Framework for Studying Emerging Policy Issues Associated with PHEVs in Managing Coupled Power and Transportation Systems

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Abstract— **As gasoline prices rise, plug-in hybrid electric vehicles (PHEVs) may be quickly becoming an economical choice for transportation. This paper explores the policy issues associated with widespread PHEV deployment. These include improving the electric grid performance, enhancing penetration of renewable energy sources and improving energy security, managing air quality and carbon footprint, creating new markets, and planning energy exchange stations that allow for driver flexibility. Coupling the transportation and power systems through PHEVs presents both challenges and opportunities that involve multidisciplinary approach, and proper policy is necessary to take maximize benefit and avoid pitfalls. A multi-layered modeling approach (including transportation, power systems, cognitive behavior, and economic feasibility) that is spatially and temporally encompassing is proposed for evaluating PHEV policy implications.**

Keywords-PHEVs; power system; transportation system; market policy; multi-layered modeling

I. INTRODUCTION

With the price of oil peaking in the past close to the once unimaginable $150 per barrel and the threat of global climate change increasingly acknowledged, the transportation sector is investigating a number of new technologies that will enhance energy security by reducing the current dependency on oil-based fuels. Gasoline costs are expected to increase further, eventually making Plug-in Hybrid Electric Vehicles (PHEVs) the economical choice for transportation. Widespread adoption of PHEVs will also improve air quality and carbon footprint, since point source pollution is easier to control than mobile source pollution. This level of control is essential for effective implementation of carbon cap-and-trade markets, which should spur further innovation. U.S. sales of HEVs have grown 80% each year since 2000, proving that PHEVs are likely an eventual reality that must be dealt with [1]. The implications of this reality will be highly dependent on the policies in place to use PHEVs to the benefit of the transportation and power systems, as well as the drivers, industry and public at large.

Beyond fuel costs and sustainability, the primary concern of the transportation sector is congestion. In 2005, congestion was estimated to cost the U.S. economy $78.2 billion in wasted time and fuel [2]. If PHEV drivers are given appropriate incentives (e.g., strategically placed energy exchange stations), traveler behavior (e.g., choice of routing, departure time, destination) impacting congestion may be affected.

In addition, the power industry is currently challenged to maintain reliability of operation while expanding the grid to meet growing demand. Large blackouts such as the northeastern one in 2003 may create loses in billions of dollars [3]. Introducing the renewable resources to meet growing demand requires energy storage to deal with interfacing [4]. If proper policy is in place PHEVs can provide a promising solution to both problems acting as mobile decentralized storage (MDS) simultaneously for two energy carriers (electricity and gasoline). In this capacity, PHEVs can serve in two modes: vehicle-to-grid (V2G) and grid-to-vehicle (G2V), each providing benefits to the power system operation. The G2V mode can be used to charge PHEVs at reduced cost when the power system load is reduced and generation capacity is abundant, such as during night time. The V2G mode may be used when demand is high or supply is accidentally lost since the stored electric energy can be released from PHEVs in an aggregated way, which will offer major contributions to regulation service and spinning reserves, as well as load-shedding prevention. The mobility of the energy storage in PHEVs allows for strategic placement of the distributed generation source to optimize power system needs.

This paper aims to be a first step towards a common policy framework for developing optimized solutions to the complex problems of increasing gasoline prices, energy security volatility, air pollution, traffic congestion, and electric grid reliability.

Figure 1 illustrates the spatial and temporal coupling of the power and transportation systems through showing an example of a PHEV driver's route, highlighting destinations where the driver could potentially engage in G2V or V2G. Options for meeting selected criteria for electricity and transportation networks simultaneously are numerous. Developing policy strategy requires understanding of trade-offs involved in pursuing certain solutions at the expense of others. The theoretical framework for such studies to the best of our knowledge is not available.
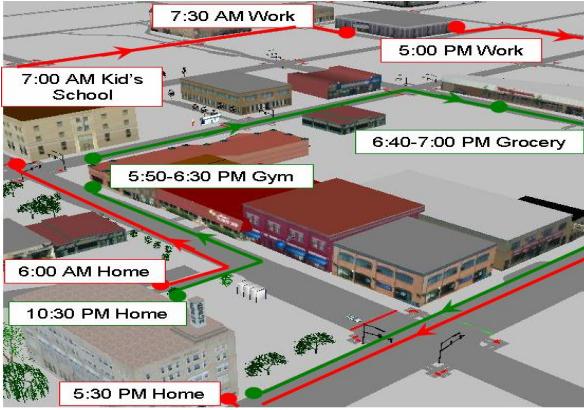
Figure 1. Temporal and spatial dimensions of plug-in opportunities

Several open policy and research goals that facilitate optimizing the integration of the transportation systems and the behavior of its travelers with the electricity systems and behavior of its end-customers are listed below:

- Improve electric grid performance

- Enhance penetration of renewable energy sources and improve energy security

- Reduce and redistribute pollution in the electric grid and transportation network

- Create new markets and further deregulate existing markets

- Plan and develop energy exchange stations

Traditionally, scientists have adopted a divide and conquer approach to understanding complex phenomena. Unfortunately, systems with emergent dynamics that are dominated by contextual interactions are not well suited to this classical approach (e.g., [5-7]). In such cases, directly addressing the couplings of system components may actually hasten progress. While this linkage presents new opportunities to improve the functioning and capacity utilization of each system, it also raises the spectrum of increasing dynamic complexity and cascading failures across systems.

