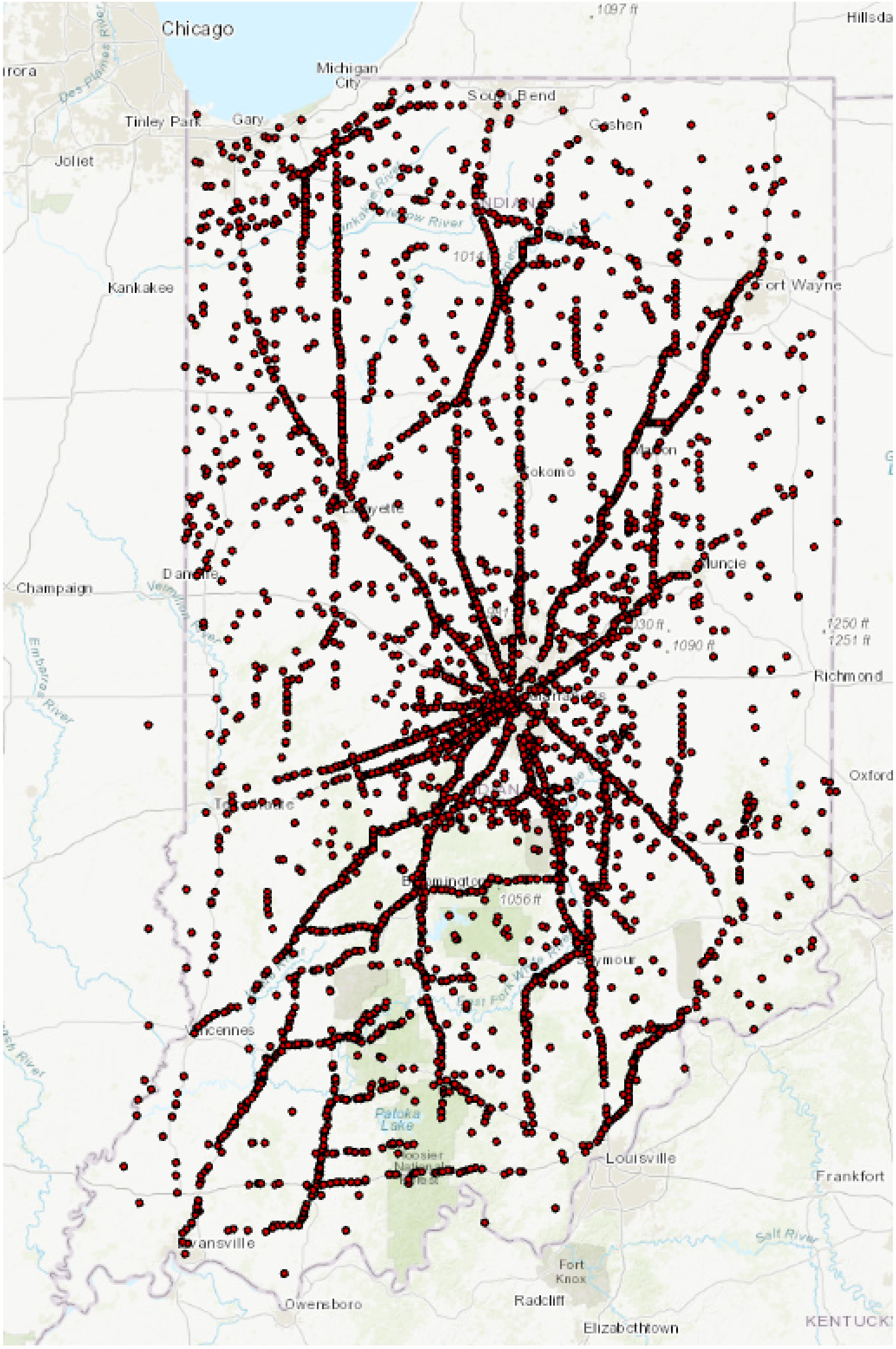

Figure B.9 Distribution map of stop markers for scenario #9.

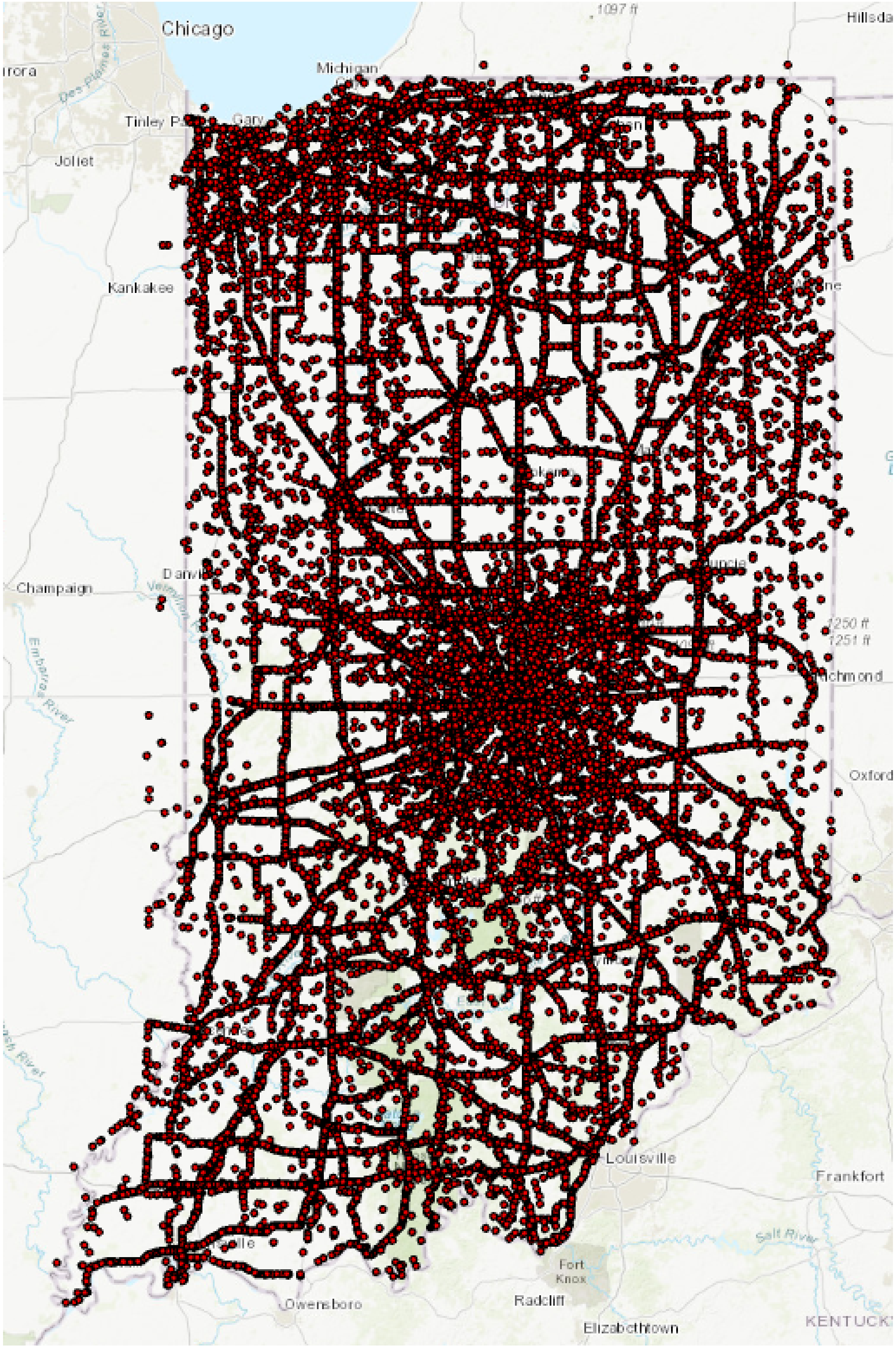

Figure B.10 Distribution map of stop markers for scenario #10.

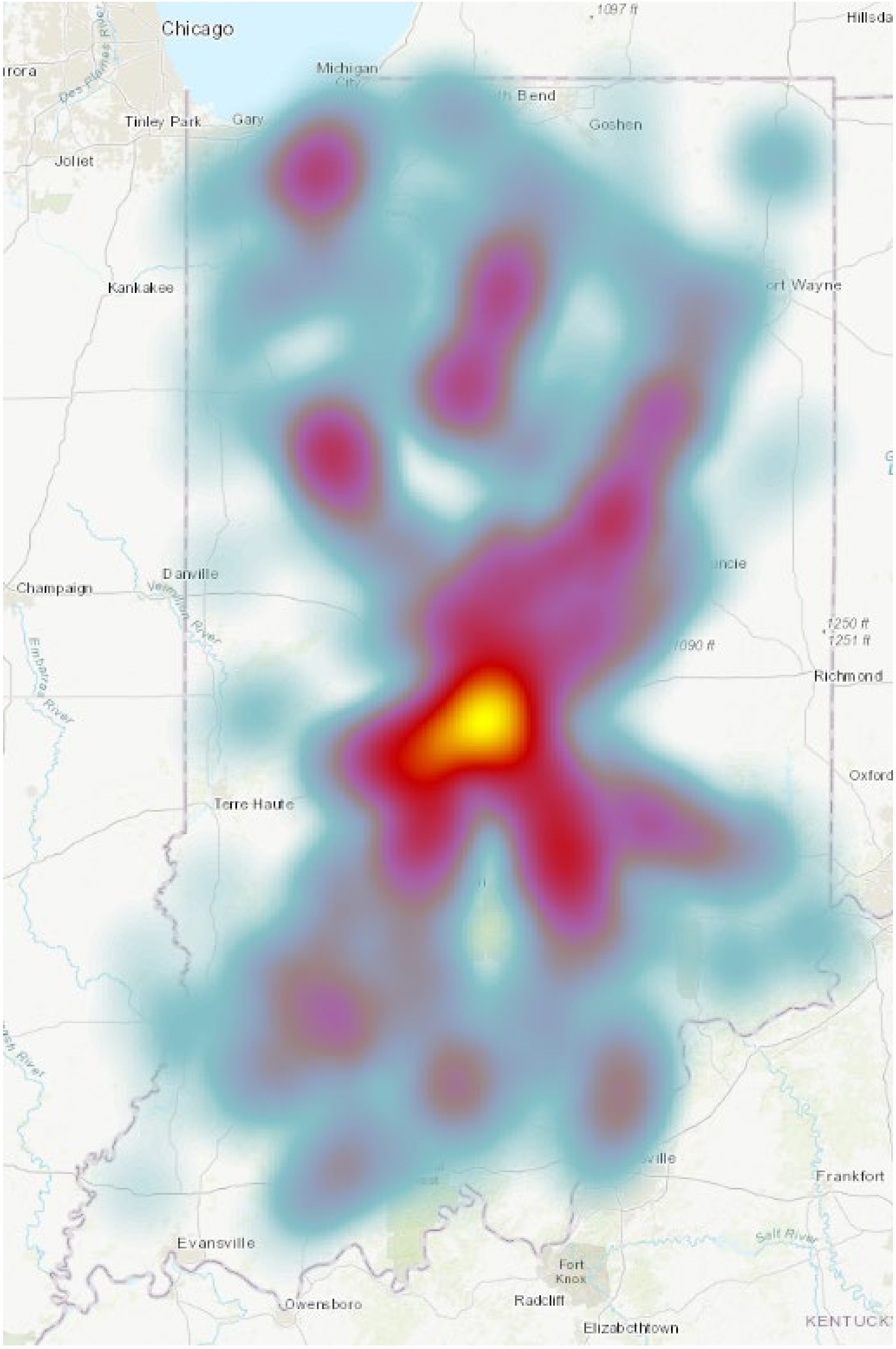

Figure B.11 Heat map analysis of stop markers for scenario #1.

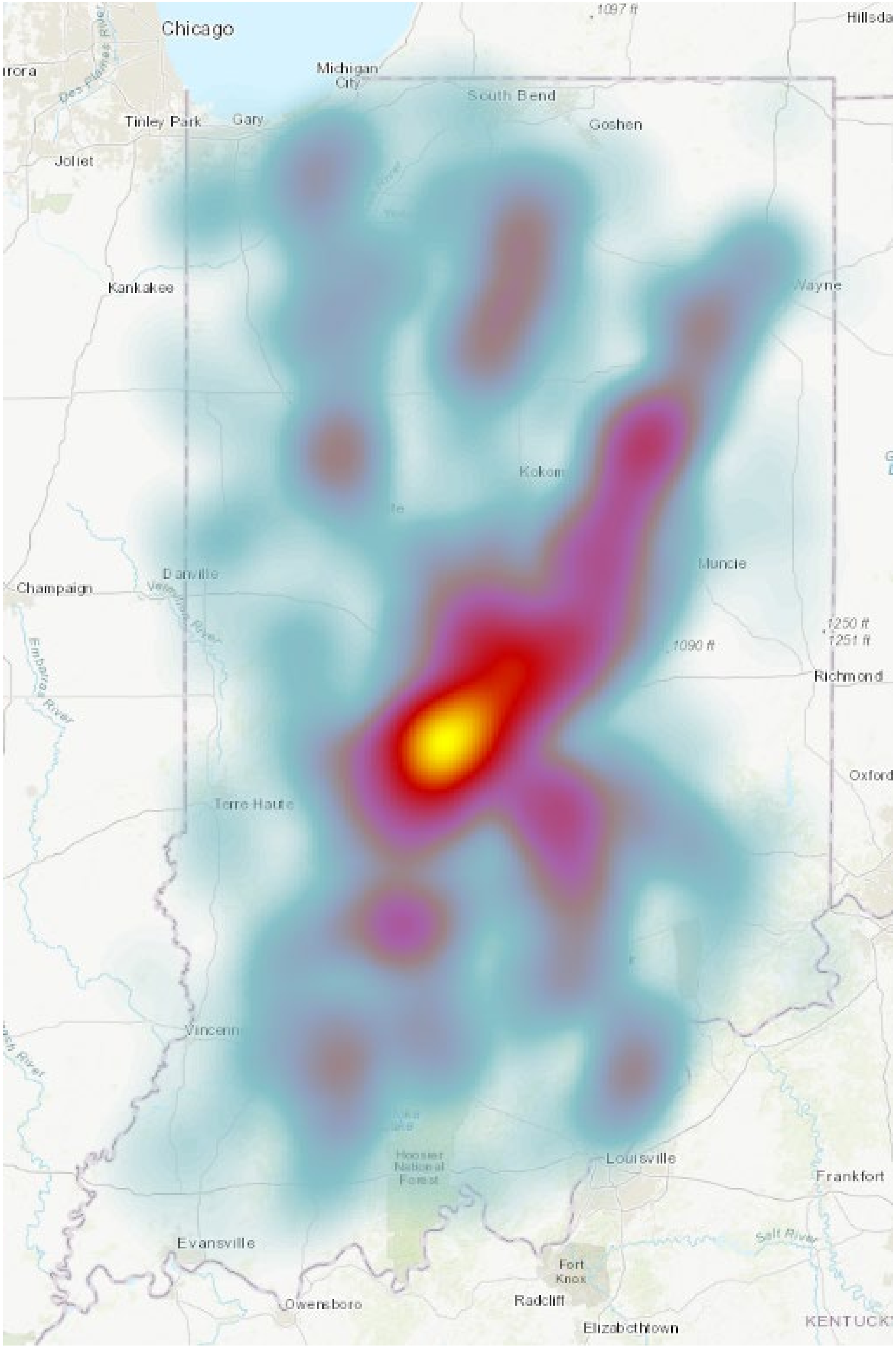

Figure B.12 Heat map analysis of stop markers for scenario #2.

