

A Method for the Technical Feasibility Assessment of Electrical Vehicle Penetration

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Abstract—In recent years, electric vehicles (EVs) have gained much attention as a potential enabling technology to support CO₂ emissions reduction targets. Furthermore, many of the cost and vehicle technology barriers that have prevented their adoption in the past are increasingly being addressed by vehicle manufacturers. Nevertheless, the question remains as to whether EVs themselves will be technically feasible within the larger infrastructure systems with which they interact. Fundamentally, EVs interact with three interconnected ‘systems-of-systems’: the (physical) transportation system, the electric power grid, and their supporting information systems often called intelligent transportation systems (ITS). These systems affect the EV operation in potentially constraining ways that can negatively impact the EV user’s final transportation experience. This paper seeks to understand and assess these interactions in such a way as to evaluate their ultimate technical feasibility in relation to their supporting infrastructure systems. A new assessment method based upon modeling tools for each infrastructure system is proposed. For the traffic system, a microscopic discrete-time traffic operations simulator is used to study the kinematic state of the EV fleet at all times. For the electric power system, power flow analysis is used to determine the electrical charging loads required by the EV traffic usage patterns. Finally, UML is used to model the intelligent transportation system functionality as compared to a template of functions deemed necessary to support EV integration. The final method of technical feasibility assessment is demonstrated on a hypothetical scenario which conceptualizes the EV adoption scenario by a taxi service operator.

I. INTRODUCTION

In recent years, electric vehicles (EVs) have gained much attention as a potential enabling technology to support CO₂ emissions reduction targets [1]–[4]. Relative to their internal combustion vehicle (ICV) counterparts, EVs are more energy efficient and consume less energy per unit distance [4]. They also have the added benefit of not emitting any carbon dioxide in operation and rather shift their emissions to the existing local fleet of power generation technology. As the power generation portfolio gains a greater penetration of renewable energy sources,

the end-to-end carbon footprint of the EV approaches neutrality [5], [6]. ICVs in contrast require CO₂ not just for gasoline refining but also in the combustion of the fuel during transportation [7] [8]. Recently, this promise of EV-enabled CO₂ emissions reductions has gained further traction as vehicle manufacturers have made cost and technological improvements in many ways [7], [9], [10]. In regards to battery technology, a wide variety of battery chemistry technologies have emerged [9] leading to greater capacity and subsequently vehicle range. Second, fast chargers (or DC chargers) have been introduced into the market which allow 80% of the battery capacity to be charged in 30 minutes [8].

Despite these achievements, the true success of EVs depends on their successful integration with the infrastructure systems that support them. To that effect, EVs interact with three interconnected ‘systems of systems’: the (physical) transportation system, the electric power grid, and their supporting information systems often called intelligent transportation systems [11]–[16]. In the first system, EVs behave differently than their ICV counterparts in two regards. First, EVs typically have a travel range of approximately 150km [17]. Second, while ICVs can refuel in a matter of minutes, a typical EV may require 6-8 hours in order to recharge [18]. These two aspects of EVs can significantly impact user driving patterns and lead to different aggregate traffic behavior.

Successful integration into the electrical power grid also has multiple aspects. It is generally accepted that most EV adoption scenarios will not place excessive demands on the national energy generation capacity [19]. Nevertheless, it is very likely that EV penetration can place excessive power demands on electric distribution. These demands can be further exacerbated if EV adoption is dense geographically at the neighborhood length scale. Furthermore, if users adopt similar charging patterns driven perhaps by similar work and travel lifestyles, the power required for charging can

be temporally concentrated. One central aspect in the upgrade of the two physical systems is the EV charging infrastructure. The location of charging stations, as the EV analog of gasoline stations serve as origin-destination nodes in the transportation system while simultaneously acting as load nodes in the electrical grid.

