A Benchmark Analysis of Open Source Transportation-Electrification Simulation Tools

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Abstract—Electrified transportation has emerged as a trend to support energy efficiency and CO_2 emissions reduction targets. While electric (road) vehicles aim to achieve this goal, they can not be considered alone. EVs must be successfully integrated with three interconnected systems: the transportation system, the electric power grid, and their supporting information systems often called intelligent transportation systems (ITS). Consequently, transportation electrification as a new trend requires simulation tools that assess vehicle-to-infrastructure integration scenarios. This paper presents a benchmark analysis of open source transportation electrification simulation tools. The holistic assessment consists of 2 level analysis. First, a list of available open-source and commercial traffic simulation tools are classified into macro, meso and microscopic simulators. Second, an in-depth comparison analysis is conducted for only micro & mesoscopic open source tools. This analysis aims to depict the overall features of these tools such as inclusion of electric vehicle functionality, source-code accessibility & customizability and simulation performance. The study finds that while none of these tools has truly addressed the breadth of transportation electrification research, MATSIM, SUMO and TRANSIMS all have promising characteristics for future development.

Index Terms—*Transportation Electrification, Electric Vehicles, Traffic Simulation Tools, Agent-Based Simulation, Microscopic.*

I. INTRODUCTION

Transportation Electrification (TE) has emerged as a trend to support energy efficiency and CO_2 emissions reduction targets. Electric vehicles (EVs) are one of the main modes of transportation electrification [1], [2]. The aim is to reduce the use of non-renewable vehicle's fuel resources (Petrol, Diesel, etc.) and depend on renewable energy. One challenge of EVs, however, is that they interact with three interconnected systems, namely: transportation system, the electric power grid, and their supporting information systems often called intelligent transportation systems (ITS) [3]–[13]. For that reason, the true success of electric vehicles depends on their successful integration with the infrastructure systems that support them. The main challenge associated with TE is that EVs generally behave differently than Internal Combustion Vehicles (ICVs) in two aspects. First, EVs typically have a travel range of approximately 150km [14]. Second, while ICVs can refuel in a matter of minutes, a typical EV may require 6-8 hours in order to recharge [15]. These two aspects of EVs can significantly impact user driving patterns and lead to different traffic behaviors [10]. Moreover, the performance in the transportation domain can not be studied independently without considering the electrical domain properties [2]. Efforts to operate and control the performance in either domain requires an assessment tool whose scope includes the functionality of both systems. Similarly, a holistic assessment of transportation electrification requires a simulation tool that is capable of coordinating between these two domains and overcome the mentioned challenges.

This paper seeks to conduct a benchmark analysis of transportation-electrification simulation tools building upon the lessons learned from the methodological contributions in this domain [2], [3], [10], [13], [16]. To that effect, several reviews of available traffic simulations have proved useful in conducting an extensive analysis [4]–[9], [11]. These studies, aggregated together, identified different sets of traffic simulation packages and used different criteria for their comparison. Their common feature was their orientation to transportation systems. A review that includes both the electrical as well as transportation aspects was not found. Therefore, this work focuses primarily on the transportation and charging infrastructure.

The remainder of the paper proceeds as follows. Section II presents an extensive list of benchmark criteria for TE as well as shows the available traffic simulation tools. Section III then conducts the detailed benchmark analysis upon this foundation. Section IV evaluates the nominated tools performance by providing a simple illustrative example for each tool. Section V concludes the work by providing the most convenient available open source candidate among the selected list for TE assessment.

II. BACKGROUND

In conducting a benchmark analysis of open-source transportation electrification simulation tools, it is necessary to identify the criteria of assessment and the available candidate simulation tools. This section first rationalizes this set of criteria and then draws upon the literature to find appropriate candidate simulation tools upon which the benchmark analysis will be built.

A. Benchmark Criteria for Transportation-Electrification Simulation Tools

The benchmark criteria fall under four categories which are:

1) The physical structure of the transportation electricity nexus
2) The physical behavior of the transportation-electricity nexus
3) The control behavior of the transportation-electricity nexus
4) The implementation of the simulation software

Definition 1. Transportation-Electricity Nexus (TEN) [2]: A system-of-systems composed of a system with the artifacts necessary to describe at least one mode of transport united with an interdependent system composed of the artifacts necessary to generate, transmit, distribute and consume electricity.

This selected list of criteria addresses the physical structure and behavior of the TEN. Since this physical system is composed of artifacts from both infrastructure systems, the criteria address the operational and control behavior for both domains. Finally, they also consider the practical implementation issues of the simulation software. Each of these criteria are now addressed in turn.