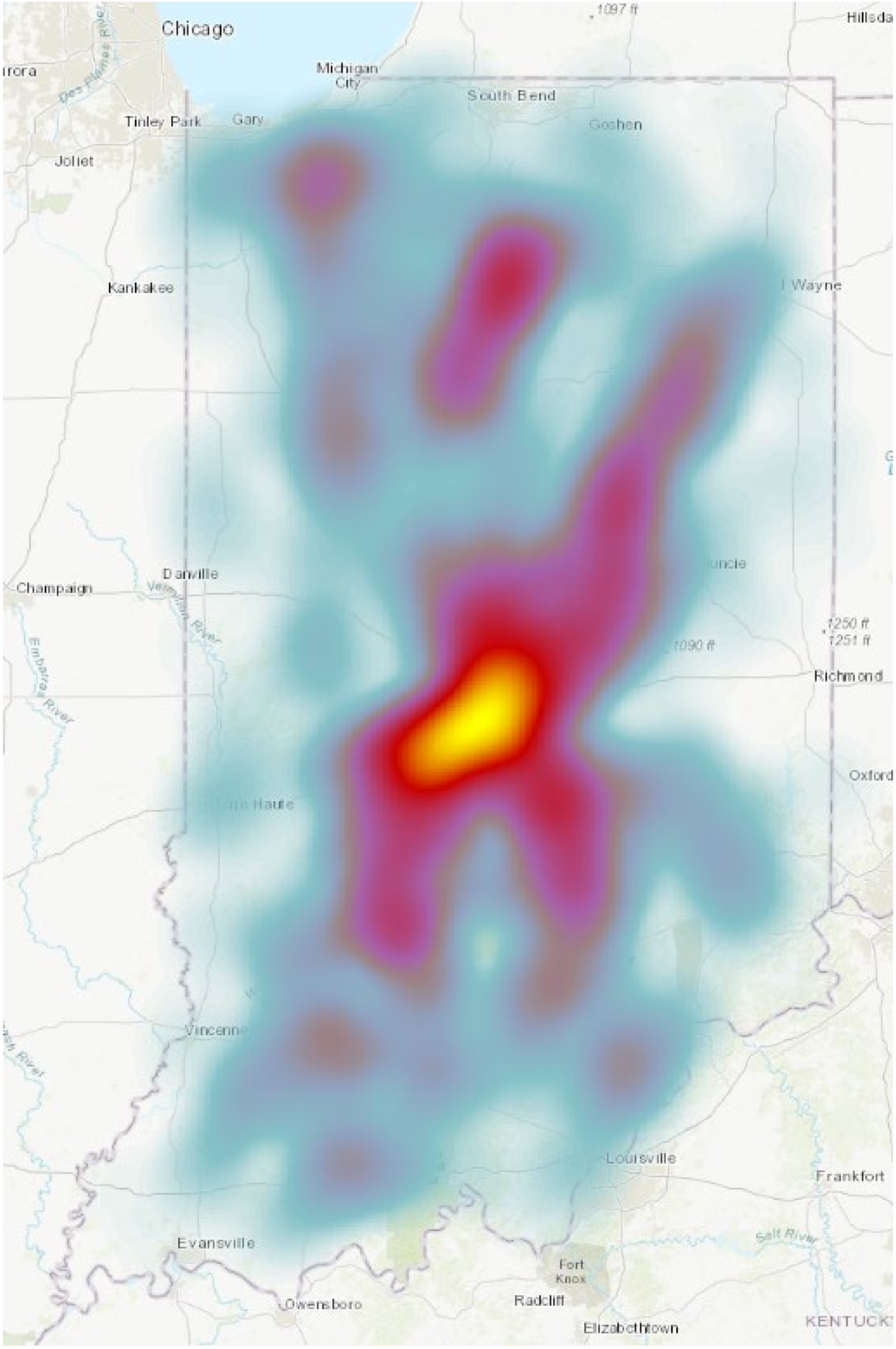

Figure B.13 Heat map analysis of stop markers for scenario #3.

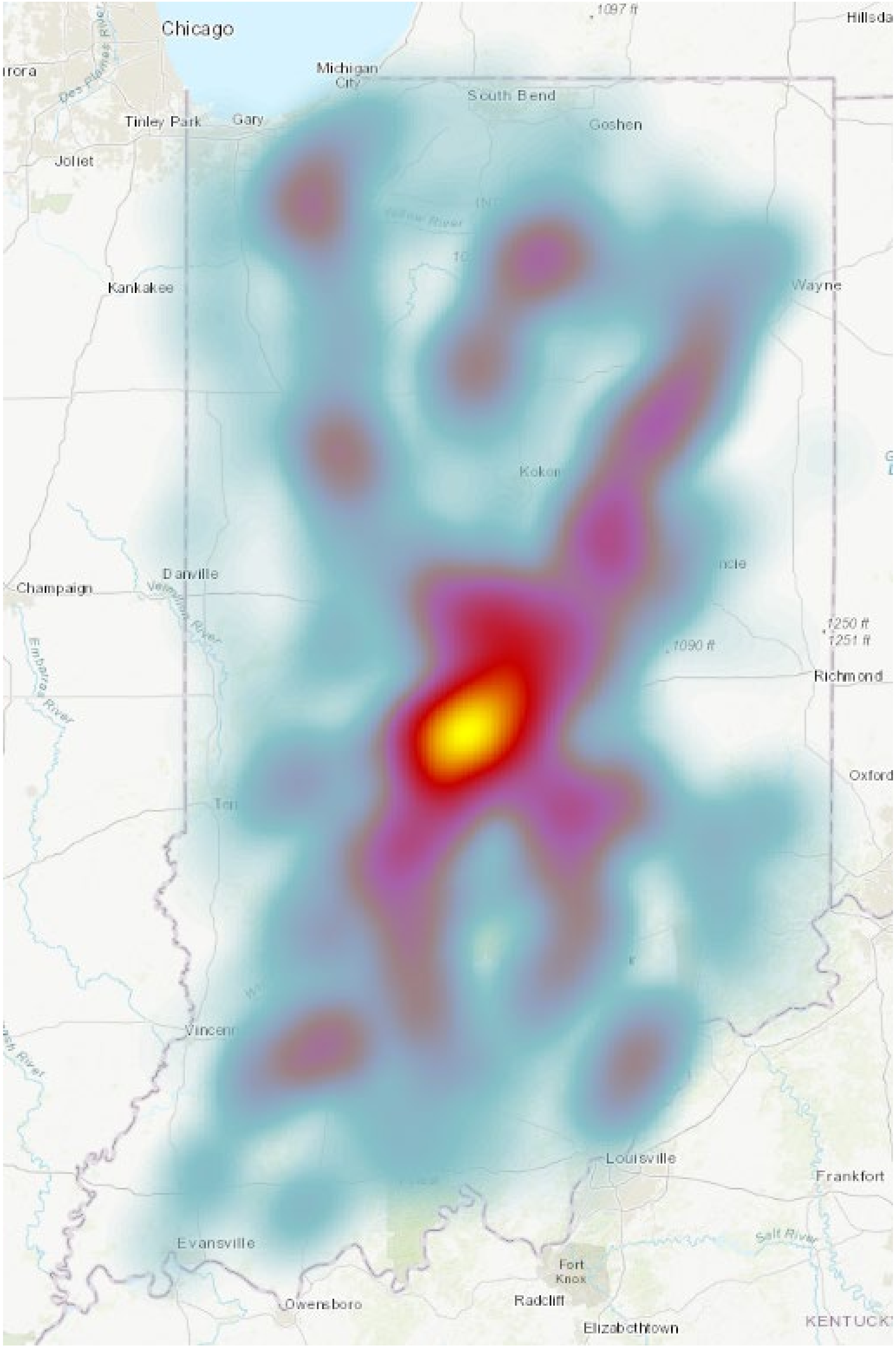

Figure B.14 Heat map analysis of stop markers for scenario #4.

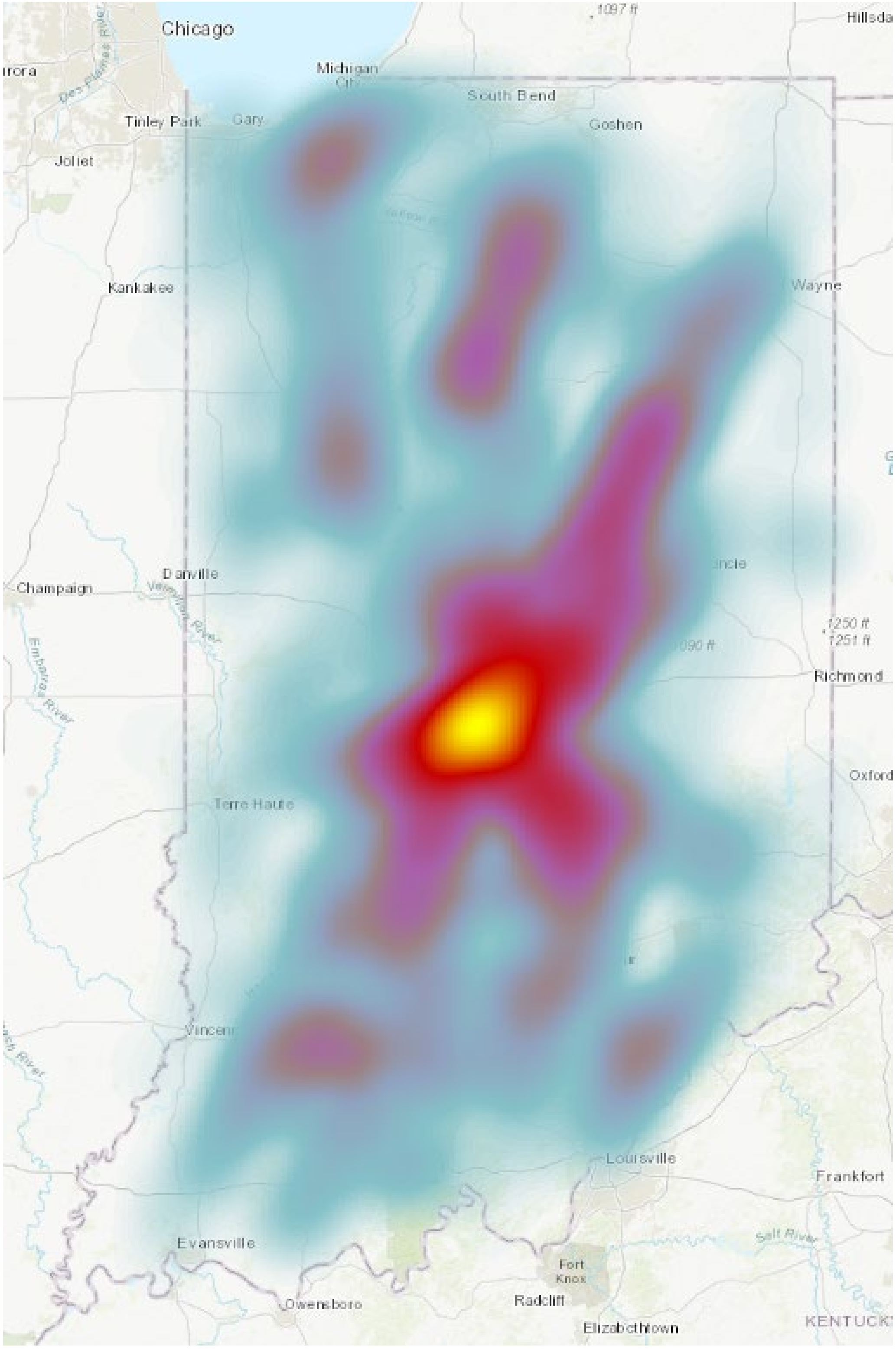

Figure B.15 Heat map analysis of stop markers for scenario #5.

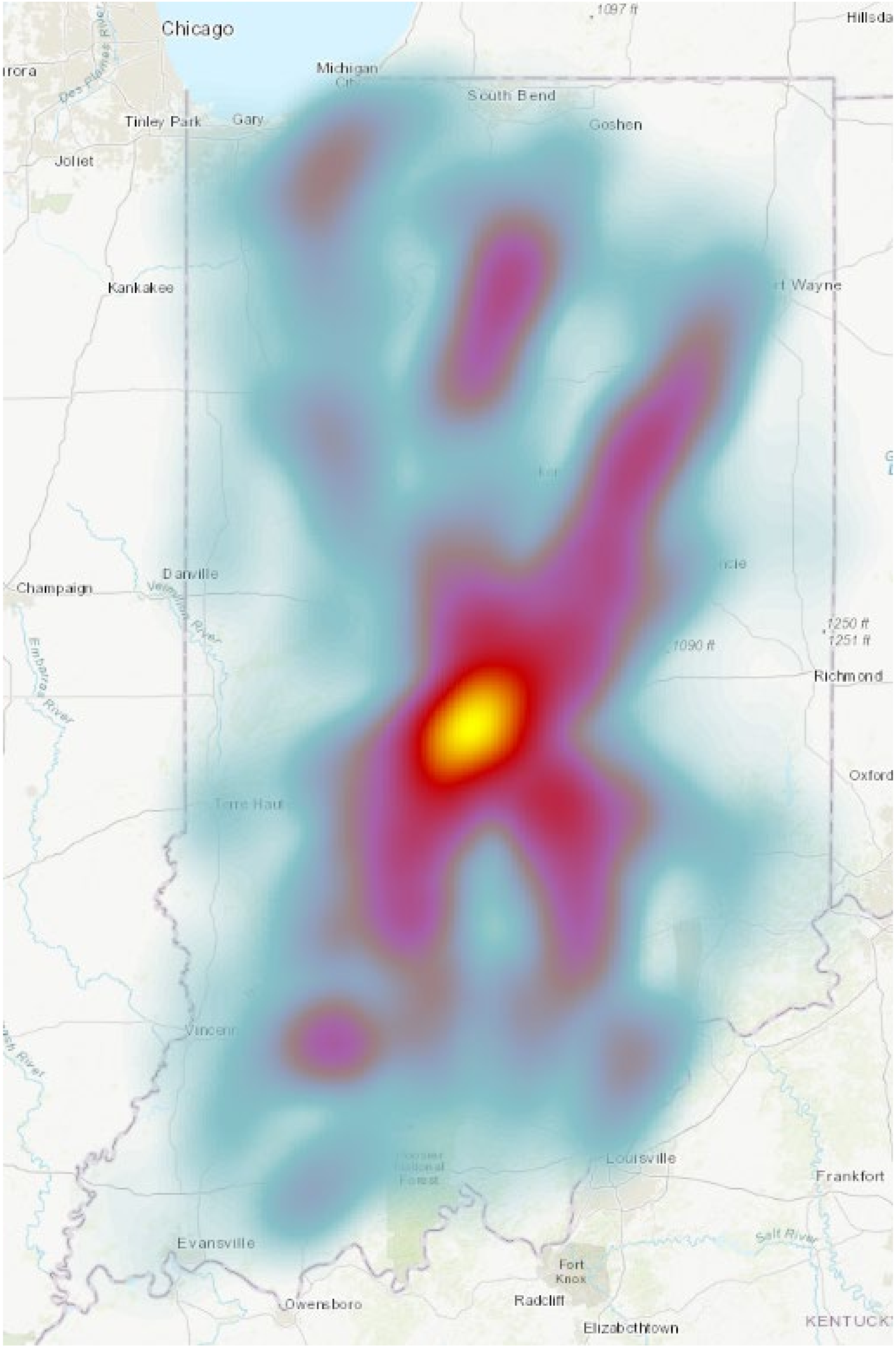

Figure B.16 Heat map analysis of stop markers for scenario #6.

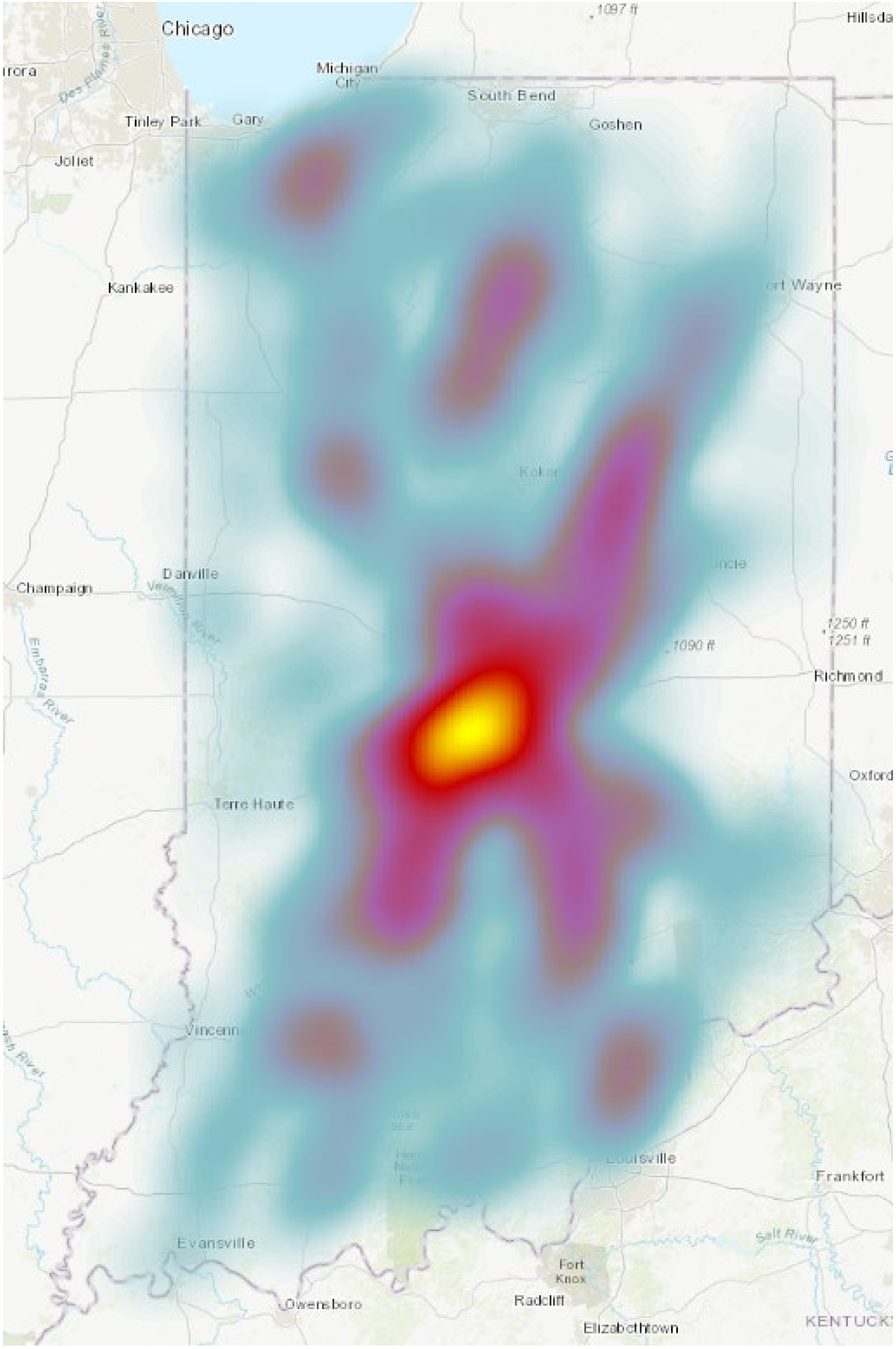

Figure B.17 Heat map analysis of stop markers for scenario #7.