Finally, the demands that EVs place on the two physical infrastructure networks imply the need for greater information support than might normally be required for ICVs [20]. For example, if the EVs were adopted in a public transport context it might be necessary to track the EV state of charge (SOC) relative to its battery capacity, its remaining available range or even the real-time electricity spot price [21]. Electric vehicles, particularly in a public transport use case, may require the ITS to provide a coordinated traffic dispatching as well as charging dispatching functionality. The latter of these can serve to minimize operating energy costs while also providing the public benefit of peak shaving and trough filling.

This paper seeks to understand and assess these interaction in such a way as to evaluate their ultimate technical feasibility in relation to their supporting infrastructure systems. The paper proceeds as follows. Section II provides a background to the modeling techniques necessary to model the three types of infrastructure systems: transportation, power and ITS. Section III then proposes a method of assessment that relies upon these tools. Section IV then provides the implementation of this assessment method on a hypothetical scenario which conceptualizes the EV adoption scenario by a taxi service operator. The paper is brought to a conclusion in Section V.

II. BACKGROUND

This section provides the background to the modeling techniques necessary to model the system of three infrastructure systems. Each system is discussed in turn: transportation, electric power, and ITS.

A. Transportation System Modeling

Transportation system modeling has received extensive treatment of the literature and a number of different modeling strategies and techniques have been employed depending upon the initial aims of the model's developer. Alecsandru [22] has reviewed these techniques and classified them according to Table I. Given the conceptual descriptions provided in the introduction, a transportation system model for EV would have to be able distinguish EV locations and speeds from the rest of traffic. It would also need to resolve when any given vehicle was stationary; particularly at charging facilities.

In such a way, EV load curves can be extracted from a combination of the transportation behavior and vehicle charging properties. For these reasons, an appropriate transportation model would have to simulate traffic operational behavior with a discrete-time evolution on the microscopic or vehicle scale.

B. Power System Modeling

The conceptual description in the introduction also introduces new electrical charging loads onto the power grid. These loads can be modeled in a pseudo-steady-state fashion thus requiring that the power flows in the grid be recalculated accordingly. Power Flow Analysis provides such a tool from the power systems engineering discipline. Given the admittance y_{hk} of a line connecting

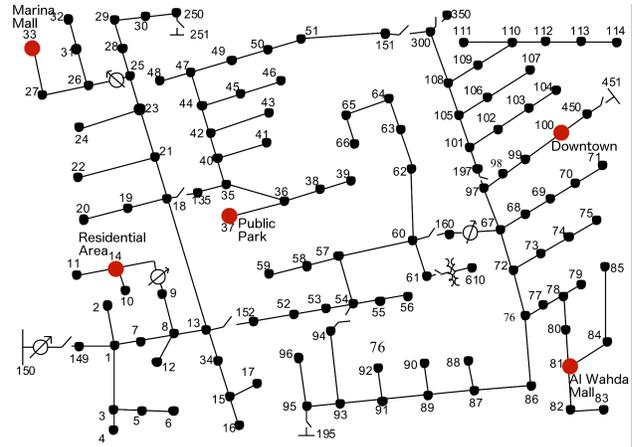


Fig. 1. A 123-bus Power Distribution System Topology [23]

bus h to bus k in a one-line power system diagram like the 123-bus distribution system shown in Figure 1, the state $(P_b, Q_b, v_b, \theta_b)$ of any given bus $b \in B$ can be calculated; where P_b is net active power generation, Q_b is the net reactive power injection, v_b is the bus voltage magnitude and θ_b is the voltage angle. A bus with an attached generator is treated as a PV bus in that P_h and v_h are given while a bus with an attached load is treated as a PQ bus in that the P_h and Q_h are given. Additionally, one bus with an attached generator is modeled as a 'slack bus' with its voltage magnitude and angle taken for reference. The state of each of the buses is then determined by the numerical solution of the following simultaneous equations. For all, buses $h \in B$

$$p_h = v_h \sum_{k \in B} [v_k (g_{hk} \cos \theta_{hk} + b_{hk} \sin \theta_{hk})] \quad (1)$$

$$q_h = v_h \sum_{k \in B} [v_k (g_{hk} \sin \theta_{hk} - b_{hk} \cos \theta_{hk})] \quad (2)$$