1) Criteria for the TEN's Physical Structure: Drawing upon Definition 1, the physical structure of a TEN includes three types of artifacts:

- **Transportation Artifacts:** These include the transportation topology as a graph composed of stations/intersections (i.e. nodes) and roads (i.e. edges) as well as artifacts that travel within it including ICVs, buses, pedestrians, bicycles, trains, trucks [17], [18].
- **Electrical Artifacts:** These include the electrical topology as a graph composed of generators, loads, and substations (i.e. nodes) and lines (i.e. edges) as well as the flows of electrical power flowing within in [17] [19].
- **Hybrid Artifacts:** These include those artifacts that serve both an electrical as well as transportation function. These include electrified roads, charging stations, and electric vehicles in all transportation modes [20].

2) Criteria for the TEN's Physical Behavior: From this physical structure, the associated criteria for the TEN's physical behavior can be inferred. Naturally, the full TEN is a dynamic system with inputs, kinematic state, energetic state, output performance and agent-based use cases that describe human transportation behavior [2], [3]. In recognition of these physical behavior properties of the TEN, the associated criteria are:

- Input: These include the sequence of human activities that define origins and destinations over the course of the day. It also includes the electric power demand not associated with electrified transportation modes.
- Kinematic state: This includes the position, velocity and acceleration of each individual vehicle. This granularity is required in order to distinguish ICVs from EVs [3].

- Energetic State: This includes the amount of fuel consumed for ICVs and the state of charge in electric vehicles. It also includes the power system's electrical state (e.g. to conduct power flow analysis).
- Output performance: This includes output values of interest such as CO_2 emissions, traffic congestion, quality of service, electrical reliability for balancing, voltage and line operation.
- Agent-Based use cases: This includes the sequences of human activities which define where individuals wish to be and when.

3) Criteria for the TEN's Control Behavior: The physical dynamics are controlled with operations management decisions within an operations time scale. Five coupled decisions have been previously identified which are summarized in Table I. Additionally, the transportation traffic light and signaling

TABLE I: Intelligent Transportation-Energy System Operations Decisions in the Transportation Electricity Nexus [10]

- **Vehicle Dispatch**: When a given EV should undertake a trip (from origin to destination)
- **Route Choice**: Which set of roads and intersections it should take along the way
- **Charging Station Queue Management**: When & where it should charge in light of real-time development of queues
- **Coordinated Charging**: At a given charging station, when the EVs should charge to meet customer departure times and power grid constraints
- **Vehicle-2-Grid Stabilization**: Given the dynamics of the power grid, how can the EVs be used as energy storage for stabilization

system serves as a form of control which may work on a fixed-time schedule or dynamically in response to traffic conditions.

4) Criteria for the Implementation of the Simulation Software: Finally, the criteria also extend to the practical implementation issues of the simulation software. Transportation electrification simulation presents a particularly challenging problem given the size of the transportation and power systems topologies, the number of vehicles traveling, and the fidelity with which they are modeled. It requires several numerical methods including sparse matrices, numerical integration of differential equations, optimization methods, and big data analytics [16]. The following criteria are included to give a sense of the feasibility level and user-friendly environment within the simulation tool which can be summarized as:

1. Programming Language: Some languages are better suited to engineering applications driven by numerical methods.
2. Simulation Performance: The practical feasibility simulation depends on the computational speed, the memory load, and the ability to use multi-core processors.
3. Documentation: The readability and accessibility of documentation facilitates the development of multiple simulation scenarios free from coding bugs and errors.
4. Visualization: The Availability of a 2D or 3D visualization tool facilitates intuition development and debugging.

B. Available Simulation Tools

The benchmark criteria identified above can be applied to a set of available simulation tools. Here, it is understood that simulation software from the transportation and electric power system domains can serve as benchmark candidates. That said, from the perspective of causality, it is the electrified transportation system that imposes a load on the power system. Therefore, it is relatively more important to simulate the dynamics of the former rather the latter. The remainder of the paper focuses on transportation system simulation tools with the recognition that there exist several open-source power system simulation tools which may be later integrated if necessary [21]–[23].

Traffic simulation models can be micro, meso and macroscopic. Microscopic models simulate individual vehicles down to basic physical & kinematic properties such as speed, locations, fuel consumption and others [24]. Mesoscopic treat individual vehicles queues within cellular automata. Finally, macroscopic models describe the traffic as flows and density of vehicles [25]. These models are used to classify the available traffic simulation tools accordingly as can be seen in Table II. An extensive literature review was conducted in order to identify transportation system simulation tools. It aggregates the results from several reviews on the topic [3]–[13]. These tools shown below were classified along two axes. On the vertical axis, open and commercial simulators were differentiated. On the horizontal axis, simulators were classified as micro, meso, and macoscopic.