Section 2 provides background information, focusing on the complexity of PHEV impacts to the power and transportation systems. These impacts are then linked to multi-purpose policy strategies in Section 3. Finally, Section 4 suggests a modeling framework for studying the policy issues and illustrates several challenging research problems.

II. BACKGROUND

The impacts PHEVs will have on transportation systems, power systems, and air quality are very complex. Studies conducted to date on this topic make many assumptions to simplify the problem. As stated in the introduction, however, the problem space must be treated as one large complex system in order to capture emergent behavior.

The complexity of the issues involved in studying PHEVs and their interaction with electricity and transportation networks is shown in Figure 2 where several disciplines that need to be involved in researching this multidisciplinary problem are shown.
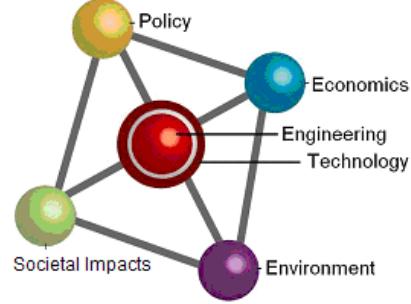

Figure 2. Illustration of multidisciplinary nature of problem

Recent analyses confirm the feasibility of the grid-to-vehicle (G2V) and vehicle-to-grid (V2G) concepts [8-13]. The Electric Power Research Institute speculates that V2G could reduce the requirement for global, central-station generation capacity by up to 20% by the year 2050 [14]. Several studies omit any consideration of vehicle locations and desired activity patterns and assume a percentage of vehicles are plugged in and available when estimating the benefits to the grid and to drivers [8, 10, 11].

One of the major advantages of PHEVs is their usefulness as an MDS. MDS is a revolutionary concept because currently the power grid has no storage except for 2.2% of its capacity in pumped storage [11]. Without significant and reliable storage of energy, maintaining grid stability and reliability under the growing electricity demand is a complex problem. Utilities may contract with others to provide power in any one of the four types of markets: base-load power, peak power, spinning reserves, and regulation services. Several studies have shown that PHEVs can provide ancillary services (spinning and regulation) at a profit [8,10,11]. Spinning reserves receive payment for providing continuous capacity regardless of whether energy is provided, and receive further payment if called on to feed energy into the grid. Regulation services feed a nominal amount of energy into the grid, and receive payment for reducing or increasing their energy consumption as needed. In the case of PHEVs, being plugged-in in a predictable way means that capacity is available to feed into the system if called upon. PHEVs are particularly well-suited for regulation services since the average throughput is zero and it is not expected to draw down the vehicle's energy resources too far.

The pricing of V2G and G2V services is expected to cause a fundamental shift in the behavior of PHEV drivers. Further research is needed to investigate the exact nature of this shift; however, if the pricing schemes are developed with both the power system and transportation system in mind, then PHEVs could help solve problems plaguing the traffic network, particularly congestion. The pricing scheme should also consider air quality impacts caused by charging at different times in the day. As mentioned earlier, MDS will allow for renewable energy to be used more efficiently. There will however remain times of the day more dominated by "dirty" fuels than others.

As observed, the body of research literature related to the multidimensional impact of PHEVs is quite small. The remainder of this section will focus separately on the dual problems of improving the stability and reliability of the electrical grid and improving the efficiency of the roadway network.

A. Stability and reliability of the electric grid

Stability and reliability of the U.S. electric grid have become issues of increasing concern since the occurrence of several blackouts in the 1990s (Western Interconnect in 1994 and 1996, and the Eastern Interconnect in 1999) and system deregulation. The devastating impact of the northeast blackout from August 14, 2003 reminded us that the situation with the grid is only worsening and not improving. Here, a stable system is defined as one in which the phase and frequency of power generation units are constant. Ability of the system to maintain the state of equilibrium during normal and abnormal conditions is a measure of stability. Reliability is defined as the ability of the system to meet unexpected demand and respond to failures. Ability of the system to deliver electricity to customers within the accepted standards, which may be affected by the failure rate, repair rate, or duration of loss,is a measure of reliability. Figure 3 illustrates the worsening stability problem. Order 888 in Figure 3 relates to the Open Access to Transmission issued by Federal Regulatory Commission in 1996, which is the result of an authorization passed by the Congress as a part of the Energy Policy Act of 1992.
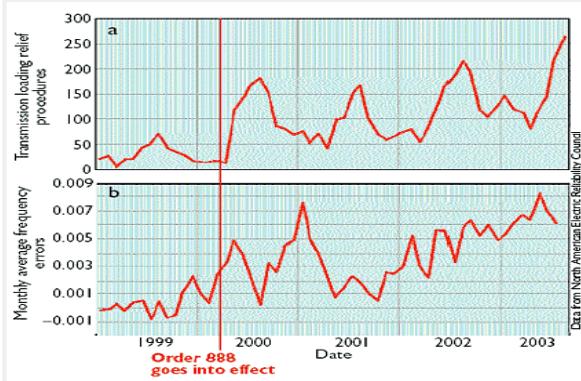