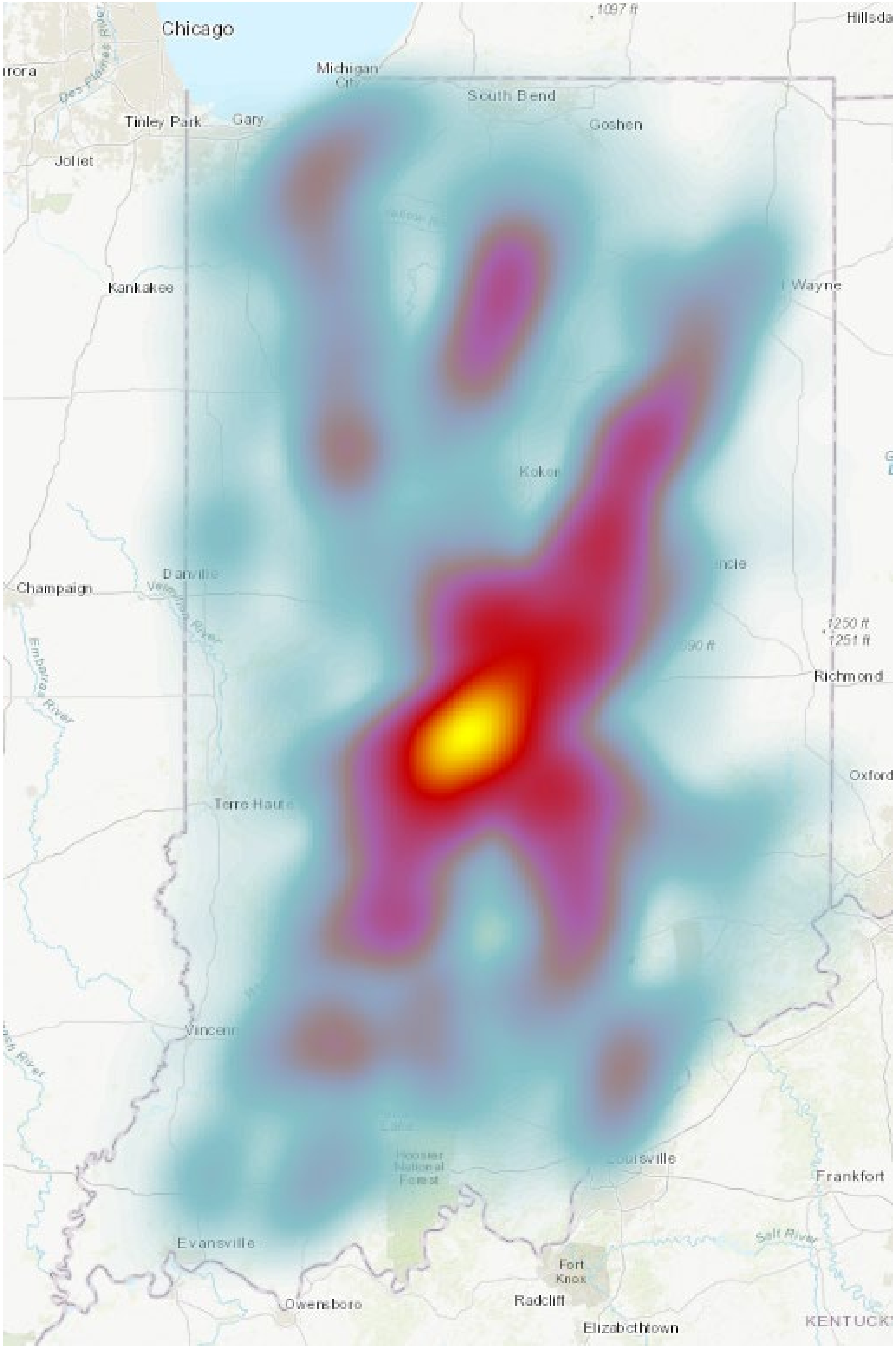

Figure B.18 Heat map analysis of stop markers for scenario #8.

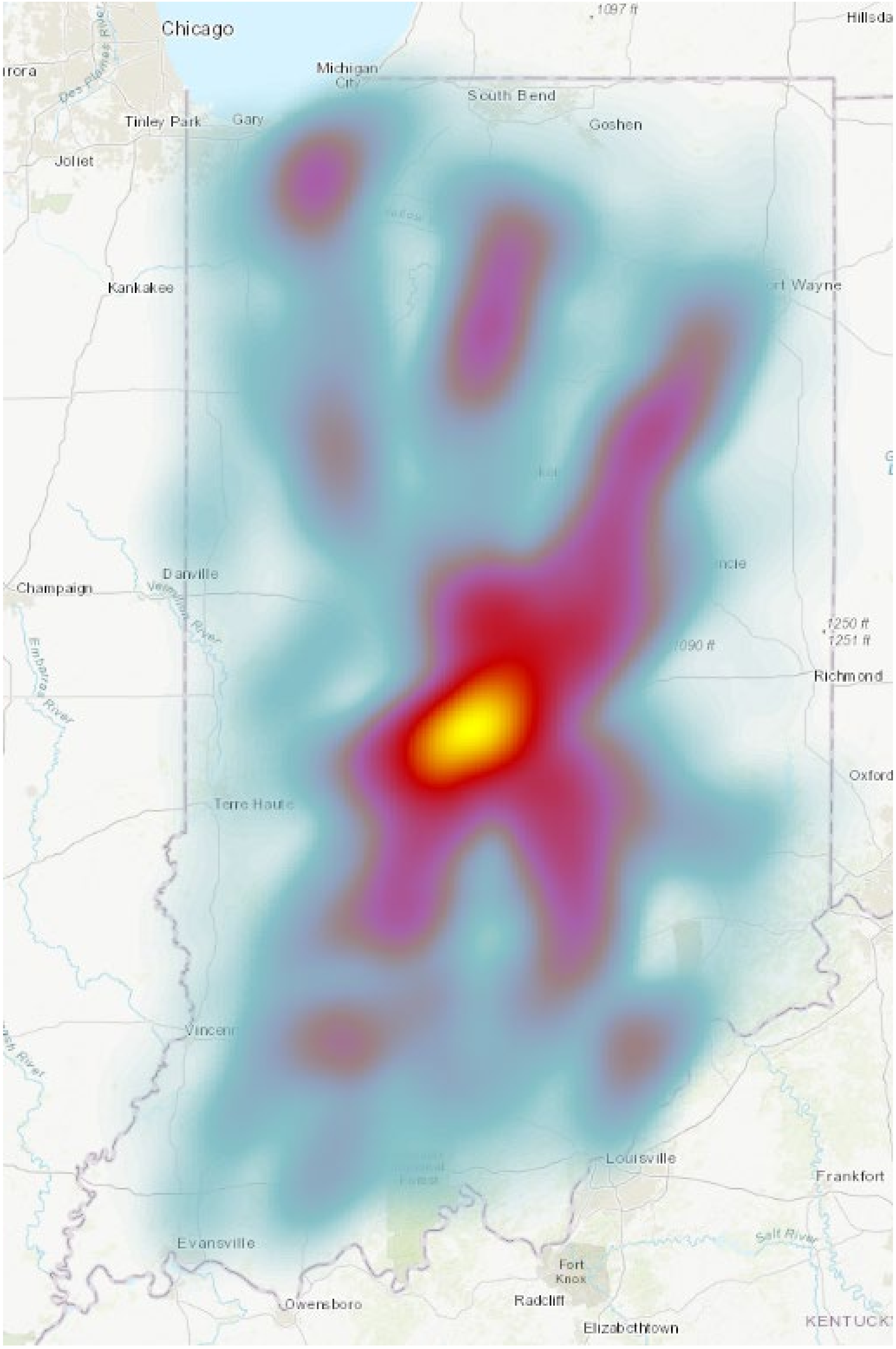

Figure B.19 Heat map analysis of stop markers for scenario #9.

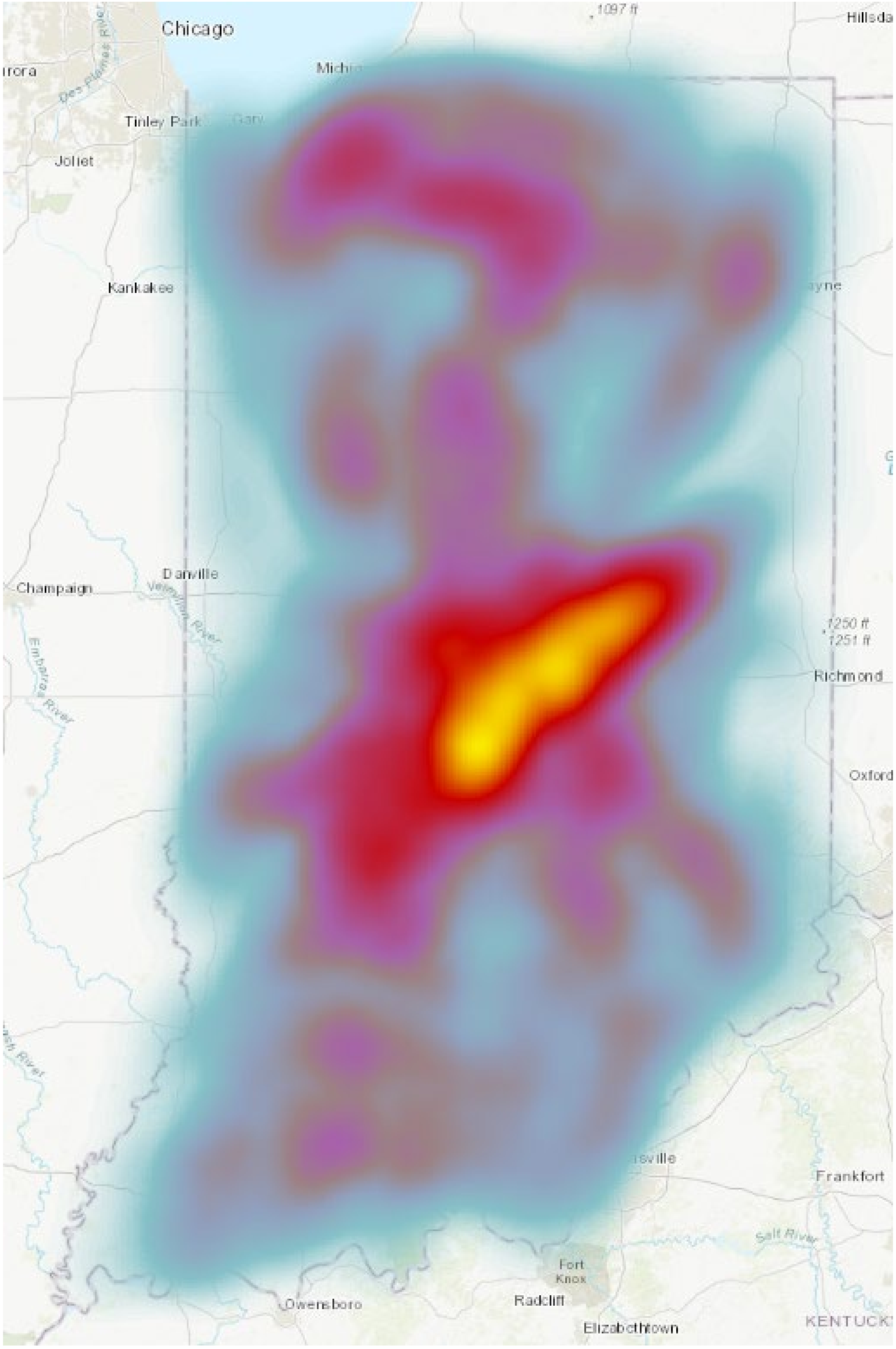

Figure B.20 Heat map analysis of stop markers for scenario #10.

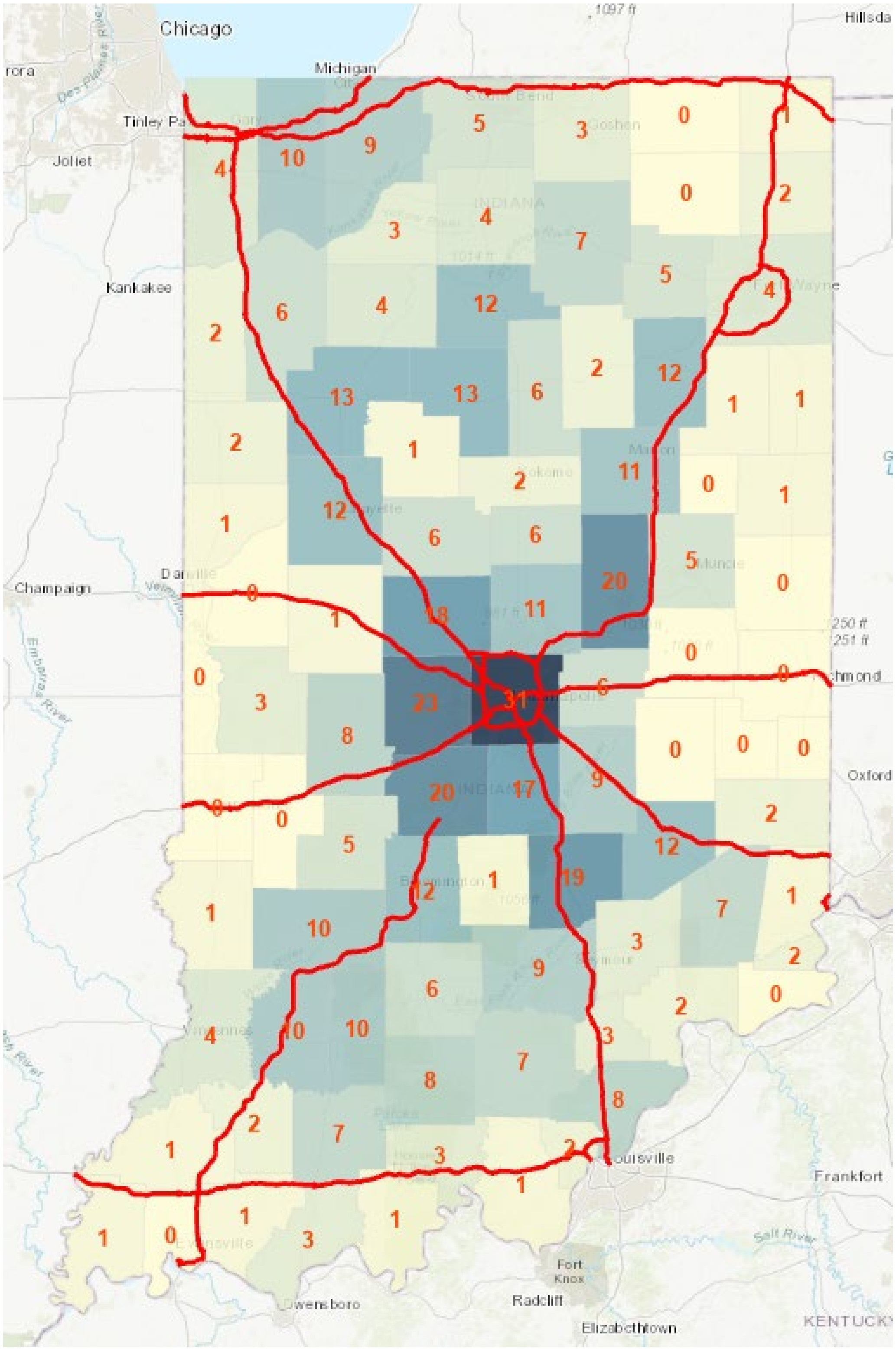

Figure B.21 Spatial aggregation analysis on count of stop markers at county level for scenario #1.