TABLE II: Traffic Simulation Tools

Criteria	Microscopic	Mesoscopic	Macroscopic
Open Source Traffic Simulation Tools	TRANSIMS [26], SUMO [27], REPAST [28], MAINSIM [29], Veins [30], Movsim [31], JAAMSIM [32], MITSIMLab [33]	MATsim [13]	Veins [30], JAAMSIM [32]
Commercial Traffic Simulation Tools	DRACULA-HUTSIM-Vista-CMS [31], VISSUM [34], Quadstone paramics [35], AIMSUN [36], MITSIM [37], ITSUMO [38], TransModeler [39], Synchro [40], SIMWALK [41], Simtraffic [41], CORSIM [42], CORFLO [43]	TransModeler [39], Dynameq [25], INTEGRATION [8], DynaMIT [11], DYNASMART [44], CONTRAM [31]	TransModeler, NETFLO1 [31], SATURN [45], KRONOS [46], TRANSYT7F-AVENUE-METANET-CASIMIR [31]

C. A First Pass Analysis

While the result of Table II presents an extensive list of traffic simulation tools, only a small number are worthy of detailed consideration for this application. None of the tools addressed the electric power system part of the transportation electricity nexus. Inclusion of such functionality could be achieved by co-simulation with commercial software but this has the potential to yield slow performance and impose limitations on the study of integrated dynamics and decision making. Furthermore, TEN applications requires the differentiation between ICVs and EVs and thus must be microscopic or mesoscopic. This left the six tools identified in the upper left two elements of Table II. Finally, the realization that significant customized

programming effort was required to address TEN simulation brought the need for easy access to documentation and code support. This left MATSim, SUMO, and TRANSims as the remaining simulation tools that could meet these first-pass criteria.

III. DETAILED BENCHMARK ANALYSIS OF TRAFFIC SIMULATION TOOLS

This section conducts the detailed benchmark analysis of the remaining traffic simulation tools. First, it provides a brief description of the selected tools. Second, the results of the analysis as summarized in Figure 1 are discussed.

A. Candidate Traffic Simulation Tools for Transportation Electrification Assessment

In order to provide an overall insight about the chosen simulation tools. This section describes each one in a more detailed manner.

1- **Multi-Agent Transport Simulation MATSim:** provides a framework for large-scale transport simulation considering different modules such as demand, agent based mobility-simulation, re-planning, transportation electrification simulation which all can be combined or used stand-alone [47].
2- **Simulation of Urban Mobility SUMO:** is an agent based traffic simulator that facilitates the modeling of various agents such as pedestrians, road vehicles and public transport [48].
3- **Transportation Analysis and Simulation System TRANSIMS:** is able to conduct transportation analysis, transportation simulation and dynamic traffic assignment within an integrated development environment [49].

B. Discussion of the Detailed Benchmark Analysis

The detailed benchmark analysis aims to describe the degree to which each tool is suitable for transportation electrification study. In the context of this scope, each criterion was applied to the three traffic simulation candidates. A summary of the discussion is shown in Figure 1.

1. The physical structure of the transportation electricity nexus

Recalling from Section II-A1, the physical structure of a transportation electricity nexus is composed of transportation, electrical and hybrid artifacts. All three tools consider the transportation system topology as well as several modes of transport along it. On the other hand, none of them addressed purely electrical artifacts such as generation, transmission and load. Thus, the physical structure of a TEN is equally treated by these tools; albeit incompletely.

2. The physical behavior of the transportation-electricity nexus

Recalling from Section II-A2, the physical behavior is a dynamic system with inputs, kinematic state, energetic state, output performance and agent-based use cases. In regards to input data requirements, the three simulators generally require the same data types albeit in different text formats. The representation of kinematic state differed significantly