Figure 3. Illustration of multidisciplinary nature of problem

A major challenge in achieving these goals (stability and reliability) is the lack of energy storage. Figure 4 depicts the peaking structure of an example power load over the course of one day. Demand grows rapidly starting at 6am and begins to decline after hitting a peak around 3pm. This peaking phenomenon is especially important to consider given that different energy sources are available at different times of day. For example, wind energy is most widely available at night when the demand for power is the lowest. While it may seem intuitive that a flat demand curve is the ideal, this is not necessarily true. More research is required to determine if parts of the system (e.g., transformers) require time to cool down. The large scale use of energy storage would significantly help meeting the stability and reliability needs, including managing the load variations shown in Figure 4.
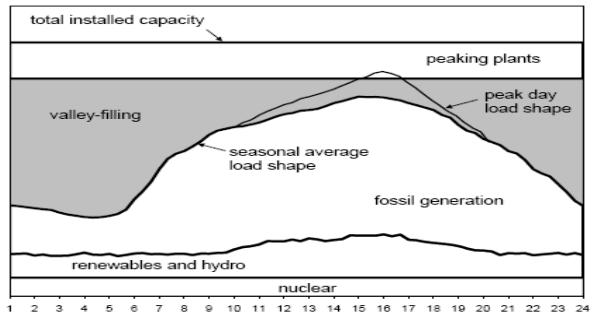

Figure 4. Illustrative peaking of electricity load [12]

B. Efficiency of the roadway network

Congestion is a problem not only in the electricity grid network, but also in the roadway network. Vehicle miles traveled (VMT) has risen consistently since the advent of the automobile, with dips when gasoline prices rise quickly (See Figure 5 for the VMT trend since 1992). If the transportation sector is shifted to an alternative fuel source (i.e., electricity) with greater price stability, and especially if the source of the fuel is renewable, then VMT is expected to continue to increase into the foreseeable future. While mobility is an indicator of economic success, the expansion of a roadway system is limited by available space and finances. Roadway network efficiency is further constrained by the individual autonomy of drivers who act in their self-interest instead of the interest of the system (see [16] for a theoretical description of traveler behavior).
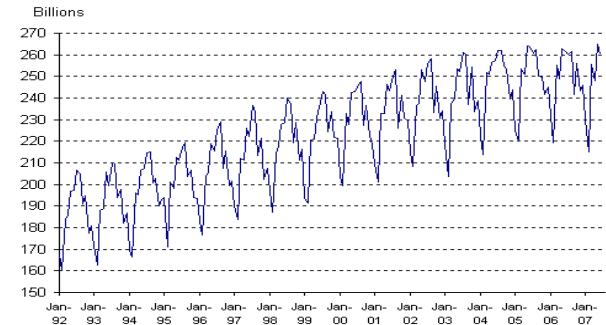

Figure 5. U.S. highway VMT [17]

Extensive research has been conducted on improving the efficiency of the transportation system via methods such as pricing and technology, but few solutions proposed offer a solution even close to being as comprehensive as PHEVs.

III. POLICY ISSUES

Five policy issues were identified in the introduction and each will be discussed in detail in this section. The policy issues presented here are centered on incentives to help industry develop and bring new value to end users of electricity and transportation networks, and society at large, while encouraging competition and development of new business opportunities.

A. Improve electric grid performance

Widespread deployment of PHEVs will allow for increased energy storage, and improved reliability and stability of the electric grid. Linking the transportation and power systems through PHEVs will allow for electrical energy storage on a scale much larger than is currently feasible. The additional energy capacity will be directly proportional to the penetration of PHEVs into the automobile market, and modeling (see §4) is needed to determine the exact increase in capacity across the space and time dimensions.

The new mobile storage can only benefit the electric grid if it is available at the right time and place to service the grid when needed. To determine PHEVs' demand for electric energy across space and time, travel patterns must be considered. Figure 1 shows an example of such a pattern, highlighting several destinations where a driver could potentially engage in G2V or V2G.

Stability and reliability issues were discussed in §2.1. V2G is poised to greatly aid the grid in becoming more reliable and stable because vehicles are only in use for a small portion of each day (average daily travel time person in 2001 was 82.3 minutes [18]). During the remainder of the day, the vehicles can be plugged in and providing services (e.g., ancillary or regulatory).

This approach requires a policy shift to allow use of the MDS for energy to maintain stability and reliability. Also, policy that encourages utilities to cooperate with the PHEVs owners and provide tariff incentives for their participation in programs aimed at demand and distributed generation management and optimization is missing at the moment.

B. Enhance penetration of renewable energy sources to improve energy security

Increasing energy capacity by using PHEVs as MDS will allow for increased investment in renewable energies by alleviating concerns related to the temporal highly variable nature of solar (daytime) and wind (primarily nighttime). Using renewable energy has benefits not only for the environment and air quality, but also for energy security by reducing reliance on the supply from oil producing countries.

This approach requires a policy shift to allow and encourage large scale use of the MDS for energy to support interfacing of renewable generation.