TABLE I
CLASSIFICATION & APPLICATION TYPES OF TRANSPORTATION SYSTEM MODELS [22]

	Discrete Time	Discrete Event	Microscopic	Classification			Application Type		
				Meso-sopic	Macroscopic	Deterministic	Stochastic	Design	Planning
DYNASMART	X		X				X		X
CORSIM	X		X			X			X
NETFLO 1		X		X			X		X
PARAMICS	X		X				X		X
SYNCRO	X				X	X			
VISSIM	X		X				X		X
TRANSIMS	X		X				X	X	
TransModeler	X		X				X		X
TRANSYT-7F	X				X		X		X
CMS	X		X			X		X	X

Once all the branch power flows and bus states have been calculated for any period of time, one can determine if the additional loads imposed by the EVs cause the power system to exceed either line limits or bus voltages.

C. Modeling of ITS

Modern traffic systems are supported by sophisticated information systems called intelligent transportation systems (ITS) that improve services in transportation system operations. Any given ITS solution delivers a diverse set of functionality including reducing congestion, improving air quality by reducing pollution, and improving safety by providing advance warning [15]. The functionality within any given ITS deployment depends very heavily on a complete requirements engineering process of all the identified stakeholders [11]. A first scan of deployed ITS in both the developing as well as developed world shows a tremendous diversity of delivered functionality [24]–[29]. For example, Table II shows a list of high level ITS functions in the Abu Dhabi ITS [29] and their potential applicability to EV deployment. This diversity in functionality requires a method of modeling that is flexible and general. To this end, the United States Department of Transportation suggests the usage of the Unified Markup Language (UML) [30] as an appropriate tool for detailed modeling of ITS functionality [11].

TABLE II
HIGH LEVEL FUNCTIONALITY OF ABU DHABI ITS [29]

ITS User Services	EV Applicability
Pre-trip Travel Information	X
En-route Transit Advisory	X
Route Guidance	X
Incident Management	X
Traffic Control	
Commercial Vehicle Preclearance	
Commercial Vehicle Administrative Services	X
Commercial Fleet Management	X
En-route Travel Advisory	X
Traveler Services Information	X
Ride Matching & Reservation	X
Travel Demand Management	X
Electronic Payment Services	X
Automated Roadside Safety Inspections	
On-board Safety Monitoring	

Subsequently, the successful EV integration ITS functionality can be viewed as a standard verification and validation process within a traditional systems engineering process [31]. In other words, functionality templates and/or use cases described in UML can be used to complete a functionality gap analysis of these templates in regards to the deployed ITS. The class diagram and the use case diagrams provide excellent candidates for describing this functionality; with the former being more appropriate for a first pass analysis and the latter more appropriate for a detailed system verification.

III. METHOD OF ASSESSMENT

Given the modeling methodologies presented in the previous section, the paper can shift to providing an integrated method of technical feasibility assessment for EV integration. Figure 2 provides a schematic of the assessment method as a whole. As before, each of the three supporting infrastructure systems are discussed in turn.

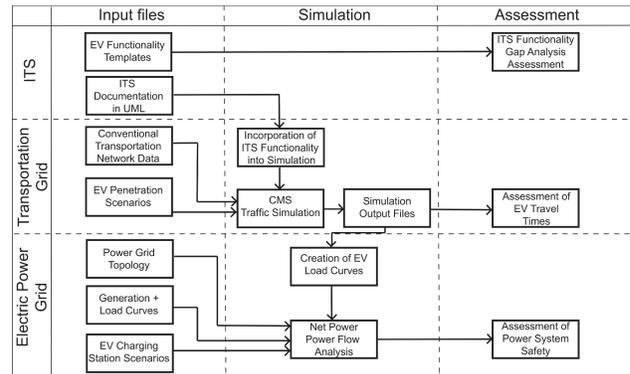


Fig. 2. An Integrated Method for Technical Feasibility Assessment of EV Penetration

A. Transportation System

The assessment of the EV integration for the transportation system focuses on the measurement of EV ‘quality of service’ (QoS) as defined by the sum of the travel times of all of the electric vehicle trips. Here, the

travel time T_i of the i^{th} EV trip is specifically defined as the difference between when the EV is requested for travel service t_{r_i} and the moment of arrival t_{a_i} . Hence, the quality of service measure becomes

$$QoS = \sum_i^{trips} [t_{a_i} - t_{r_i}] \quad (3)$$

This definition of QoS includes any remaining time required for EV charging plus the time needed to traverse the distance between the origin and the destination of the EV trip.