Criteria/Software	MATSim	SUMO	TRANSIMS
1.The physical structure of the transportation electricity nexus			
1.1- Transportation Artifacts	**Has:** Nodes, Edges, Multi-modes of transport: Pedestrian, Public Transport, Vehicles	**Has:** Nodes, Edges, Multi-modes of transport: Pedestrian, Public Transport, Vehicles	**Has:** Nodes, Edges, Multi-modes of transport: Pedestrian, Public Transport, Vehicles
1.2- Electrical Artifacts	None	None	None
1.3- Hybrid Artifacts	**Has:** modes of Electrical transport: Electric Vehicles. **Lacks:** electrified nodes and links (Charging stations, electrified roads).	**Has:** modes of Electrical transport: Electric Vehicles. **Lacks:** electrified odes and links (Charging stations, electrified roads).	**Has:** modes of Electrical transport: Electric Vehicles. **Lacks:** electrified odes and links (Charging stations, electrified roads).
2. The physical behavior of the transportation-electricity nexus			
2.1 Transportation Behavior			
2.1.1- Kinematic State	**Has:** Cellular Automata Model includes Position & Speed. **Lacks:** Acceleration	**Has:** Full Kinematic Model includes Position, Speed and The Grade of the Road.	**Has:** Full Kinematic Model includes Speed, Position, Acceleration, Time of Arrival (total trip time) and Lanes include shape and speed limit.
2.1.2.1- Energetic State in Transportation	**Has:** Algebric Fuel consumption model based on the avg. Speed. **Lacks:** Fuel Model based on instantenous speed	**Has:** Differenttional Equation Consumption Model based on distance, speed and acceleration.	**Has:** Differenttional Equation consumption model based on distance, speed and acceleration.
2.1.2.2. Energetic State in Power System	None	None	None
2.1.3- Output Performance	**Has:** Alegbric Fuel Consumption Model	**Has:** Differenttional Equation Consumption Model	**Has:** Differenttional Equation Consumption Model
2.1.4- Agent-Based Use Cases	**Has:** Agent Based daily full itinerary.	**Has:** Agent Based daily full itinerary.	**Has:** Agent Based daily full itinerary.
2.1.4.1- Non-Electrified Motion	**Has:** Queuing-Free Road	**Has:** Queuing-Car following	**Has:** Queuing-Car following
2.1.4.2- Electrified Motion	None	None	None
2.1.4.3- Non-Electrified Stationary Function	**Has:** Evaluate the capacity on the parking.	**Lacks:** Evaluate the capacity on the parking.	**Has:** Evaluate the capacity on the parking.
2.1.4.4- Electrified Stationary Function	**Has:** Charging Electric Vehicles while stationary	**Lacks:** Charging Electric Vehicles while stationary	**Lacks:** Charging Electric Vehicles while stationary
3. The control behavior of the transportation-electricity nexus			
3.1- Vehicle Dispatch (O-D)	*Yes -- As Fixed Input Data*	*Yes -- As Fixed Input Data*	*Yes -- As Fixed Input Data*
3.2- Route Choice	*Yes -- On Transportation criteria only*	*Yes -- On Transportation criteria only*	*Yes -- On Transportation criteria only*
3.3- Charging Queue Management	*No*	*No*	*No*
3.4- Coordinated Charging	*No*	*No*	*No*
3.5- Vehicle-2-Grid Functionality	*No*	*No*	*No*
3.6- Traffic Lights Control	**Has:** Traffic Lights control based on fixed time. **Lacks:** Traffic Lights control based on queue length at the interesection (traffic conditions).	**Has:** Traffic Lights control based on fixed time and queue length at the interesection (traffic conditions).	**Has:** Traffic Lights control based on fixed time and queue length at the interesection (traffic conditions).
4. Implementation of the Simulation Software			
4.1- Language	JAVA	C++	The code is written in ANSI C++
4.2- Simulation Performance			
4.2.1- Default example size?	24,000 nodes and 500 vehicles	14 Nodes	18 Nodes
4.2.2- Computational Time	less than 7 seconds	5.5 seconds	6 seconds
4.2.3- Multi-core processsing.	Yes	Yes	Yes
4.3- Documentation	Excellent	Very Good	Good
4.4- Visualization	GIS, Google Earth, Senozon	SUMO. GUI	Transims Visulizer
4.5- Customizable and ease to access code	Yes	Yes	Yes

Fig. 1: Detailed Benchmark Analysis Results of Open-Source Transportation-Electrification Simulation Tools

across the three. MATSim's transportation model is based upon cellular automata and therefore only considers position and average speed as a kinematic state [13]. However, SUMO considers speed, position and acceleration. TRANSIMS also adds the road grade in its kinematics. Consequently, while all three simulators calculate fuel consumption, they do so in fundamentally different ways. MATSim can not resolve fuel burn due to the acceleration in aggressive driving. MATSim and SUMO can not resolve fuel burn in hilly and mountainous geographies. Similar conclusions apply to CO_2 emissions. These differences are particularly important in the electrified transportation case where user driving patterns and regenerative braking have been shown to make significant impacts on charge depletion [50]. Finally, while all three simulators are classified as agent-based, this does not mean that the agents have the full functionality required of transportation electrification. All three packages have agents moving within a transportation system but none can distinguish whether that motion is conventional or electrified. The recent developments in inductively-charged online electric vehicles, suggest that this will be a key TEN simulation requirement [16], [51], [52]. Similarly, transportation electrification requires the simulation

of remaining stationary as well as motion be it to park conventionally or to charge [16]. To that effect, only MATSim explicitly describes the stationary charging of electric vehicles.