C. Reduce and redistribute pollution in the electric grid and transportation network

By shifting the source of pollution away from vehicles, PHEVs change the transportation-based air pollution problem from a mobile source issue to a point source issue. This redistribution of pollution will likely have the effect of reducing pollution because point sources are much easier to control and some already have emission caps in place. Hadley [19] conducted initial research into the potential air quality impacts of PHEVs, describing the impacts of G2V charging on air quality, and considering the types of power generation that are typically used at different times of day (e.g., coal-fired generation is prevalent at night in some regions).

Some policies are already in place to ensure that the redistribution of pollution that will occur with widespread deployment of PHEVs will actually be a reduction in pollution. Further policy analysis is needed to ensure that V2G and G2V services are incentivized to occur at times when it will result in the maximum improvement in air quality.

D. Create new markets and further deregulate existing markets

PHEVs are poised to open new markets and increase opportunities in existing ones. Carbon trading markets will be aided because they change the transportation-based air pollution problem from a mobile source issue to a point source issue (as described in §3.3). While point sources of pollution are much easier to control. If they are non-renewable, they will likely need to trade carbon credits to counter the increased emissions.

PHEVs will also create new modes for participation in the electricity markets. There will be opportunities for businesses to act as Qualified Scheduling Entities (QSE) to the electric utility by facilitating V2G/G2V interactions. Such a QSE that aggregates across vehicles is necessary because any one vehicle's contribution will be too small to allow it to participate directly in the market. PHEVs will likely function akin to small generators as a distributed energy resource.

Policy that enhances market development and deregulation allowing a new type of QSE to bid in a variety of markets is needed to facilitate the aggregated use of PHEVs in "transportation-energy" markets.

E. Plan and develop energy exchange stations

Energy exchange stations (for G2V and V2G) could take one of at least two forms. The first, the way considered by most electric vehicle research to date, assumes that individual drivers plug in and charge their vehicle over a period of several hours. Some examples of potential charging station locations are shopping malls, recreational areas, schools, and of course homes.

Further, rather than requiring drivers to plug into the grid and wait several hours to charge their batteries, battery exchange locations could be as ubiquitous as gas stations and automatically exchange empty batteries with full batteries. Charging PHEVs in this way has benefits for drivers because the process takes only a few minutes as opposed to several hours. Also, this system would require a leasing system for batteries similar to the system in place for leasing cell phones, alleviating driver concerns about battery life. The benefit for utilities is that control over charging and servicing the grid is centralized.

In reality, charging (G2V) and discharging (V2G) services will likely be based on a hybrid of the two methods mentioned above (individual drivers plugging into the grid and stations designed to exchange batteries). Depending on the pricing structure in place, it may make sense for drivers to exchange batteries during long drives and plug-in to a household plug at night. Incentive structures will need to be developed that

consider the different players – energy exchange stations and individual drivers.

The temporal and spatial aspects of the activity patterns travelers choose (see, e.g., Figure 1) adds a layer of complexity to the problem of locating charging stations to link the transportation and energy systems. This requires both micro (neighborhood, city, and metropolitan area) and macro (region, state, and nation) behavioral dynamics to be studied in detail. If appropriate incentives are developed, drivers could be encouraged not only to act in a way that best serves the grid, but also to act in a way that best serves the transportation system. The incentives could be passive such as pricing electricity for planned contribution at the location of charging facilities (either stations or induction charging embedded in the roadway), or active such as pricing electricity based on congestion in both the power grid and local transportation system. Cognitive and behavioral research (§4.3) is needed to determine the appropriate incentives.

Policy that addresses the planning requirements for charging stations and regulates emerging energy exchange markets is needed. Comprehensive policy that develops joint electricity and transportation programs for incentivizing drivers to participate in the transportation and electricity grid optimization are not yet proposed or even clearly defined.

IV. MODELING OF COMPLEX SYSTEMS

To develop policy strategies that allow for faster and more significant penetration of PHEVs, research is needed to model the interactive performance of two complex systems, power and transportation, linked through the behavior of individual vehicle operators, where this linkage is determined by the location of interface infrastructure. The behavior of travelers defines the required inputs into power modeling since time-dependent PHEV locations are critical. Every aspect of this meta-system enterprise (power, transport, consumer choice, infrastructure development) is inter-linked, therefore fully understanding policy issues is quite challenging. This section explores each aspect of the modeling approach beginning with transportation modeling, and then power systems modeling, then modeling the role of human agents, and finally determining economic feasibility (see Figure 2 for illustration).

A. Transportation modeling

Travel models typically contain demand and supply components. While most demand models used in practice are static and consider each leg of a trip separately, activity-based models are gaining momentum. Lemoine et al. [1] illustrate the problems that PHEVs could pose if proper incentives are not given to ensure that energy exchange occurs at times beneficial to the grid. Activity-based travel models are better suited for PHEV modeling because they recognize that travel arises from a fundamental need to participate in activities, and thus the models capture trip-chaining behavior (e.g., home to work to grocery to home). Other benefits of activity-based models are the incorporation of intra-household interactions, inter-personal and intra-personal consistency measures, consideration of space-time constraints on activities and travel, and emphasis on individual level travel patterns (as opposed to monitoring aggregate travel demands). A number of micro-simulation platforms that employ the activity-based paradigm of transportation demand forecasting have been developed in the last five years (e.g., [20-22]).