The QoS measure can be calculated following the method provided in the middle third of Figure 2. In order to complete the simulation, three sets of complementary data are required. First, conventional transportation network data such as road network and the origin-destination data of conventional vehicles provides the baseline for traffic behavior simulation. Next, the EV penetration scenario is added in terms of the number of EVs and trips as well as the number and location of EV charging stations. Finally, any ITS functionality that may impact traffic behavior is included into the traffic simulation.

For the purposes of this work, the MHI ‘Clean Mobility Simulator’ [32] was chosen as a discrete-time microscopic traffic simulator to keep track of each EV trip in its simulation output files. A schematic of the simulator’s behavior is shown in Figure 3.

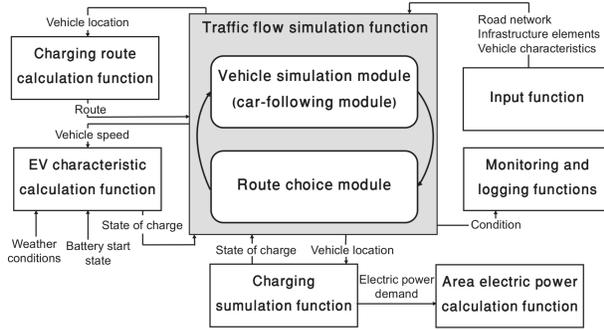


Fig. 3. Schematic of CMS Behavior [32]

B. Electric Power System

The assessment of EV integration for the power system focuses on the grid’s safety. In that regard, power line ratings place a physical limit on the amount of transferred active power. Given a set of N_l lines, a given line i may have a line limit P_i^* . Over a simulation period

T_s , a line safety criterion SC_1 can be defined as the average amount of excess active power in all the lines:

$$SC_1 = \frac{1}{N_l T_s} \sum_i^{N_l} \left[\frac{1}{P_i^*} \int_0^{T_s} f_i(t) dt \right] \quad (4)$$

where

$$f(i) = \begin{cases} P_i(t) - P_i^* & \text{if } P_i > P_i^* \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

Furthermore, IEEE Standard 519 [33] places bus voltage limits to be within 0.95 and 1.05 volts per unit. Over a simulation period T_s , a bus safety criterion SC_2 can be defined as the average amount of excess or insufficient voltage in all of the buses:

$$SC_2 = \frac{1}{N_b T_s} \sum_i^{N_b} \left[\int_0^{T_s} g_i(t) dt \right] \quad (6)$$

where

$$g(i) = \begin{cases} v_i(t) - 1.05 & \text{if } v_i > 1.05 \\ 0.95 - v_i(t) & \text{if } v_i < 0.95 \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

For the purposes of this work, MATPower [34] [35] is chosen as an open-source MATLAB based tool capable of numerically solving the power flow equations provided in the previous section.

C. Intelligent Transportation System

The assessment of the EV integration into the intelligent transportation system is done by functional gap analysis. For this, a UML-based template EV system specification is developed. Given the scenario, provided in the next section, the UML functionality template was developed in the context of an EV taxi system deployment. Figure 4 shows a UML class diagram of such a system with required parameters and methods. It is composed of a centralized ITS EV module which provides the monitoring, decision-making, coordinated dispatching, and displaying functionality as methods. It also includes a class for the EV Taxi data and another for the EV Charging Station data.