3. The control behavior of the transportation-electricity nexus Recalling from Section II-A3, the TEN's control behavior consists of five operations management decisions and the traffic light signaling system. Here, all three tools have fixed-schedule traffic light and routing functionality while SUMO and TRANSIMS also have responsive models that respond to road queue length [6]. Only MATSim, however, has the ability to consider toll road pricing [53]. The importance of this property helps in evaluating the queue lengths on charging stations [24]. The control functionality found in all three tools, while advanced from a transportation-only lens, do not address the full scope of potential decision-making which may one day make up an intelligent transportation energy system [10]. Vehicle dispatch, routing, charging queue management, coordinated charging and vehicle-2-grid functionality all can be enhanced to incorporate both kinematic as well as electrical state; locally or centrally. There remains significant space and need for systems research to support decision-making in a TEN and then include such methods into simulation tools such

as the ones presented here.

4. The implementation of the simulation software

In addition to the functionality of simulation software, it is important to assess its implementation. The basic characteristics related to user interface and usage options are of particular interest. The software must also be able to accommodate large scale traffic simulations, and have well structured modules that may be combined or used alone. This would enable downstream flexibility to support new or modified transportation electrification code. It would also allow rigorous testing as every new piece of functionality is validated and verified. ddsssssaszzCurrently, the chosen simulators are open-source. This represents a development model that promotes universal access via a free license [54] where codes are accessible and changeable. In addition to that, the documentation among these tools are available, upgraded and well written. Interestingly, MATSim also offers a toolbox for demand-modelling, agent-based mobility-simulation (traffic flow simulation), re-planning, and a customizable controller to iteratively run simulations [53].

The results of the comparison analysis is shown in Figure 1. As a summary, only SUMO and TRANSIM consider electric vehicles information as a transport mode. Also it was found that they have the ability to calculate emissions which can be used in the future as a way to estimate the state of charge. MATSim is capable of considering most of the TE aspects in comparison to the other two tools. It has the ability to identify electric vehicles, charging while stationary and compute state of charge. However, as an overall assessment there are many criteria of TE, MATSim has not encountered. As mentioned earlier, in order to develop a holistic TE model both transportation and electrical domains must be analyzed. From transportation system perspective, the new proposed charging methodology through electrified roads is not included [17]. From power system point of view, MATSim does not include any of the electrical artifacts associated with the power grid such as transmission, generation and consumption [13].

IV. SIMULATION PERFORMANCE

Once the detailed benchmark analysis and its outcomes have been demonstrated, the discussion proceeds to present the simulation performance evaluation as a particularly important and practical criterion. It indicates the limits on the network size while continuing to operate with high speed and efficiency. This section uses the each simulator's default simulation example to practically compare their performance and usability.

A. TRANSIMS Simulation Performance

TRANSIMS was developed as a micro-simulation projected for traffic forecasting and emissions analysis [4]. It can typically simulate large regional areas with several millions of agents. It's simulation performance was evaluated on the basis of its default small example. In all, its performance is very similar to SUMO. Meanwhile, its architecture structure represents the baseline upon which MATSim was built [47]. Many of the configuration methodologies such as agent plans and activities are very similar between the two.

The overall performance assessment of TRANSIMS results can be summarized as:

1. Provides a strong tool for planning purposes.
2. Is capable of conducting large networks simulations. However, the performance speed is considerably low in comparison to the other two.
3. Is able to to assess high level of congestion as well as access the code and implement changes
4. Provides good documentation although not as recent as MATSim documentation.

B. SUMO Simulation Performance

SUMO is a purely microscopic traffic simulation that is capable of handling a wide range of traffic data types [48]. In order to assess its performance, a small default example was simulated. While SUMO's performance is similar to TRANSIMS, it is significantly slower than MATSim. However, SUMO can still handle large networks efficiently and answer many ongoing research questions. A screen shot of the SUMO default example is depicted in Figure 2.
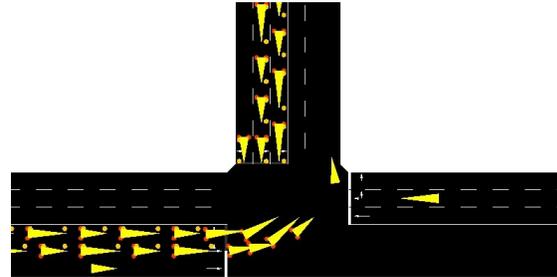

Fig. 2: The simulated example on SUMO

SUMO's overall performance results and simulation characteristics can be summarized as:

1. Considers a wide range of entities that can be simulated such as: Pedestrian, Bicycle, Train, Trucks, car, electric vehicles and their combination [4].
2. Lacks different charging methodologies of electric vehicles in its native code.
3. Capable of conducting large networks simulations within a short duration [6].
4. Allows users to access the code and implement changes.
5. Has a high level of performance and well-written documentation.