On the supply side, conventional techniques of trip assignment are static in nature, and consider vehicle flows aggregated over one or several hour time periods. The limitations of the static assignment procedures and the increase in computing capacity have allowed the field to move toward more behaviorally realistic dynamic traffic assignment (DTA) models. DTA techniques offer a number of advantages including capturing the spatial and temporal evolution of traffic dynamics across the transportation network, superior capability to capture traffic congestion build-up and dissipation, and explicitly representing the route-choice effect of external dynamic prices and other costs and incentives. A number of simulation-based DTA modules have been developed in recent years [23-26]. The above mentioned features of DTA make it an ideal choice for modeling the network congestion patterns induced by PHEV usage and their impact on other vehicles.

Travel models produce numerous outputs, metrics, and system properties. Of critical importance for connecting the transportation and energy models are predictions regarding time-dependent vehicle locations. This inference directly relates to the number of PHEVs present at a specific power grid node, which will be related to the node's self-admittance described in the next sub-section on power systems modeling. Consideration of multiple classes of travelers, PHEV and non-PHEV, will be critical until PHEVs reach high % penetration.

It has been long understood that through pricing-based incentives, the system-level performance of transportation networks can be greatly improved. The entire field of congestion pricing (e.g., [27, 28]) addresses this fact. For instance, PHEVs provide a novel opportunity to achieve gains in controlling and managing congestion in transportation systems through an incentive based approach that persuades users to act in an altruistic manner. Further, such incentives provide a unique opportunity (and complexity) in that dual objectives must be balanced: improving the efficiency of the transportation as well as that of the power system. For the transportation system, incentives influence route, departure, as well as destination choice. Incentives change the fundamental costs traveler's associate with their choices and a new general cost dynamic equilibrium emerges (for normal operating states). This requires a further broadening of the previously mentioned integrated modeling approach to include generalized costs as well as heterogeneous values of time.

Clearly, there will be significant uncertainty in the model inputs that must be built-in to ensure that the policy recommendations work well for a wide range of potential future outcomes. A vast amount of research has already been performed on stochastic transportation modeling both on the demand and supply side [30-34].

B. Power systems modeling

The planning, design and operation of modern power systems call for extensive and detailed simulation. Models used to simulate power system behavior depend on the purpose and

uses. When considering the need of studying PHEV impacts on power system, different levels of modeling are required.

At the macro level, the power system planning related to the uses of PHEVs requires understanding of the generation, storage and load characteristics, as well as power flow projections impacted by the anticipated use of PHEVs. A stochastic nature of PHEV use in the multiple possible roles will require advanced probabilistic methods for power flow analysis, as well as stochastic optimization related to operation and investment planning of dispersed generation [35, 36]. Enhanced modeling techniques must be developed for PHEV behavior as a load to assess dynamic stability of the power system operating in G2V mode [37]. Hadley [19] used the Oak Ridge Competitive Electricity Dispatch (ORCED) model to simulate PHEV electricity demand. It did not directly include transmission and distribution impacts, but discussed the issues of increased continuous transmission. Also, power system contingency analysis must be improved to account for the dynamic nature of both temporal and spatial properties of PHEVs. In the V2G mode, PHEVs may impact power grid operation in many different roles, both as energy storage used to improve performance of renewable such as wind and solar [38], as well as a market participant through aggregated distributed generation [10, 11, 39] . While it has been recognized that PHEVs can be used for regulation services [10, 11], some studies also suggested the PHEV use for peak power "shaving" services [40]. A customized modeling tool that allows examining the potential impacts of large scale deployment of PHEVs on a given electricity system, such as the "PHEV-load" tool developed by the National Renewable Energy Laboratory (NREL) may be needed [41]

At the micro level, the PHEV powertrain system itself, which as a very complex dynamic electro-mechanical system may be studied. Specialized modeling and simulation tools, such as Argon National Laboratory's (ANL's) Powertrain System Analysis Toolkit (PSAT) are well suited for such an analysis [42]. This toolkit allows detailed modeling of charging and discharging dynamics of PHEVs, which is crucial when defining properties of PHEVs as loads, energy storage or generation. as discussed above, Other ANL's tools such as GCtool, GREET and AirCred may also be needed to asses other impacts [42].

The impact of PHEVs ranges from the macro to micro scales, both in size and time. Different power system states (steady state, dynamic, transient) may need to be represented in a framework using different types of mathematical formulations (waveforms, phasor, algebraic). This leads to a new requirement for developing a method for linking different modeling techniques for accurate and efficient simulation when representing large scale penetration of PHEVs as generators, storage elements or loads [43].

C. Human behavior modeling

The widespread adoption of PHEVs will place human vehicle operators at the intersection of power and transportation systems. Thus, it is critical to understand human decision making in the context of PHEV usage and how behavior can be shaped by incentive structures and training interventions. The large disparate group of decision makers includes not only drivers, but also utilities, battery exchange location coordinators, and fleet managers. Cognitive research will be critical to not only to understand and optimize human decision making involving PHEVs, but to also increase the rate of PHEV adoption.