IV. APPLICATION SCENARIO: HYPOTHETICAL TAXI SERVICE OPERATOR

The method for the technical feasibility assessment of EV penetration is applied to a hypothetical deployment of EVs within a taxi service operator (TSO). The TSO has taken the city of Abu Dhabi as its geographical region of operation with a map of the city’s downtown area shown in Figure 5. The TSO has also decided to upgrade five of its taxi stands to include charging stations appropriately named: Marina Mall, Residential

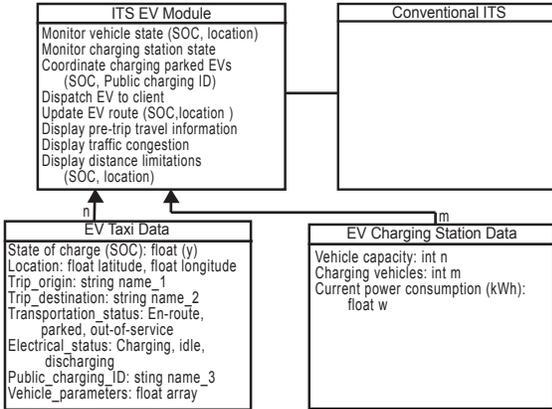


Fig. 4. UML Template for a Hypothetical EV Taxi System Deployment

Area, Public Park, Downtown and Al Wahda Mall. This transportation system map is taken to geographically coincide with the electric power distribution system found in Figure 1. The TSO has a well-developed Taxi Dispatch functionality within its information systems but has not made any significant update to address the electrical nature of its enhanced taxi fleet. In this

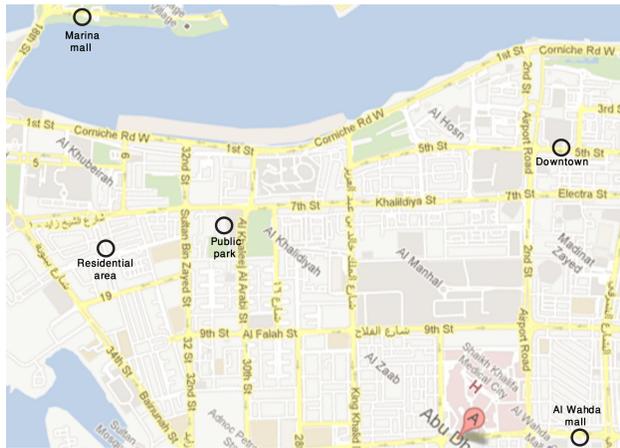


Fig. 5. A Transportation Map of Abu Dhabi

scenario, one might expect that the Downtown, Marina Mall, and Al Wahda charging stations have heavy queues of taxis and clients. Charging may create a charging bottleneck leading to a deteriorated quality of service in the transportation system. Here, the EV deployment in a TSO context, (and unlike a private vehicle deployment context) lends itself to the easy calculation of the QoS measure because the time of requested transportation service is clearly defined. Furthermore, these three charging stations would place heavy electric loads on

the underlying power grid thus potentially exceeding line limits in the radial grid. The condition that these particular charging stations appear at the very end of radial distribution lines also suggests the potential for significantly reduced voltage levels which may fall below the lower limits of the IEEE 519 standard. Finally, the UML template for EV deployment in a TSO suggests that the only the conventional transportation aspects of the ITS have been implemented suggesting the need for significant ITS upgrade.

V. CONCLUSION

This paper sought to provide a new method for the technical feasibility assessment of EV penetration. Fundamentally, EVs interact with three interconnected ‘systems-of-systems’: the (physical) transportation system, the electric power grid, and the ITS. For the traffic system, a microscopic discrete-time traffic operations simulator was used to study the kinematic state of the EV fleet at all times. For the electric power system, power flow analysis was used to determine the electrical charging loads required by the EV traffic usage patterns. Finally, UML was used to model the intelligent transportation system functionality as compared to a template of functions deemed necessary to support EV integration. For each of these, assessment criteria were developed. The final method of technical feasibility assessment was envisioned on a hypothetical scenario which conceptualizes the EV adoption scenario by a taxi service operator. A full case-study analysis using this method is currently in progress for the city of Abu Dhabi, UAE.

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