C. MATSim Simulation Performance

MATSim is an open source agent-based transport simulator, that simulates very large networks [55]. A district of Zurich is often used as an illustrative example. A screenshot of this

example is provided in Figure 3. MATSIM takes advantage of its cellular automata mechanics to provide very efficient simulation. Despite the considerably large network, it took less than 7 seconds to present its results. Similarly, MATSim has
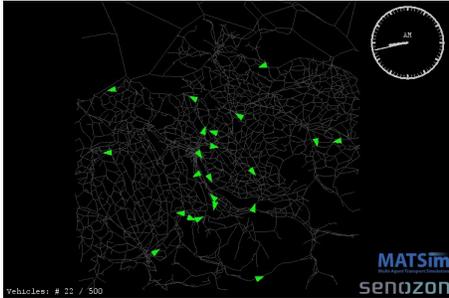

Fig. 3: The simulated example on MATSim

a high performance behavior in terms of TE. In summary, it

1. is the only open source tool which considers electric vehicles in a very detailed way and many transportation artifacts [56].
2. specifically allows the modeling of electric vehicle charging while stationary.
3. is capable of conducting large network simulations within seconds.
4. allows users to access the code and implement changes.
5. demonstrates high performance and well-written documentation.

Despite these many advantages, the in-built cellular automata model does present inherent limitations in making calculations that depend on vehicle acceleration This limits the accuracy of fuel consumption, CO_2 emission, and state of charge calculations for varying vehicle types; especially with advanced functionality such as regenerative breaking.

V. CONCLUSION

This paper has developed a 2 level top-down benchmark analysis of transportation-electrification simulation tools. The aim of this work was to reach a definitive conclusion as to the most suitable open source tool for TE assessment given the available options. A list of all the open source and commercial software was presented and classified into micro, meso and macroscopic categories. Finally, an in depth examination for the most common open source tools was carried out. The assessment paradigm mainly focused on the transportation electrification aspect and the degree to which it can be implemented within each open source tool. All of the mentioned simulation tools perform efficiently for a conventional transportation network but may be considered incomplete from a TE perspective. None of the tools include the underlying power grid. The analysis also showed several additional gaps in functionality; particularly in addressing electrified roads, and

advanced decision-making that spans both the transportation and electric power infrastructure. Much work remains to be done to advance transportation electrification research from interdisciplinary & systems perspectives [16]. The remaining functionality gaps are perhaps most easily addressed with a co-simulation strategy. The JAVA based simulators presented here can be coupled to MATLAB-based power system simulators [16]. Nevertheless, at the current stage of the given available tools, the research results show that MATSIM, SUMO and TRANSIMS are all highly reliable and well documented. The overall performance level is similar although MATSIM's mesoscopic traffic engine provides faster albeit more coarse results. With these qualifications and limitations regarding transportation electrification, MATSim may be considered as the most suitable open source tool with the most advanced functionality to support electric vehicles.

REFERENCES

[1] M. W. B.-B. C. B. L., *Integrating Vehicles and Smart Electric Grids*, 1st ed. MIT Press, 2010, no. pp. 114 - 129.

[2] A. Viswanath and A. Farid, "A hybrid dynamic system model for the assessment of transportation electrification," in *American Control Conference (ACC), 2014*, 2014, pp. 4617–4623.

[3] R. Al Junaibi and A. Farid, "A method for the technical feasibility assessment of electrical vehicle penetration," in *Systems Conference (SysCon), 2013 IEEE International*, 2013, pp. 606–611.

[4] G. Kotusevski and K. Hawick, *A Review of Traffic Simulation Software*. Res. Lett. Inf. Math. Sci., 2009, vol. 13.

[5] Z. Kokkinogenis, L. S. Passos, R. Rossetti, and J. Gabriel, "Towards the next generation traffic simulation tools: a first evaluation," in *6th Iberian Conference on Information Systems and Technologies*, 2011, pp. 15–18.

[6] M. Maciejewski, "A comparison of microscopic traffic flow simulation systems for an urban area," in *Poznan, Poland*, vol. 5, no. 60-965, 2010, pp. 27–38.

[7] N. T. Ratrout and S. M. Rahman, "A comparative analysis of currently used microscopic and macroscopic traffic simulation software," in *The Arabian Journal for Science and Engineering,*, vol. 34, no. 1B, 2009.

[8] M. Van Aerde, B. Hellinga, M. Baker, and H. Rakha, "Integration: An overview of traffic simulation features," *Transportation Research Board Annual Meeting, Washington, D.C.*, 1996.