Route planning for any type of vehicle is an example of a dynamic decision task [42]. Choosing a route requires a series of inter-related decisions that occur in a changing and uncertain environment. PHEVs introduce a number of additional decision elements, such as whether to draw energy from the grid or deliver energy to the grid at destinations with facilities allowing such interfaces. Complicating this decision process, G2V costs and V2G credits vary through time and are not perfectly predictable from the driver's perspective.

One successful framework for modeling human performance in dynamic decision making tasks is reinforcement learning (RL) [45, 46]. The theory of RL comprises an array of techniques for learning temporally extended tasks in dynamic environments. An agent is assumed to be immersed in its environment, with some number of actions available to be taken at any given time. The chosen action has an effect, depending on the current state of the environment, the immediate reward (or punishment) the agent receives, and the future state of the environment. Thus actions can influence situations and rewards arbitrarily far into the future, and successful performance hinges on effective planning and coordination of extended sequences of actions [47].

Previous research demonstrates that RL agents and humans are more likely to discover the underlying structure of a task when state cues are present that allow for generalization [48]. A state cue in the context of PHEV decision making would include observable properties - such as time of day, weather conditions, and congestion - that enable prediction of G2V credits and V2G costs. State cues play a critical role in shaping learning and it has been shown that variability in state predictors disrupts performance more than equivalent variability in the reward structure [49]. Further research is needed to examine how variability in state cues and reward structure affects PHEV route selection. Establishing how PHEV driver performance (with respect to improving conditions on the grid and transportation system) declines with variability in state cues is important because transient changes in incentives could have negative, unintended consequences, making it difficult for people to acquire the basic pricing contingencies. Research is also needed to find the best methods for PHEV operators to learn about incentive structures. Various types of feedback are available (e.g., Reward Only, First Error) and the optimal approach should be determined via experiment.

D. Determining economic feasibility

To take advantage of the proposed "transportation-energy" markets, interface infrastructure - the facilities that will bridge the two systems and serve as energy transfer points - must be developed and planned. While prevalence of PHEVs in the future is unknown, their ultimate value can only come if the interfaces are in place. This leads to a situation where the

demand for PHEVs depends on the infrastructure supply, which in turn is defined by the demand. The traditional project valuation models fall short of accounting for this feedback loop.

Developing interface infrastructure is a uniquely challenging problem because the equipment must not only adjust energy flow over time, but the location of transfer points must be determined to maximize long-term value and minimize risks. Technology adoption, incentives, and systems interdependencies all play a role.

To maximize the value of developing interface infrastructure in a particular location, two aspects of the problem must be considered: 1) the value created to the grid by using PHEVs for regulation services, and 2) the value of the activity-based travel patterns that could include a visit to the interface infrastructure. The former value can be explicitly determined, but unless the latter is considered and travelers are enticed to use the new infrastructure, the value to the grid will not be achieved. Typically, the traveling public selects route and activity patterns without considering energy exchange opportunities. New methodologies and modeling techniques must be developed for valuing interface infrastructure given its dependence on traveler behavior.

Unlike most past research into making investment decisions for infrastructure projects that focus on a single system (e.g., [50,51]), the problem posed here must consider the interdependencies between several systems as well as the rate of technology adoption (availability of PHEVs to use this facility and generate value). In fact, this problem exhibits both spatial network effects and strategic "bandwagon" network externalities (see seminal contributions in this area by Rohlfs [52], Farrell and Saloner [53], and David and Greenstein [54]).

It is clear that in the face of this bandwagon effect, the value of deferral flexibility is marginal. Hence, the project developer action space should consider actions that promote early adoption without fully committing to irreversible capital expenditures. Stochastic modeling approaches could be useful here to consider that the outcome and uncertainty space of the valuation problem is decision dependent (see, e.g., [55]).

V. Conclusions

This paper explored the policy implications of widespread PHEV deployment on the energy and transportation systems. Previous research has approached the problem from selected angles, making many simplifying assumptions. This paper gives initial thoughts on how the problem may be approached from a non-myopic perspective.

In summary, numerous policy shifts are needed to realize the full potential of PHEVs, and the cooperation of the transportation and energy sectors is vital. If such policies are adopted as outlined in this paper, PHEVs can provide many benefits to the electric grid in terms of reliability and stability by acting as mobile decentralized storage and allowing for vehicle-to-grid and grid-to-vehicle services. PHEVS will also allow for enhanced penetration of renewable energies such as wind and solar, which will also aid with energy security by reducing dependence on foreign provisions of oil. Important

benefits can be made to air quality through transferring pollution from numerous mobile sources to fewer point sources that are easier to control and may participate in cap-and-trade. In addition the carbon market, new markets will be created in power systems due to the potential for PHEVs (or aggregators of PHEVs) to participate, particularly with ancillary and regulation services. Lastly, charging stations must be planned and developed carefully to allow for flexibility in driver options and optimal performance of the transportation and electricity networks.

A multi-layered modeling framework was proposed that is the first to consider the spatial and temporal nature of the system interactions. PHEV time-dependent travel patterns are outputs of a transportation model and inputs to power systems model. The framework also includes cognitive behavior modeling for the purposes of developing appropriate incentives to encourage drivers to behave in a way that improves the efficiency of the transportation and energy systems.