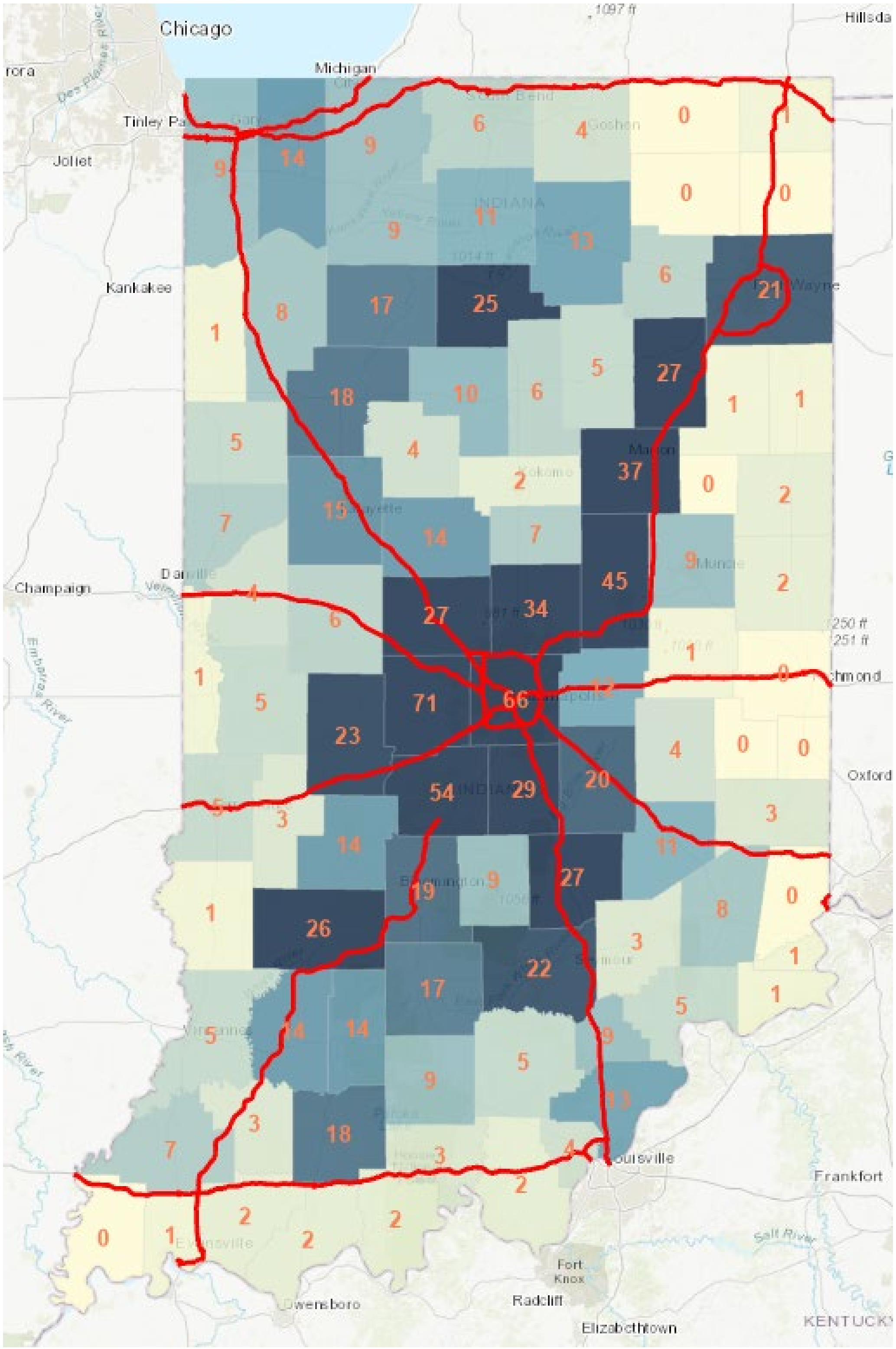

Figure B.22 Spatial aggregation analysis on count of stop markers at county level for scenario #2.

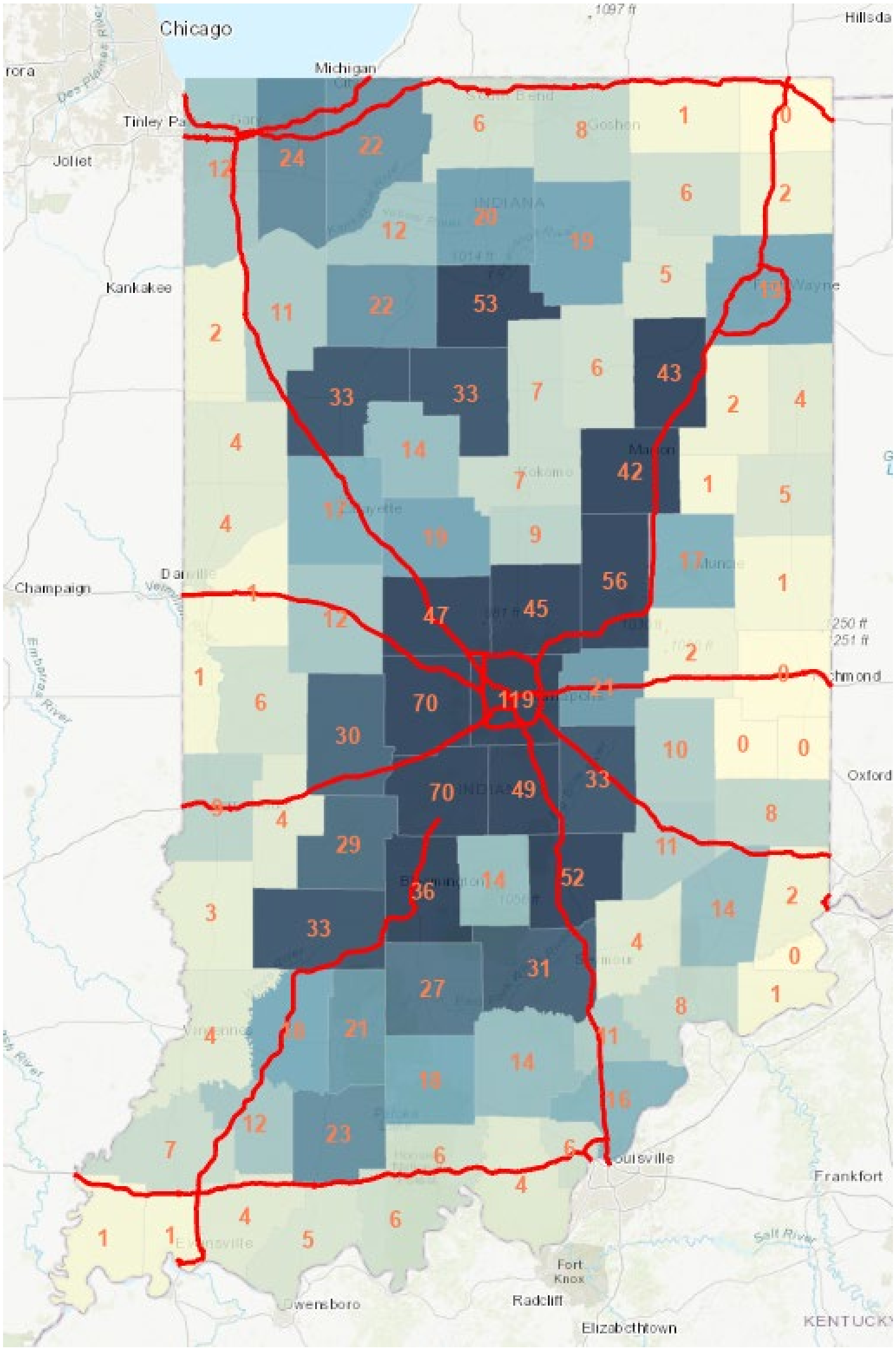

Figure B.23 Spatial aggregation analysis on count of stop markers at county level for scenario #3.

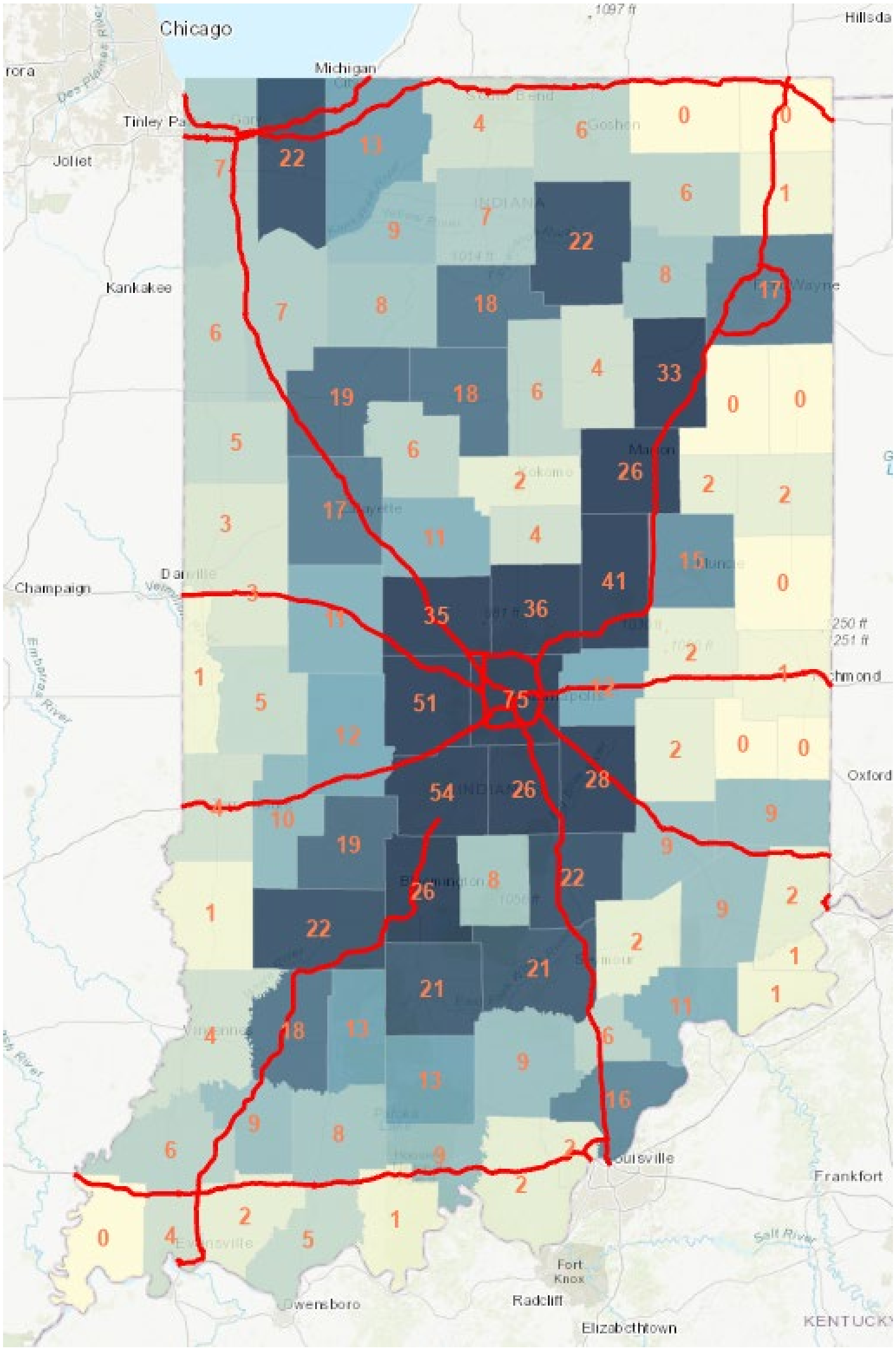

Figure B.24 Spatial aggregation analysis on count of stop markers at county level for scenario #4.

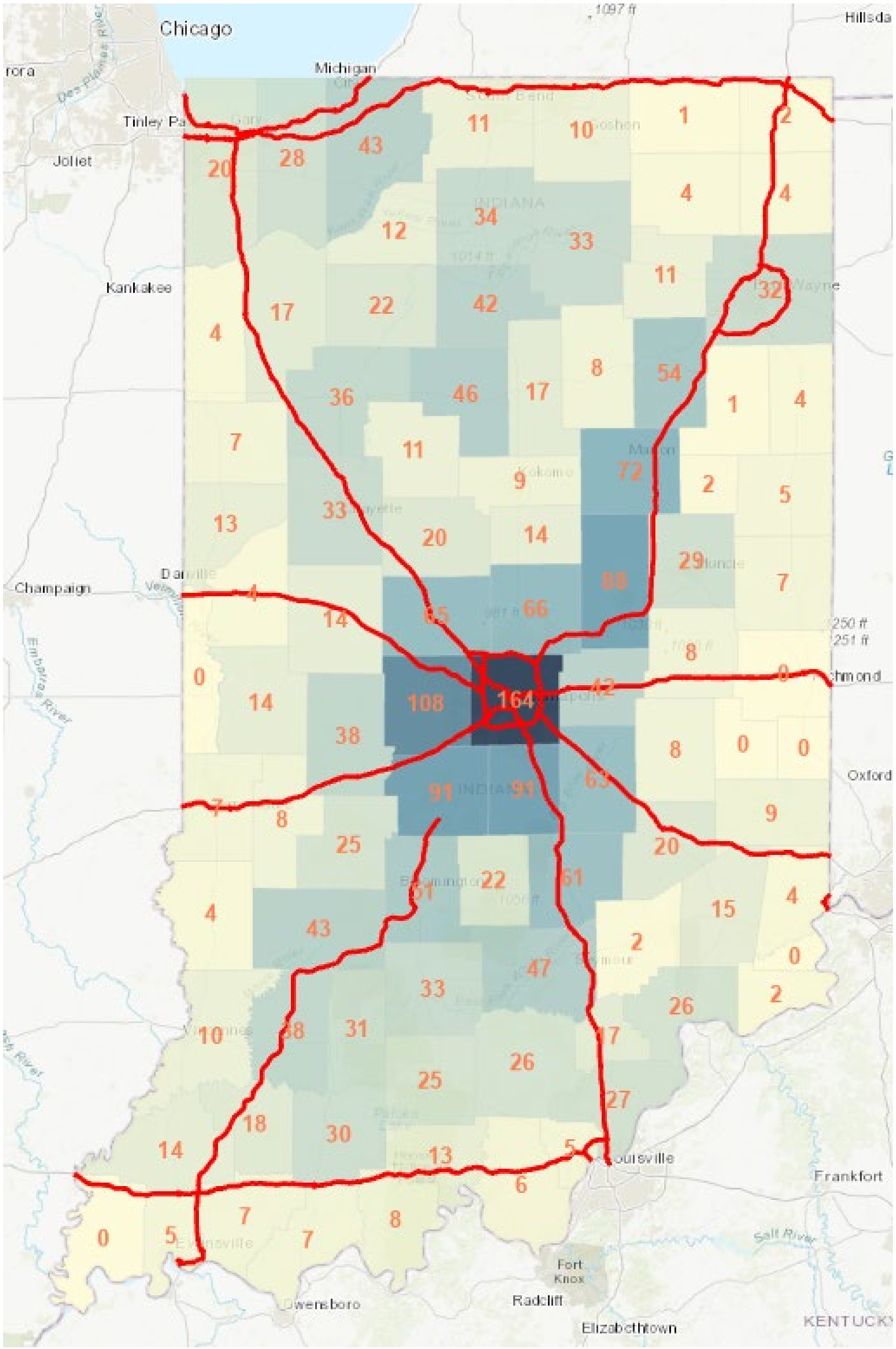

Figure B.25 Spatial aggregation analysis on count of stop markers at county level for scenario #5.