[9] S. Arunachalam, R. Zalila-Wenkstern, and R. Steiner, "Environment mediated multi agent simulation tools – a comparison," in *Self-Adaptive and Self-Organizing Systems Workshops, Second IEEE International Conference, Dallas*, 2008, pp. 43–48.

[10] R. Al Junaibi, A. Viswanath, and A. Farid, *Technical Feasibility Assessment of Electric Vehicles: An Abu Dhabi Example*. 2013 International Conference on Connected Vehicles and Expo, 2013.

[11] S. A. Boxill and L. Yu, "An evaluation of traffic simulation models for supporting its," in *Center for Transportation Training and Research*. Houston, 2000.

[12] P. C. C. Z. J. H. F. S., *International Series in Operations Research & Management Science*. Springer, vol. 145.

[13] M. D. Galus, R. Waraich, F. Noembrini, K. Steurs, G. Georges, K. Boulouchos, K. Axhausen, and G. Andersson, "Integrating power systems, transport systems and vehicle technology for electric mobility impact assessment and efficient control," *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 934–949, 2012.

[14] S. Skippon and M. Garwood, "Responses to battery electric vehicles: {UK} consumer attitudes and attributions of symbolic meaning following direct experience to reduce psychological distance," *Transportation Research Part D: Transport and Environment*, vol. 16, no. 7, pp. 525 – 531, 2011.

[15] J. Pointon, "The multi-unit dwelling vehicle charging challenge," *Electric Vehicles Virtual Summit*, vol. 69, 2012.

[16] K. Y.-T. Sergio Rivera, Amro Farid, *Chapter 15 - A Multi-Agent System Coordination Approach for Resilient Self-Healing Operations in Multiple Microgrids*. Elsevier Inc., 2015, no. pp. 269-285.

[17] A. M. Farid, "Electrified transportation system performance conventional vs. online electric vehicles," in *Electrified Transportation System Performance Conventional vs. Online Electric Vehicles*, 2015.

[18] M. P. E. Ibragimova and M. K. Thompson, *Global Product Development*, A. Bernad, Ed. Nantes, France, Springer-Verlag, 2010.

[19] A. M. Farid and A. Muzhikyan, *The Need for Holistic Assessment Methods for the Future Electricity Grid*. GSS CIGRE Power Conference, 2013.

[20] P. Tulpule, V. Marano, and G. Rizzoni, "Effects of different phev control strategies on vehicle performance," in *American Control Conference, 2009. ACC '09.*, 2009, pp. 3950–3955.

[21] S. Cole and R. Belmans, *MatDyn, A New Matlab-Based Toolbox for Power System Dynamic Simulation*. Institute of Electrical & Electronics Engineers (IEEE), Aug 2011, vol. 26, no. 3.

[22] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Trans. Power Syst.*, vol. 26, no. 1, p. 1219, Feb 2011.

[23] F. Milano, *Power System Modelling and Scripting*. Spain: Springer, 2010.

[24] P. Jaworski, T. Edwards, K. Burnham, and O. Haas, "Microscopic traffic simulation tool for intelligent transportation systems," in *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference*. IEEE, 2012, pp. 552–557.

[25] W. Burghout, *Mesoscopic Simulation Models for Short-Term Prediction*. Center of Traffic Research, 2005, vol. 3.

[26] S. Eubank, *What Makes a Simulation Useful? [TRANSIMS]*. Los Alamos: IEEE, 1999, vol. 4.

[27] Z. Liang and Y. Wakahara, "City traffic prediction based on real-time traffic information for intelligent transport systems," in *ITS Telecommunications (ITST), 2013 13th International Conference on*, 2013, pp. 378–383.

[28] S. Luke, C. Cioffi-Revilla, L. Panait, K. Sullivan, and G. Balan, "Mason: A multi-agent simulation environment," in *Society for Computer Simulation International*, 2005.

[29] J. Dallmeyer and I. J. Timm, *MAINSIM–Multimodal Innercity Simulation*. Conference on Artificial Intelligence, 2012.

[30] H. Noori, *Realistic Urban Traffic Simulation as Vehicular Ad-Hoc Network via Veins Framework*. 12th Conference of Fruct Association, Tampere, Finland, 2013.

[31] M. I. D. Barbinta, *Aspects Regarding Road Traffic Simulation*. Cluj-Napoca, Romania: Indian Jorunal of Applied Research, 2013, vol. 3, no. 4.

[32] R. P. S.-H. K. A. T. R. H. M. E. K. eds, *Open Source Simulation and Software JAAMSIM*. Vancouver, Canada: Proceedings of the 2013 Winter Simulation Conference, 2013.