References

[1] D.M. Lemoine, D.M. Kammen, and A.E. Farrell, "An Innovation and Policy Agenda for Commercially Competitive Plug-In Hybrid Electric Vehicles," Environmental Research Letters, Vol. 3, 2008.

[2] D. Schrank and T. Lomax, "The 2007 Urban Mobility Report," Texas Transportation Institute, September 2007.

[3] U.S.-Canada Power System Outage Task Force, "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations", April 5, 2004, Available: http://www.nerc.com

[4] K. Burges and J. Twele, "Power Systems Operation with High Penetration of Renewable energy - the German case," 2005 Int. Conf. on Future Power Systems, 2005, pp. 1-5.

[5] Kelso, J.A.S. Dynamic Patterns: The Self-Organization of Brain and Behavior, MIT Press, Cambridge, MA, 1995.

[6] M.T. Turvey and M. Moreno, "Physical metaphors for the Mental Lexicon," The Mental Lexicon, Vol. 1, 2006, pp 7-33.

[7] G.C. Van Orden, J.G. Holden, and M.T. Turvey, "Self-Organization of Cognitive Performance," Journal of Expr.. Psychology: General, Vol. 132, 2003, pp 331-350.

[8] A.N. Brooks, Vehicle-to-Grid Demonstration Project: Grid Regulation Ancillary Service with a Battery Electric Vehicle, AC Propulsion, Inc., 2002.

[9] R. Duncan and M.J. Osborne, Report on Transportation Convergence, Austin Energy, March 1 2005.

[10] W. Kempton, J. Tomic, S. Letendre, A. Brooks, and T. Lipman, "Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California," Report # UCD-ITS-RR-01-03, Electric Transportation. Program, 2001.

[11] W. Kempton and J. Tomic, "Vehicle to Grid Implementation: from Stabilizing the Grid to Supporting Large-scale Renewable Energy, Power Sources, Vol. 144, No., 1, 2005, pp 280-294.

[12] M. Kintner-Meyer, K. Schneider and R. Pratt, "Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids, Part 1: Technical Analysis," November 2007.

[13] J. Solomon and R. Vincent, "Development and Evaluation of a Plug-in HEV with Vehicle-to-Grid Power Flow," Final Report, A.C. Propulsion, 2003.

[14] S. Letendre, R. Perez, and C. Herig, "Battery-Powered, Electric-Drive Vehicles Providing Buffer Storage for PV Capacity Value," Proceedings of the 2002 American Solar Energy Society Annual Conference, Boulder, CO, 2002.

[15] E.J. Lerner, "What's Wrong with the Electric Grid?" The Industrial Physicist, October/November 2003.

[16] J.G. Wardrop, "Some Theoretical Aspects of Road Traffic Research," Proceedings of the Institute of Civil Engineers, Vol. 1, No. 2, 1952, pp 325-378.

[17] U.S. Department of Transportation, Federal Highway Administration, Office of Highway Policy Information, "Traffic Volume Trends," available at http://www.fhwa.dot.gov, August 2007.

[18] L. Toole-Holt, S.E. Polzin, and R.M. Pendyala, "Two Minutes per Person per Day Each Year: Exploration of Growth in Travel Time Expenditures," Transportation Research Record, No. 1917, 2005, pp 45-53.

[19] S.W. Hadley, "Impact of Plug-in Hybrid Vehicles on the Electric Grid," Oak Ridge National Laboratory, for the U.S. Department of Energy, ORNL/TM-2006/554, 2006.

[20] C.R. Bhat, J.Y. Guo, S. Srinivasan, and A. Sivakumar, "A Comprehensive Econometric Microsimulator for Daily Activity-Travel Patterns," Transportation Research Record, Vol. 1894, 2004, pp 57-66.

[21] P. Vovsha, E. Petersen, and R. Donnelly, "Impact of Intra-Household Interactions on Individual Daily Activity-Travel Patterns," Proceedings of the 83rd Annual Meeting of the Transp. Research Board, Washington, D.C., 2004;

[22] J.L. Bowman and M.A. Bradley, "Activity-Based Travel Forecasting Model for SACOG", Technical Memos Numbers 11-11, Available at http://jbowman.net, 2005.

[23] S.T. Waller and A.K. Ziliaskopoulos, "A Visual Interactive System for Transportation Algorithms," Proceedings of the 78th Annual Meeting of the Transportation Research Board, Washington, D.C., 1998.

[24] N.B. Taylor, "CONTRAM 5: An Enhanced Traffic Assignment Model", TRLL Research Report 249, 1990.

[25] M. Ben Akiva, M. Bierlaire, H. Koutsopoulos, and R. Mishalini, DynaMIT: A Simulation-based System for Traffic Prediction and Guidance Generation," Presented at TRISTAN III, 1998.

[26] H.S. Mahmassani, T-Y. Hu, and R. Jayakrishnan, "Dynamic Traffic Assignment and Simulation for Advanced Network Informatics (DYNASMART)," Proc. of the 2nd Intl Capri Seminar on Urban Traffic Networks, Italy, 1992.

[27] R. Arnott and K. Small, "The Economics of Traffic Congestion," American Scientists, Vol. 20, 1994, pp 123-127.