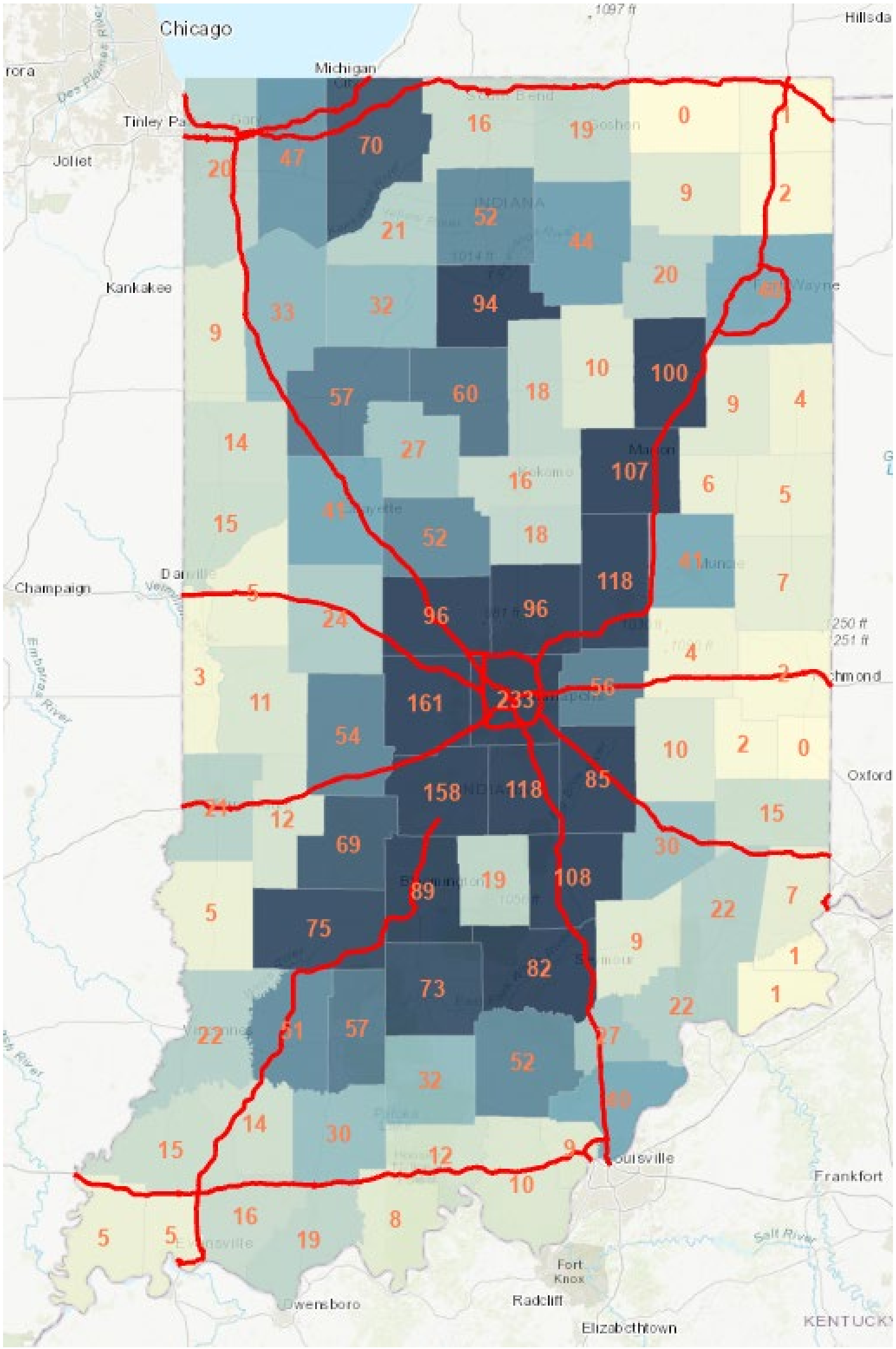

Figure B.26 Spatial aggregation analysis on count of stop markers at county level for scenario #6.

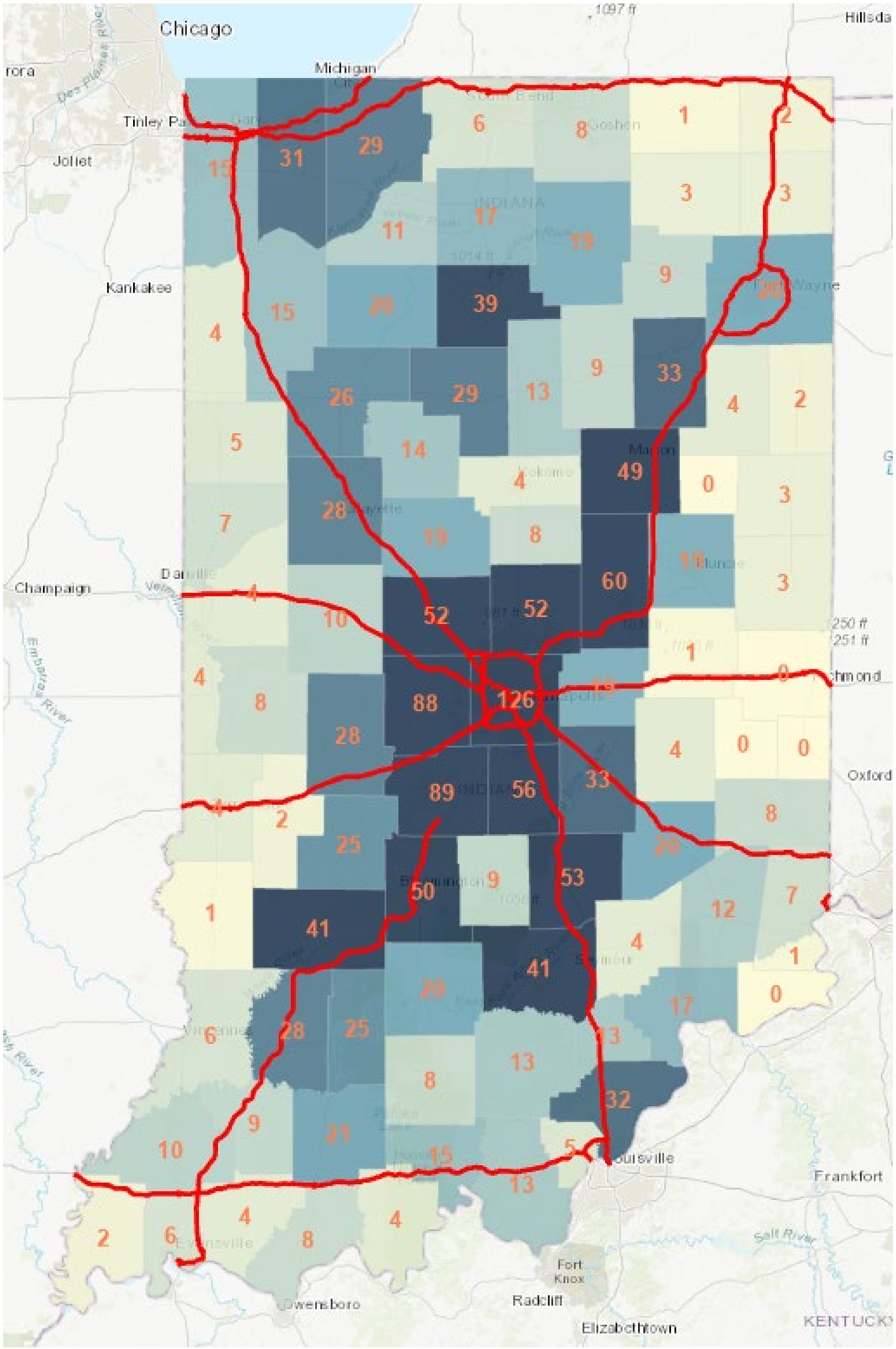

Figure B.27 Spatial aggregation analysis on count of stop markers at county level for scenario #7.

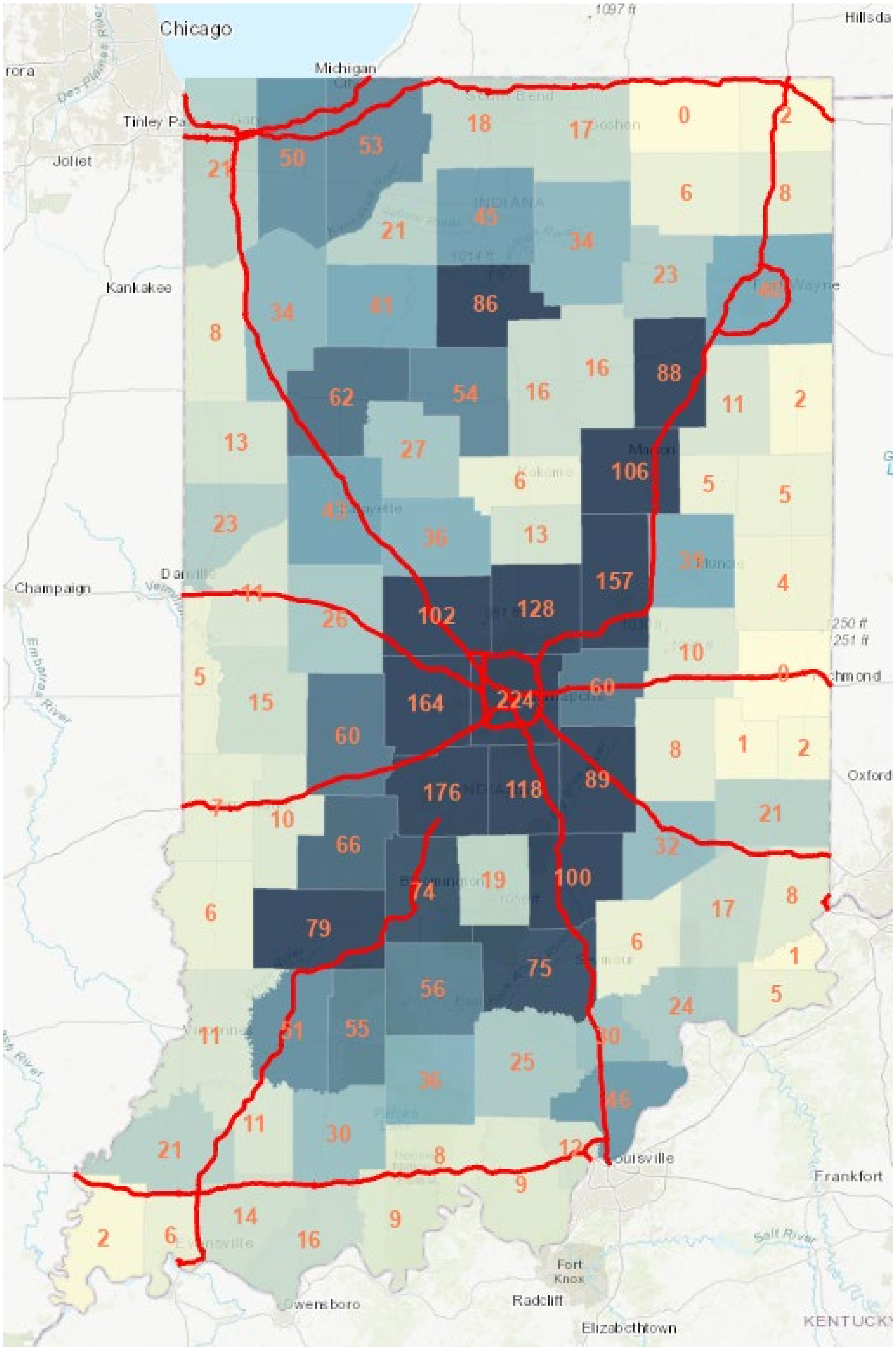

Figure B.28 Spatial aggregation analysis on count of stop markers at county level for scenario #8.

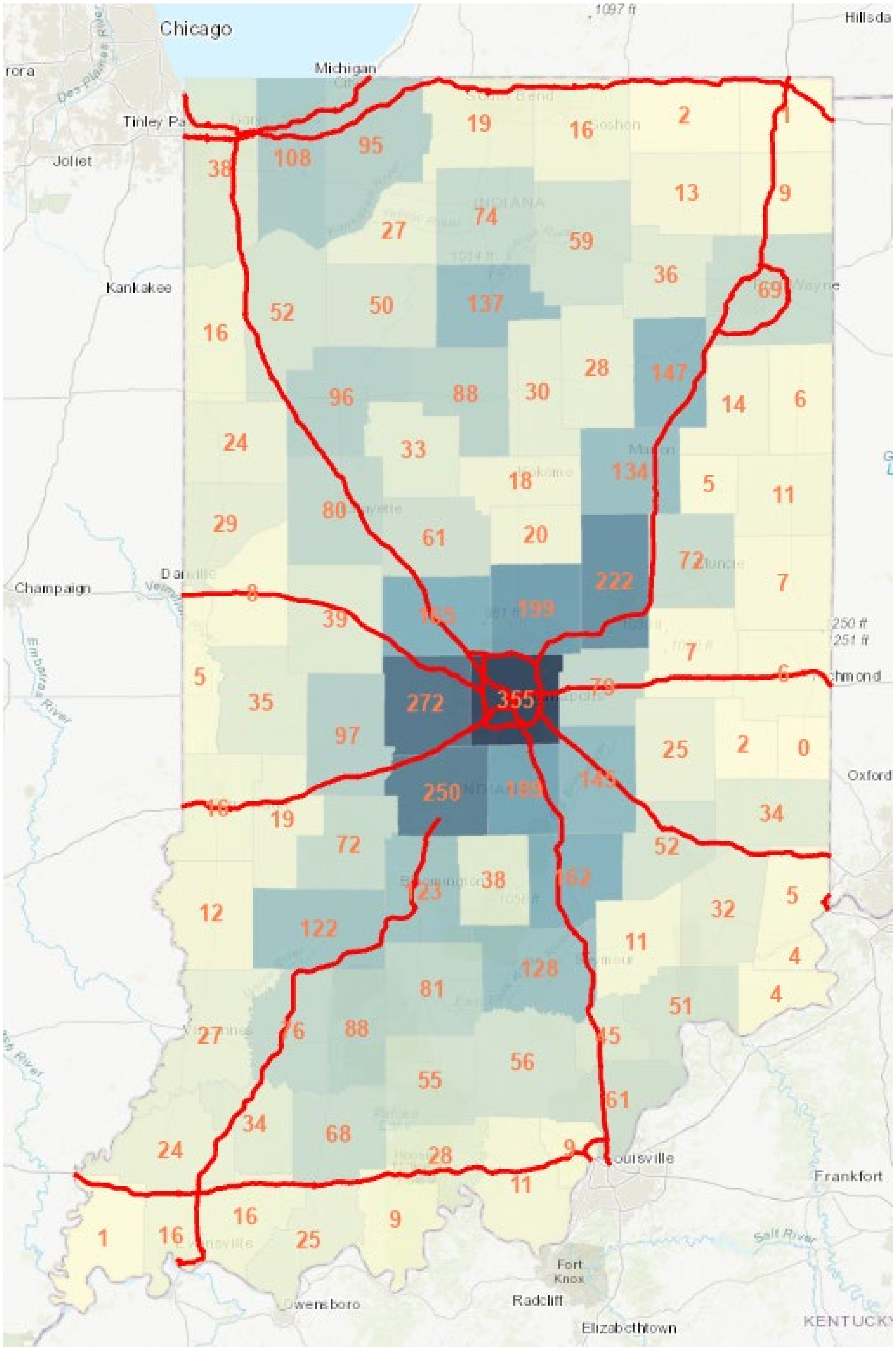

Figure B.29 Spatial aggregation analysis on count of stop markers at county level for scenario #9.

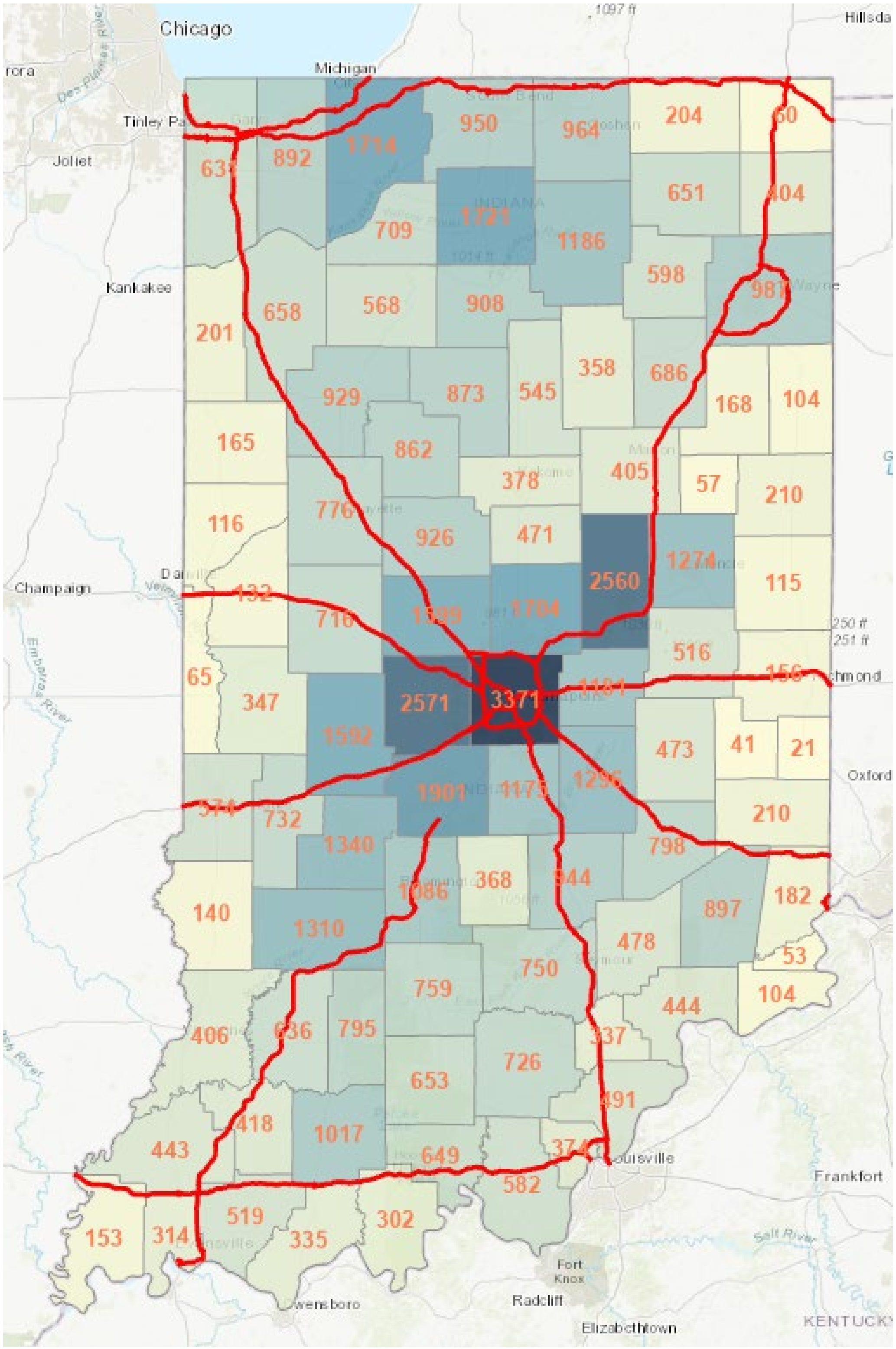

Figure B.30 Spatial aggregation analysis on count of stop markers at county level for scenario #10.