[33] J. J. S. M. M. J. G. M. E. R. Royo, *Evolutionary Computation and Applied to and Urban Traffic and Optimization*. Innovation Center for Information Society, 2008.

[34] M. Fellendorf and P. Vortisch, *Microscopic Traffic Flow Simulator VISSIM*. Springer Science and Business Media, 2010.

[35] A. A. T. Hesham Rakha, Montasir Abbas, *Calibration and Comparison of the VISSIM and INTEGRATION Mircoscopic Traffic Simulation Models*. Yu Gao, Blacksburg, Virginia, 2008.

[36] T. Simulation and Systems, *Aimsun Microscopic Traffic Simulator: A Tool For the Analysis and Assessment of Microscopic Traffic Simulator*. Barcelona, Spain, 2014.

[37] M. Hasan, *Evaluation of Ramp Control Algorithms using a Microscopic Traffic Simulation Laboratory, MITSIM*. Department of Civil and Environmental Engineering Bangladesh University, 1999.

[38] A. L. C. Bazzan, M. de Brito do Amarante, T. Sommer, and A. J. Benavides, *ITSUMO: an Agent-Based and Simulator for ITS and Applications*. RS, Brazil, 2010.

[39] C. Corporation, *Whats NEW in TransModeler*. Caliper, 2012.

[40] F.-b. L. Ziad Sabra, Charles E. Wallace, *Traffic Analysis Software Tools*. Transportation Research Board and National Resarch Council, Florida, 2000.

[41] R. A. Raslan, A. F. Bakr, and H. A. Ayad, *Simulation of Pedestrian Behaviour in Urban Spaces. A Case Study of Sidi Gaber Public Space, Alexandria, Egypt*. Proceedings Real Corp Tagungsband, Alexandria, Egypt, 2011.

[42] B. E. S. R. Malfabon, *CORSIM Modeling Guidelines*. Nevada Department of Transportation, Carson, 2012.

[43] J. Palen, B. Coifman, C. Sun, S. G. Ritchie, and P. Varaiya, *Section-Related Measures of Traffic System Performance: Prototype Field Implementation*, C. P. R. Report, Ed. California Partners for Advanced Transit and Highways (PATH) enhanced loop-based traffic surveillance program, 2000.

[44] M. M. Roelofsen, *Dynamic modelling of traffic management scenarios using Dynasmart*. Auckland, New Zealand, 2012.

[45] E. E. Gaitanidou, *Sixth Framework Programme- Sustainable Development, Global Change and Ecosystem*. Auckland, New Zealand,, 2005.

[46] N. Al-Dmour, *TarffSim: Multiagent traffic simulation*. Mutah, Jordan, 2011, vol. 53, no. 4.

[47] M. Balmer, K. Meister, M. Rieser, K. Nagel, K. W. Axhausen, K. W. Axhausen, and K. W. Axhausen, *Agent-based simulation of travel demand: Structure and computational performance of MATSim-T*, A. V. und Raumplanung, Ed. 2nd TRB Conference on Innovations in Travel Modeling, Portland, 2008.

[48] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, *Sumo-Simulation of Urban Mobility-an Overview*, I. of Transportation Systems, Ed. The Third International Conference on Advances in System Simulation, 2011.

[49] M. Rickert and K. Nagel, "Dynamic traffic assignment on parallel computers in transims," *Future generation computer systems*, vol. 17, no. 5, pp. 637–648, 2001.

[50] J. Donadee, M. Ilic, and O. Karabasoglu, "Optimal autonomous charging of electric vehicles with stochastic driver behavior," in *Vehicle Power and Propulsion Conference (VPPC), 2014 IEEE*, 2014, pp. 1–6.

[51] S. N.P., "Designing-in of quality through axiomatic design," *IEEE TRANSACIIONS ON RELIABILITY*, vol. 44, no. 2, pp. 256–264, 1995.

[52] D.-H. C. Seungyoung Ahn, Nam Pyo Suh, *Charging Up The Road*. Spectrum, IEEE, North America, 2013.

[53] W. Trochonowicz, "Integration of multiagent crossing controllers for measure-oriented traffic control," *Annales UMCS, Informatica*, vol. 13, no. 2, Jan 2013.

[54] L. Jesse, "Translating open source into monetary business value," 2013.

[55] R. A. Waraich, D. Charypar, M. Balmer, and K. W. Axhausen, *Performance Improvements for Large-Scale Traffic Simulation in MATSim*. Springer, Ascona, 2015.

[56] J. Bischoff and M. Maciejewski, *Agent-Based Simulation of Electric Taxicab Fleets*, I. S. C. on Mobility and Transport, Eds. Elsevier, 2014, vol. 4.