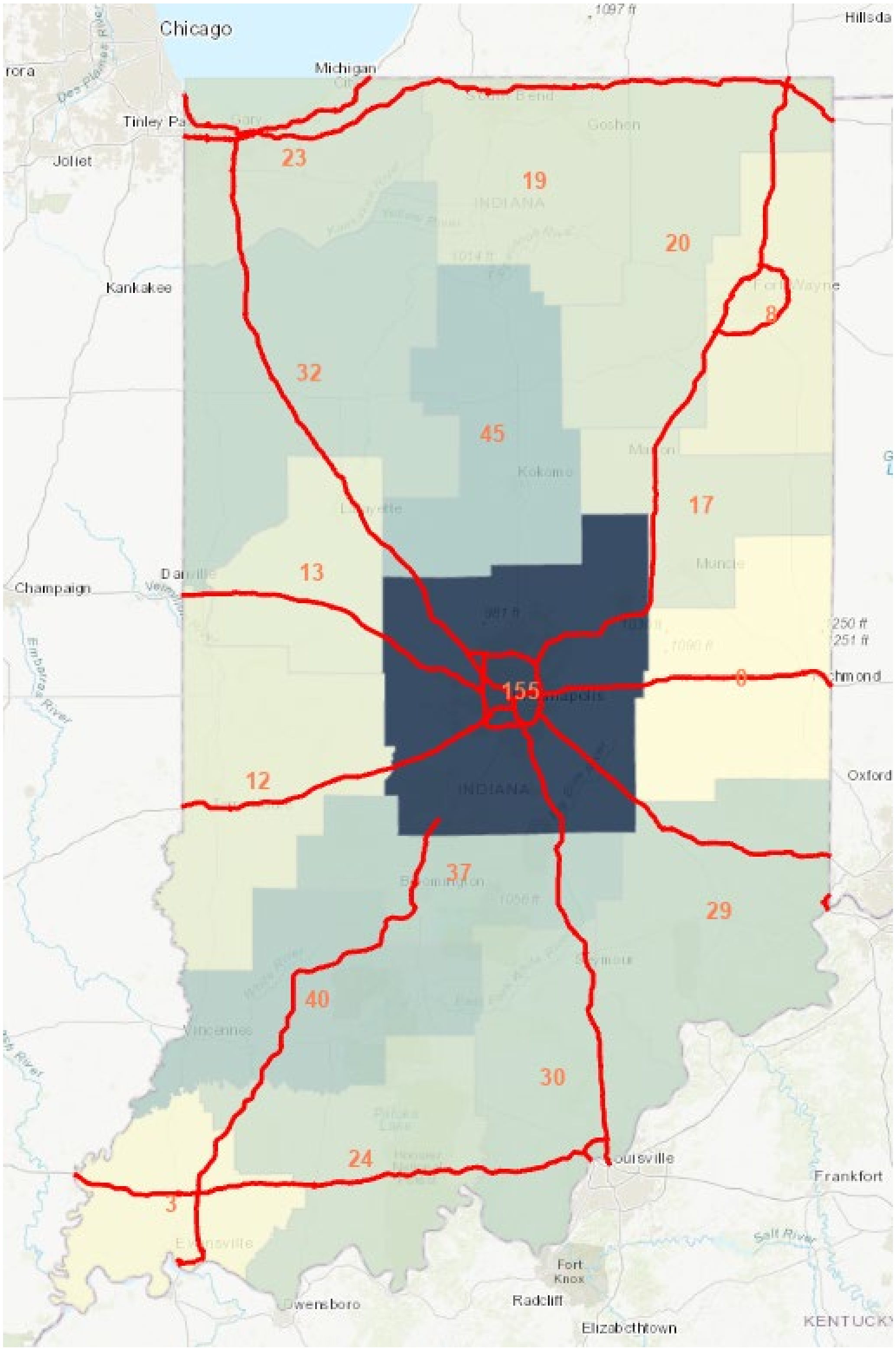

Figure B.31 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #1.

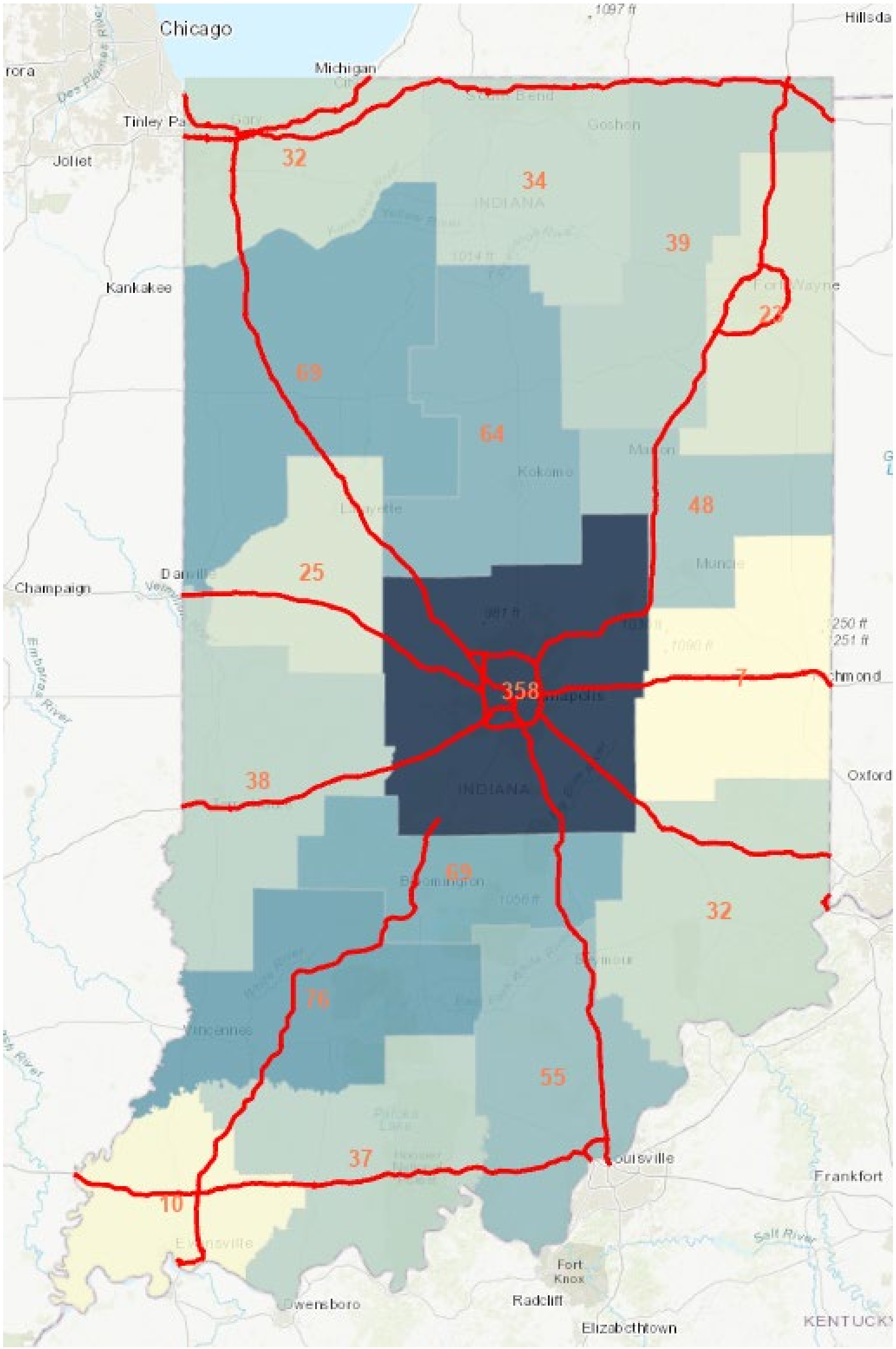

Figure B.32 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #2.

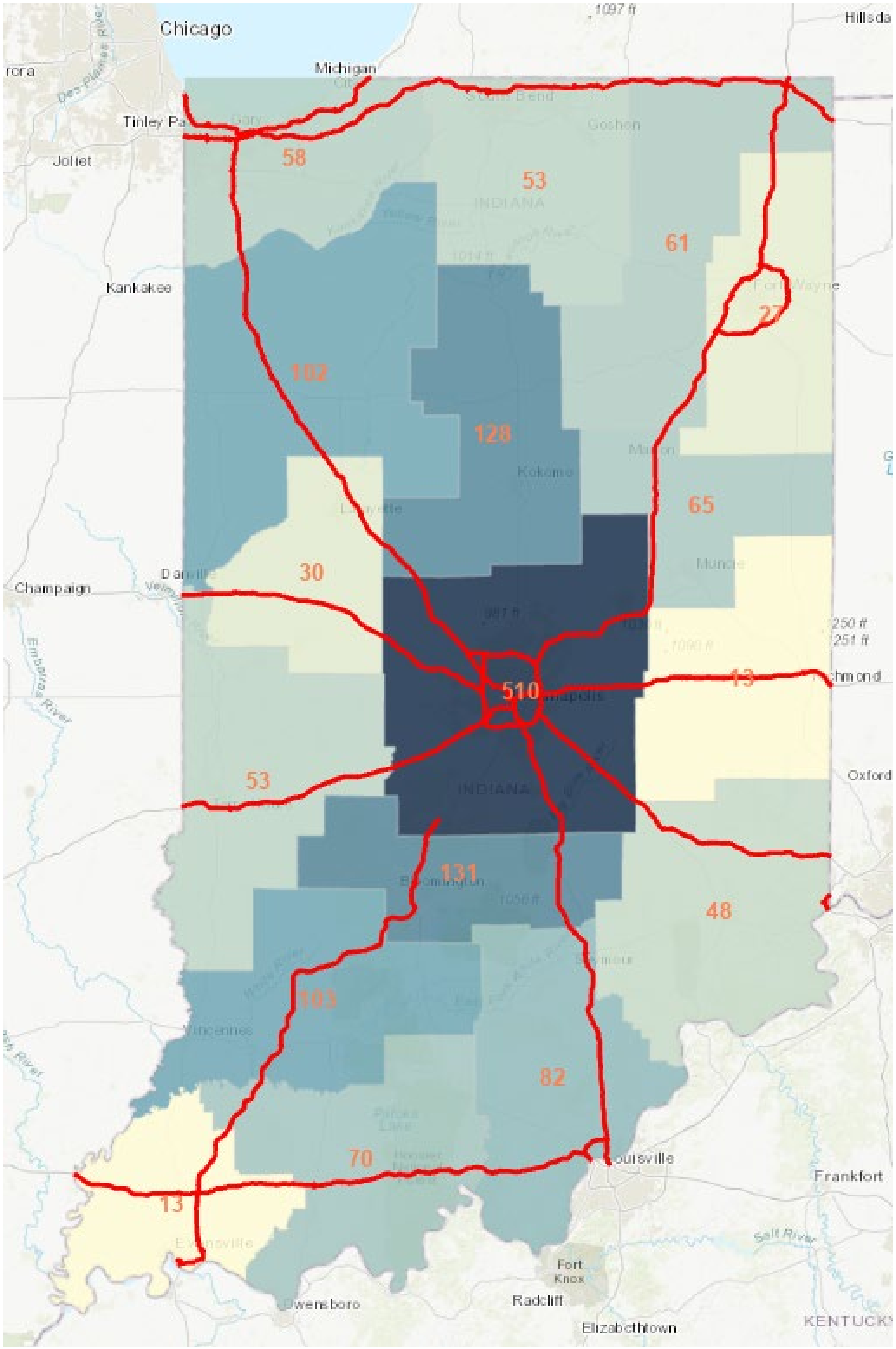

Figure B.33 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #3.

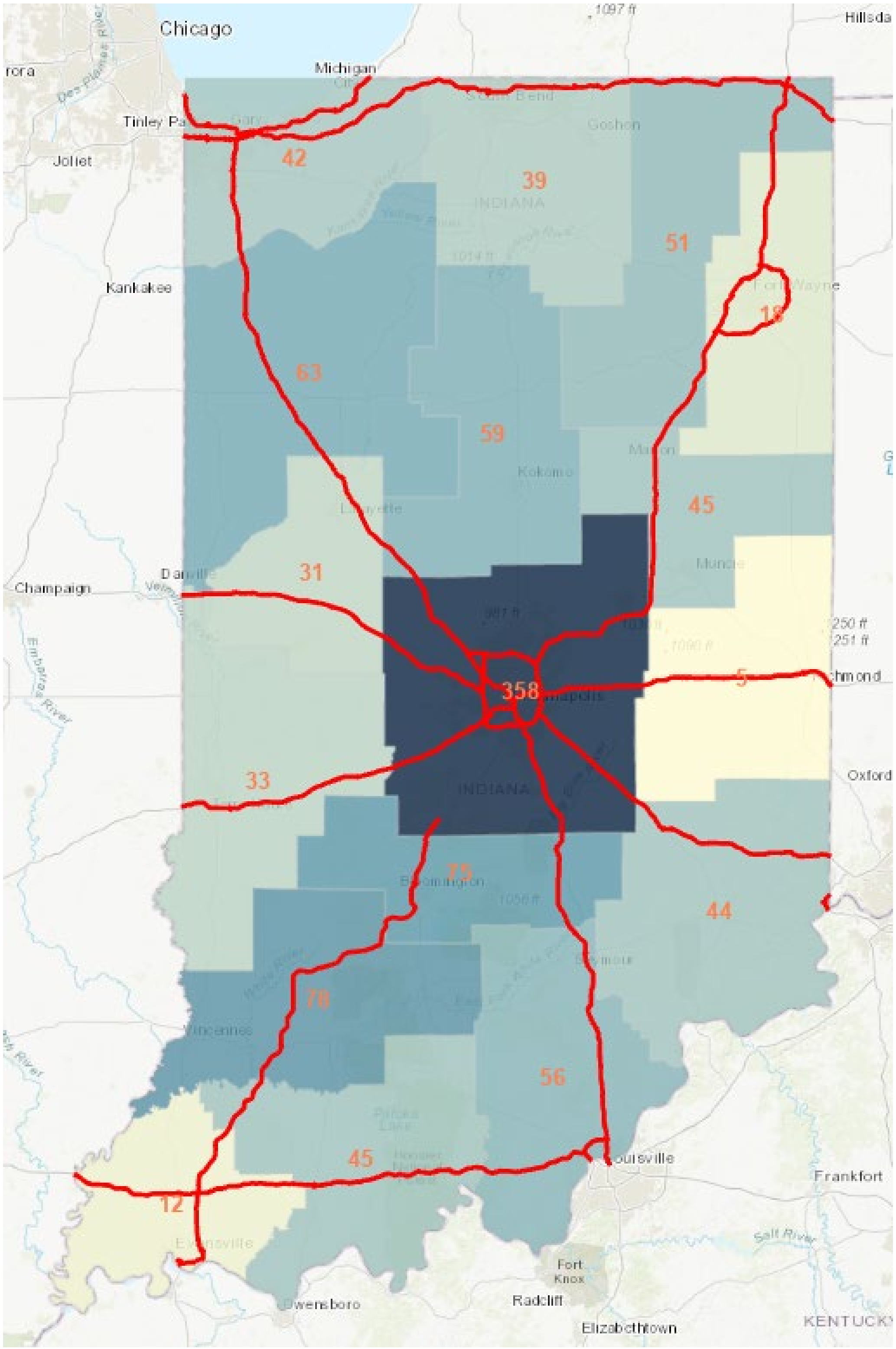

Figure B.34 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #4.

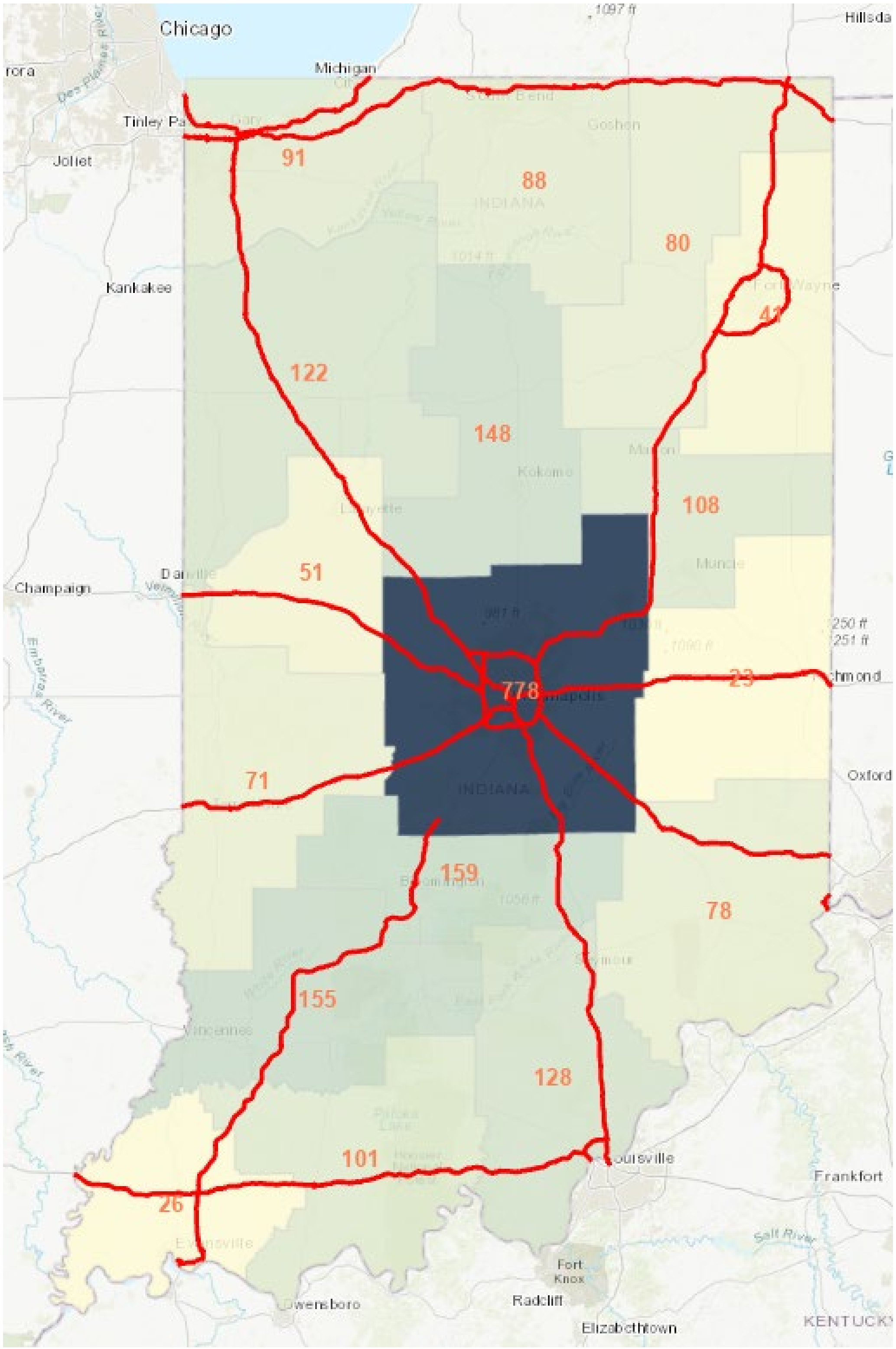

Figure B.35 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #5.

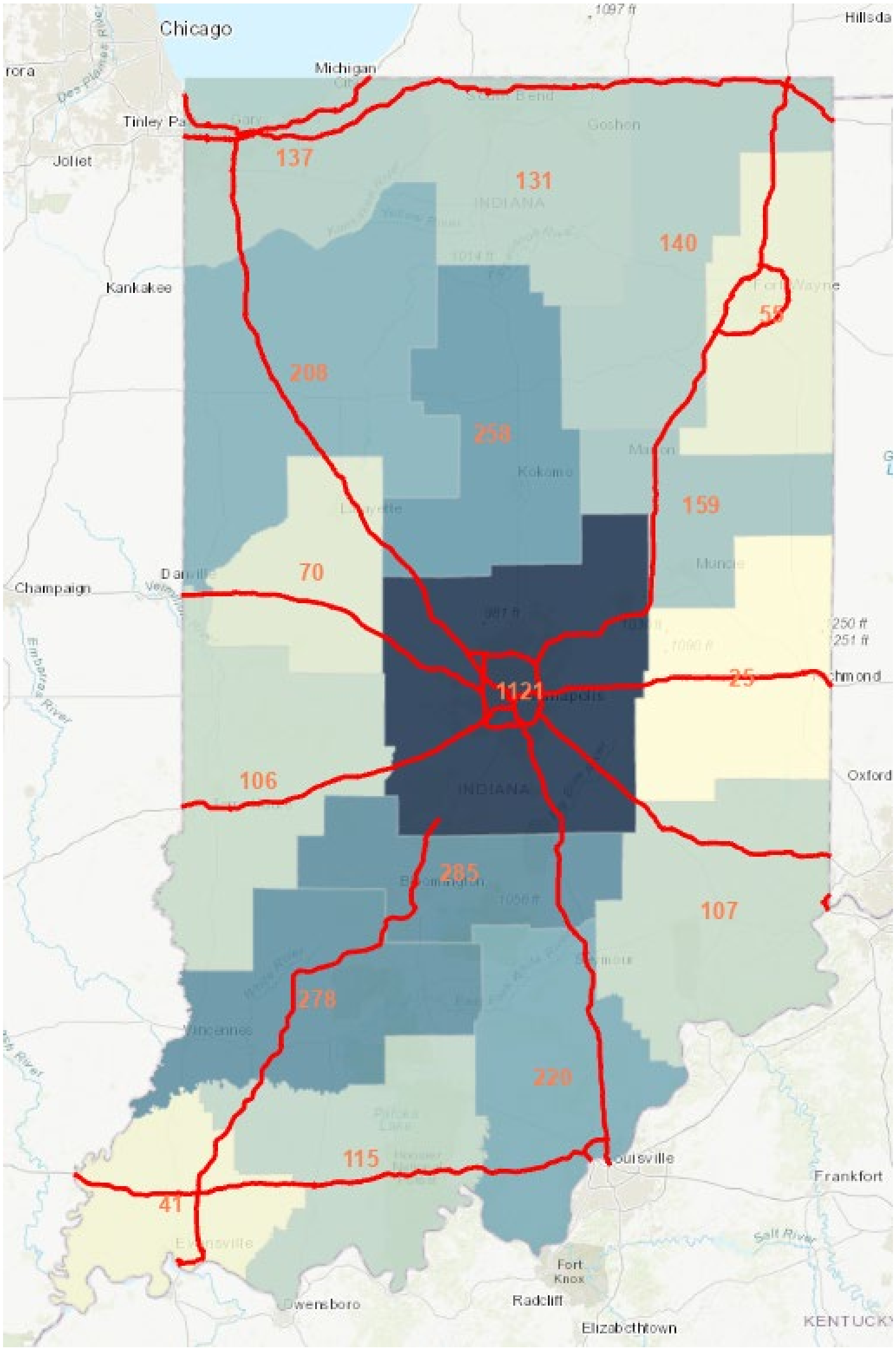

Figure B.36 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #6.

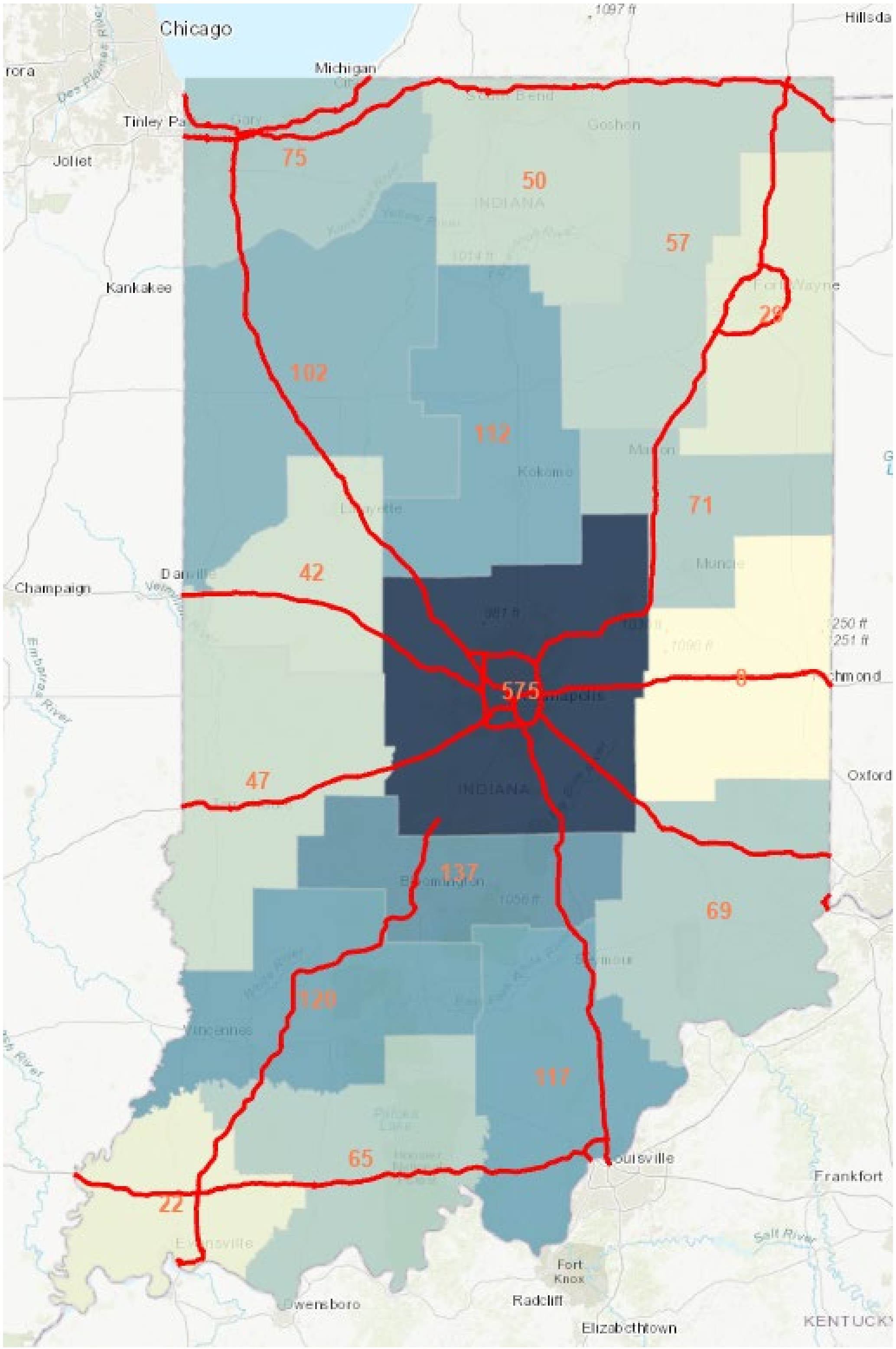

Figure B.37 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #7.

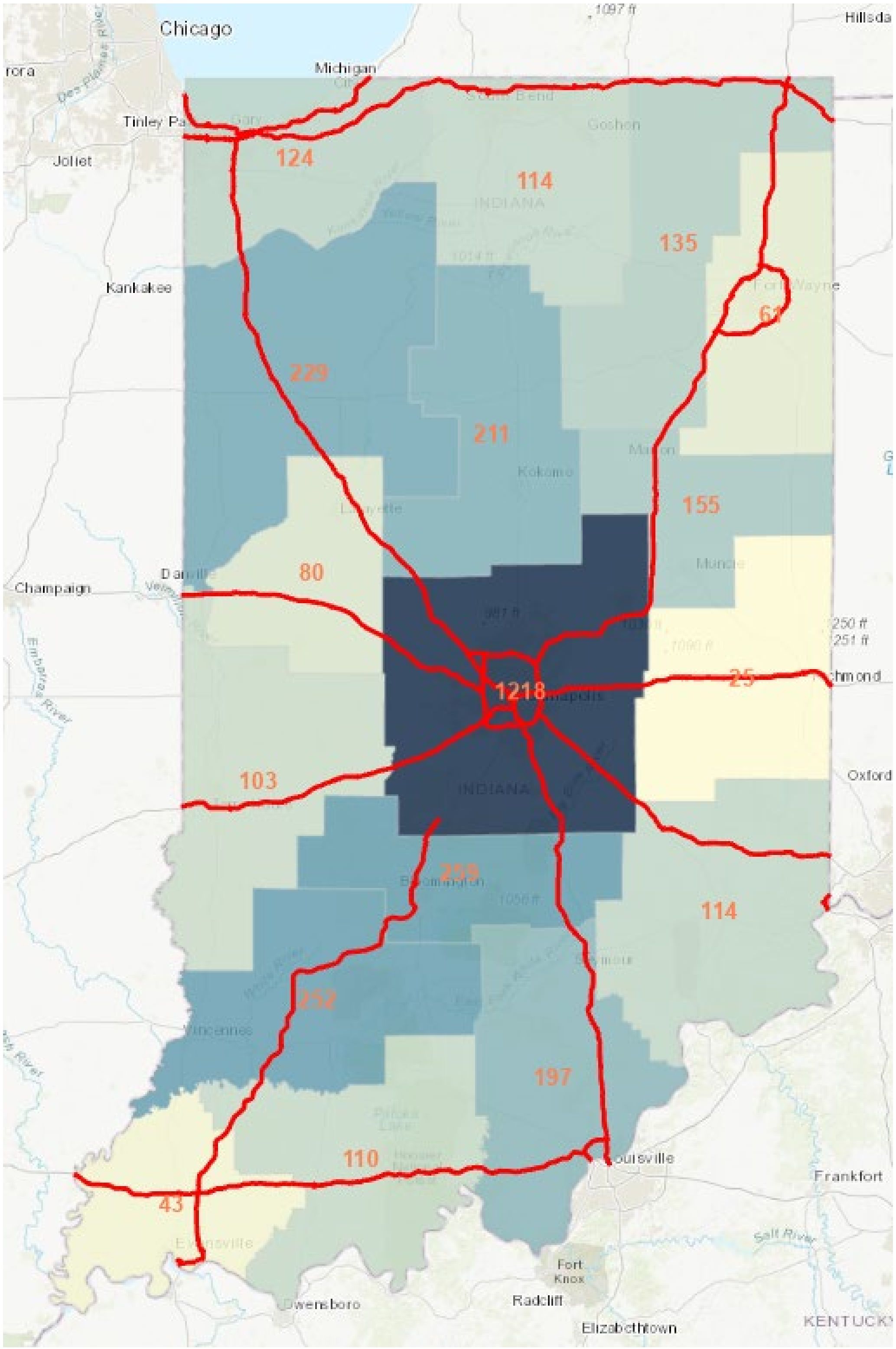

Figure B.38 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #8.

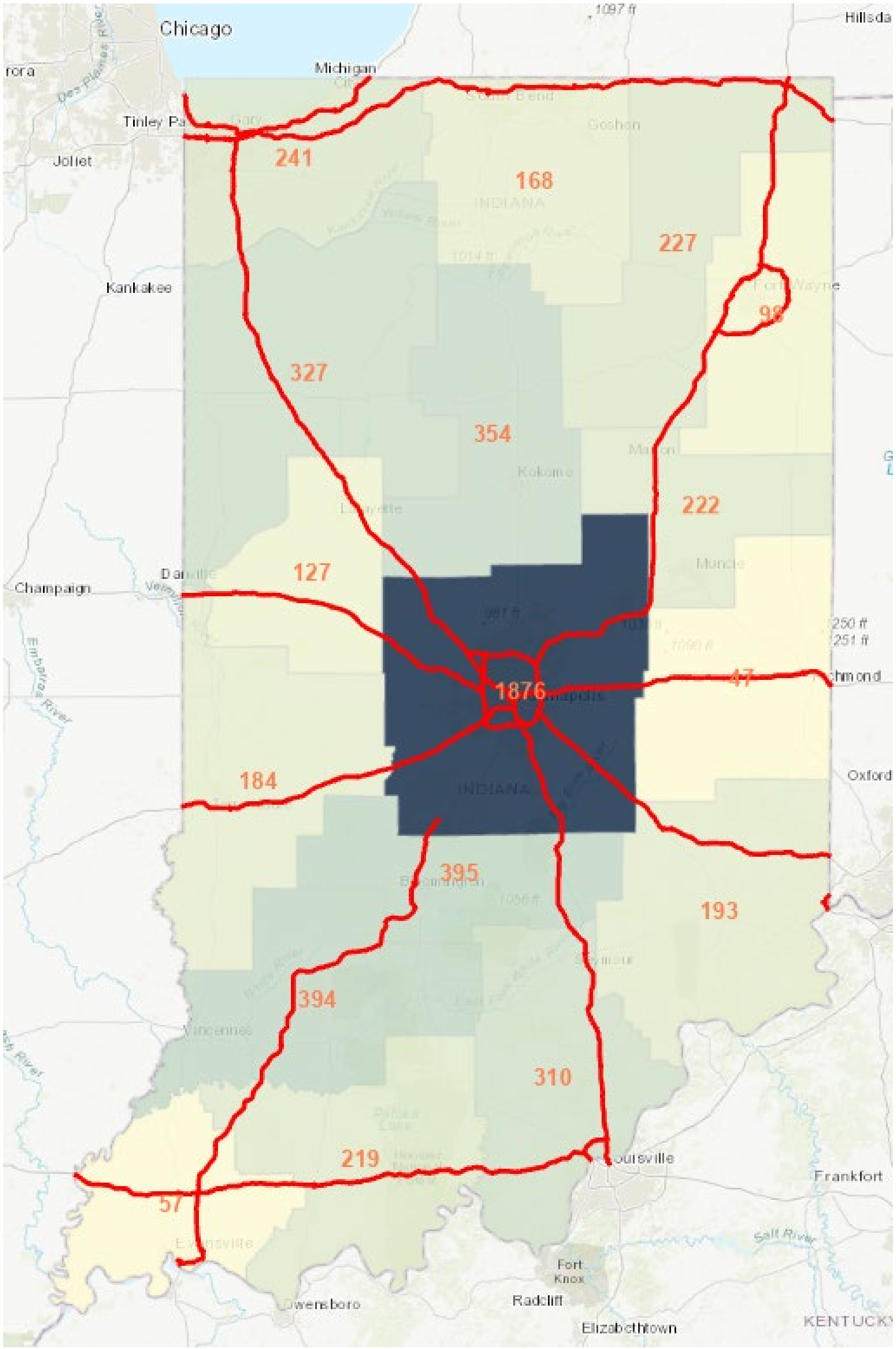

Figure B.39 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #9.

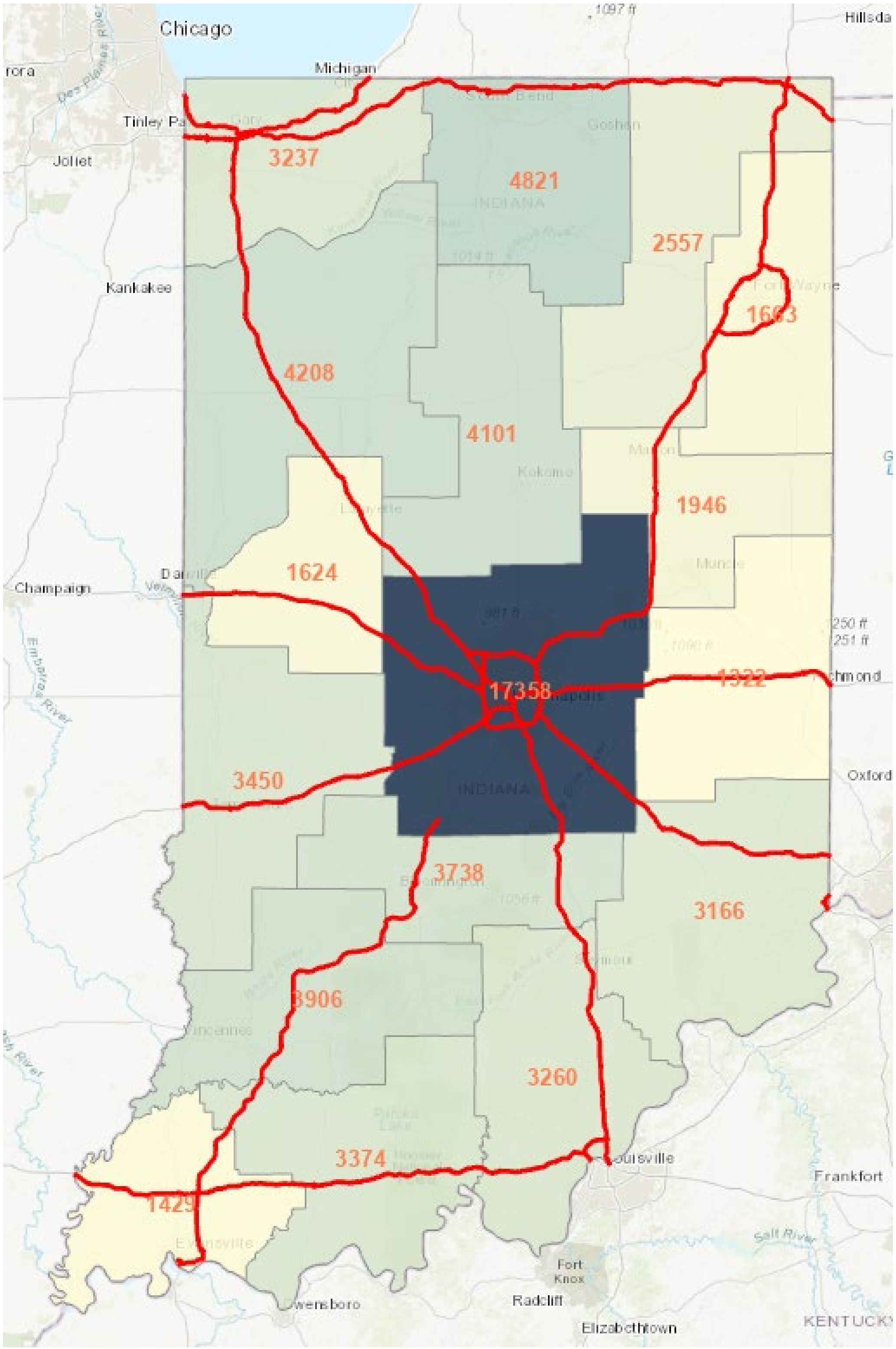

Figure B.40 Spatial aggregation analysis on count of stop markers at ISTDM region level for scenario #10.

APPENDIX C. ASSESSMENT OF FUNDING NEEDS AND FEASIBILITY ANALYSIS OF NEW INCOME GENERATION STREAM MODELS

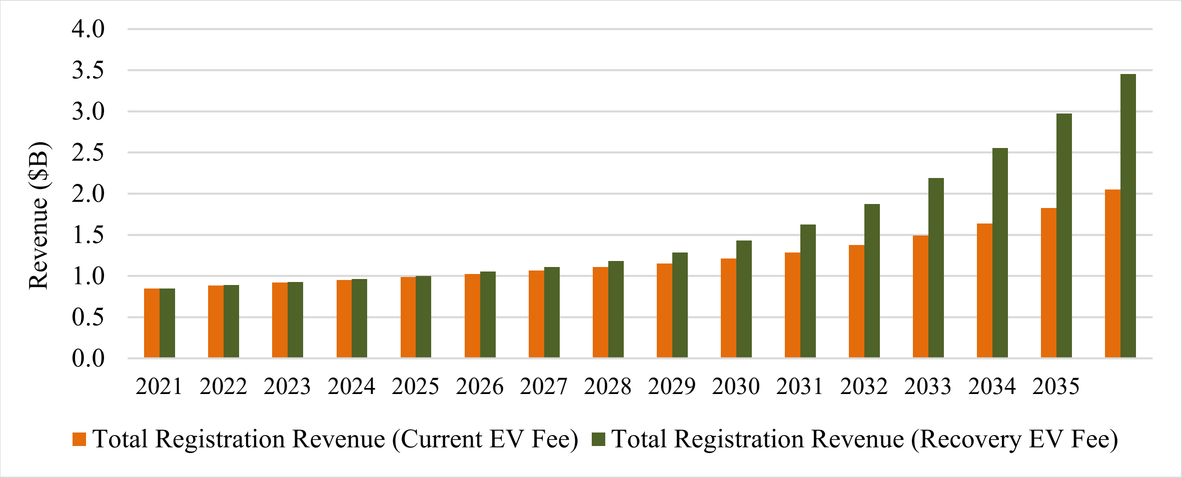

Figure C.1 Projections of generated from total vehicle registrations, including revenue from EV registrations (for the most likely scenario).

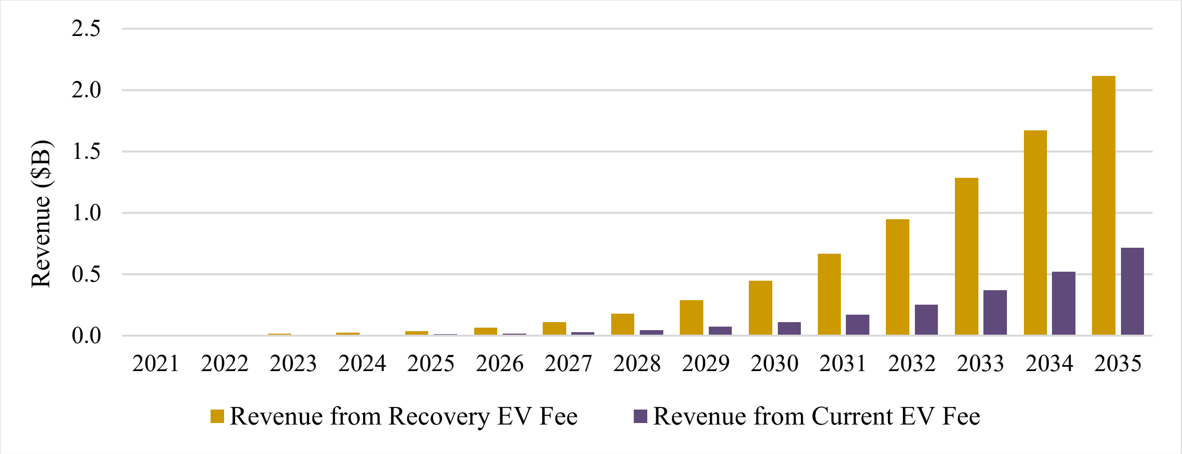

Figure C.2 Projections of revenue generated only from current EV fee and recovery EV fee (for the most likely scenario).

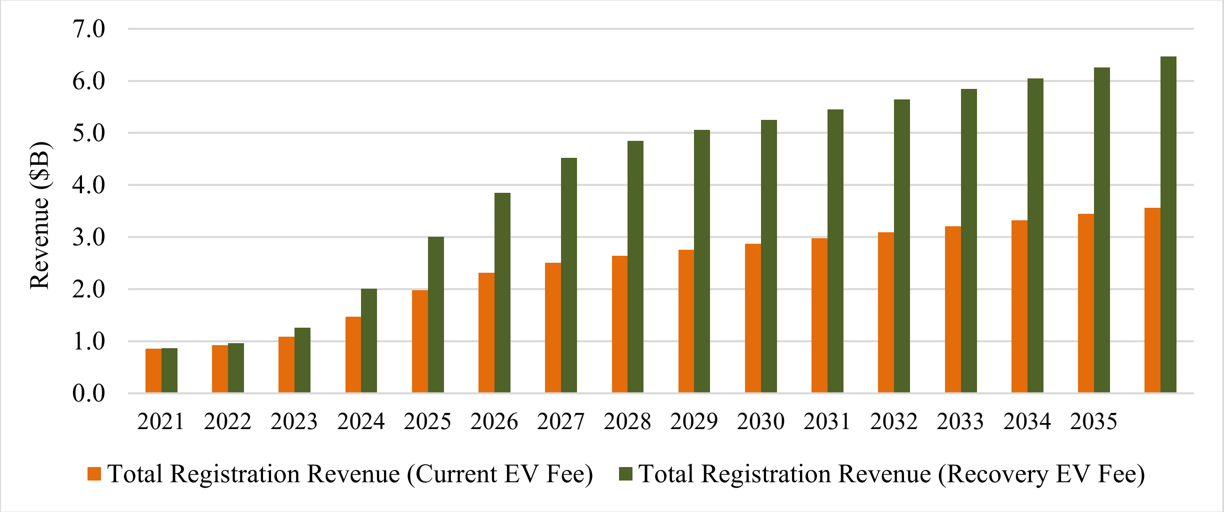

Figure C.3 Projections of revenue generated from total vehicle registrations, including revenue from EV registrations (for the optimistic and pessimistic scenarios).

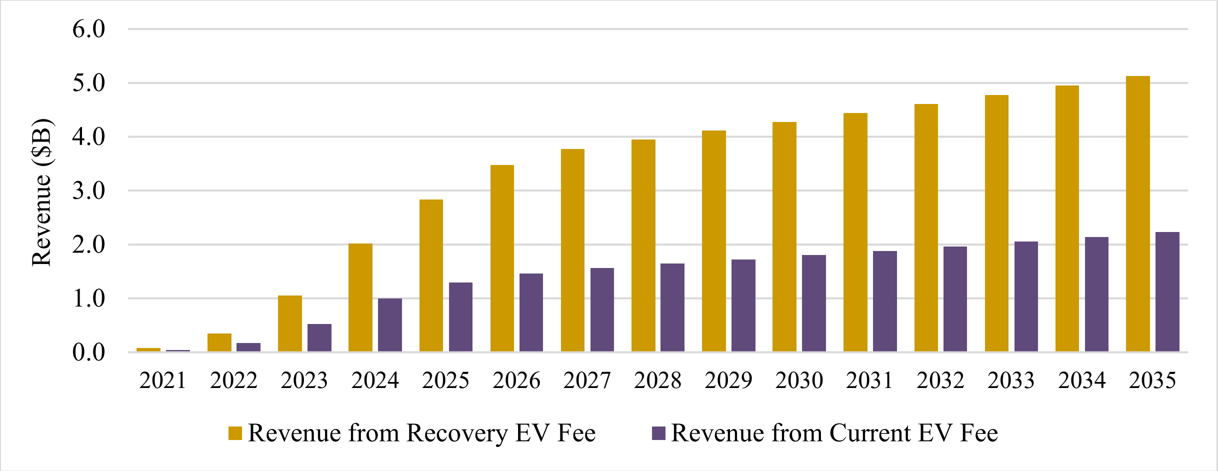

Figure C.4 Projections of revenue generated only from current EV fee and recovery EV fee (for the optimistic and pessimistic scenarios).

APPENDIX D. EVALUATION OF STRATEGIC PARTNERSHIPS AND GUIDANCE FOR EV PREPAREDNESS BASED ON STAKEHOLDER INPUT

Document 1. Interview agenda

A Strategic Assessment of Needs and Opportunities for Wider Adoption of Electric Vehicles in Indiana

Evaluation of strategic partnerships and recommendations for electric vehicle preparedness based on stakeholders' inputs (IRB-2021-1263)

Meeting Agenda & Meeting Objectives

Meeting Objectives:

1. Discuss strategic partnerships and business models for a successful implementation and use of electric vehicles
2. Discuss ways to promote the adoption of electric vehicles
3. Discuss impacts, important aspects or concerns related to the adoption of electric vehicles

Meeting Facilitators: Dr. Konstantina "Nadia" Gkritza
Konstantinos Flaris
Theodora Konstantinou

Agenda:

I. Welcome and introductions
II. Strategic partnerships for electric vehicle adoption and ways to promote electric vehicle (EV) adoption
III. Potential impacts/Important aspects/Concerns of EVs
IV. Closing questions
V. Summary and final suggestions/comments
VI. Adjournment

Document 2. Discussion guide

DISCUSSION GUIDE

You will be asked to provide your perspective as a representative of your agency/organization.

I. *INTRODUCTION (4–5 min)*

- Greeting/welcome
- Purpose of interviews, general plan, agenda
- Confidentiality, consent form.

II. *STRATEGIC PARTNERSHIPS FOR ELECTRIC VEHICLE ADOPTION AND WAYS TO PROMOTE ELECTRIC VEHICLE ADOPTION (10-12 min)*

- Strategic partnerships for a successful implementation and use of EVs/ Stakeholders involved
- Interrelationships between the stakeholders involved/ Needs of different stakeholders
- Your relationship with other stakeholders involved regarding the efforts to deploy/adopt EV technology
- Potential business models (for EV charging infrastructure) that meet the needs of stakeholders/ Funding for EV charging infrastructure
- Stakeholders/agencies/organizations that you are partnering with or planning to partner with, to prepare for or promote EV adoption
- Ways to prepare for and accelerate/promote the adoption of EVs

III. *POTENTIAL IMPACTS/IMPORTANT ASPECTS/ CONCERNS OF ELECTRIC VEHICLES (10–12 min)*

- Policy aspects to be considered regarding the high adoption of EVs
- Impact of EVs on the grid and factors affecting the effective distribution of energy to charge EVs
- Environmental and societal impacts related to the high adoption of EVs
- Impact of EVs on fuel tax revenue
- Current EV charging infrastructure availability, accessibility and reliability
- EV adoption across different vehicle classes (light-, medium-, heavy-duty vehicles)
- Other impacts/concerns regarding EVs

IV. *CLOSING QUESTIONS (3–6 min)*

- Your involvement in a current or past project related to EVs
- Your plans for the next 5–10 years regarding electrification adoption
- Your role in the adoption of electric vehicles

V. *CLOSING (3–5 min)*

- Summary (what did we achieve today, what's next)
- Have we missed anything? Final thoughts/suggestions/comments?

THANK YOU (total 30+10 buffer → 40 min)

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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