[28] Hearn, D.W. and M.V. Ramana, Solving Congestion Toll Pricing Models In Equilibrium and Advanced Transportation Modeling eds. Marcotte, P. and S. Nguyen, Kluwer Academic Publishers, Boston, 1998, pp 109-124.

[29] S.A. Morrison, "A Survey of Road Pricing," Transportation Research,, Vol. 20A, No. 2, 1986, pp 87-97.

[30] S.T. Waller, J.L. Schofer, and A.K. Ziliaskopoulos, "Evaluation with Traffic Assignment under Demand Uncertainty, Transportation Research Record, Vol. 1771, 2001, pp 69-75.

[31] A. Karoonsoontawong and S.T. Waller, "Dynamic Continuous Network Design Problem: Linear Bi-Level Programming and Metaheuristic Approaches, Transportation Research Record, Vol. 1964, 2006, pp 104-117.

[32] S. Ukkusuri, V.M. Tom, S.T. Waller, "Robust Network Design Problem under Demand Uncertainty, Computer Aided Civil and Infrastructure Engineering, Vol. 22, 2007, pp 6-18.

[33] S.T. Waller and A.K. Ziliaskopoulos, "A Chance-Constrained Based Stochastic Dynamic Traffic Assignment Model: Analysis, Formulation and Solution Algorithms," Transportation Research C, 2007.

[34] J. Duthie, A. Unnikrishnan, and S.T. Waller, "Network Evaluation with Uncertain and Correlated Long-Term Demand," Proceedings of 85th Transportation Research Board Meeting, Washington, D.C., 2006.

[35] G. Stefopoulos, A. P. S. Meliopoulos and G. Cokkinides, "Probabilistic Power Flow with Non-Conforming Electric Loads", Int. Journal of Electrical Power & Energy Systems, Vol. 27, Issues 9-10, pages 627-634, Nov.-Dec. 2005.

[36] R. Gollmer, U. Neise, R. Schultz, "Risk Modeling via Stochastic Dominance in Power Systems with Dispersed Generation," Technical Report, Department of Mathematics, University of Duisburg, Germany, 2007.

[37] B-K. Choi., H.D. Chiang, and Y.H. Li, "Measurement-based Dynamic Load Models: Derivation, Comparison, and Validation," IEEE Trans. on Power Systems, Vol. 21, 2006.

[38] W. Short, P. Denholm, "A Preliminary Assessment of Plug-in Hybrid Electric Vehicles on Wind Generation Markets," Tech. Report, NREL/TP-620-39729, April 2006

[39] J. Tomic, W. Kempton, "Using Fleets of Electric Drive Vehicles for Grid Support," The Journal of Power Sources, Vol.168, Issue 2, pp. 459-468, June 2007.

[40] W. Kempton, T. Kubo, "Electric-drive Vehicles for Peak Power in Japan," Energy Policy, Vol. 28, pp 9-18, 2000.

[41] P. Denholm, W. Short, "An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-in Hybrid Electric Vehicles," Technical Report, NREL/TP-620-40293, Oct 2006.

[42] Argon National Laboratory Tools, Available at: http://www.transportation.anl.gov/software/PSAT/index.html

[43] B. Kasztenny, M. Kezunovic, "A Method for Linking Different Modeling Techniques for Accurate and Efficient Simulation," IEEE Trans. on Power Systems, Vol. 15, No. 1, pp 65-72, Feb. 2000.

[44] Busemeyer, J.R., Dynamic Decision Making, In International Encyclopedia of the Social and Behavioral Sciences, Vol. 6, eds: Smelser, N.J. and P.B. Baltes, Elsevier Press: Oxford, 2002, pp 3903-3908.

[45] W.-T. Fu and J.R. Anderson, "From Recurrent Choice to Skill Learning: A Reinforcement-Learning Model," Journal of Experimental Psychology: General, Vol. 135, 2006, pp 184-206.

[46] W.D. Gray, C.R. Sims, W.-T Fu, and M.J. Schoelles, "The Soft Constraints Hypothesis: A Rational Analysis Approach to Resource Allocation for Interactive Behavior," Psychological Review, Vol. 113, 2006, pp 461-482.

[47] Sutton, R.S. and A.G. Barto, Reinforcement Learning: An Introduction, MIT Press, 1998.

[48] T.M. Gureckis and B.C. Love, "Short Term Gains, Long Term Pains: Reinforcement Learning in Dynamic Environments," Cognition, 2008.

[49] T.M. Gureckis and B.C. Love, "Learning Sequential Decision Strategies in Noisy Environments," Journal of Mathematical Psychology, 2008.

[50] T. Zhao and C.C. Fu, "Infrastructure Development and Expansion under Uncertainty: A Risk-Preference-based Lattice Approach," ASCE Journal of Construction Engineering and Management, Vol. 132, No. 6, 2006, pp 620-625.

[51] Z. Zhang and I. Damnjanovic, "Quantification of Risk Cost Associated with Short-Term Warranty-based Specifications for Pavements," Transportation Research Record, No. 1946, 2006, pp 3-11.

[52] J.H. Rohlfs, "A Theory of Interdependent Demand for a Communication Service," Bell Journal of Economics and Management Science, Vol. 5, No. 1, 1974, pp 16-74.

[53] J. Farrell and G. Saloner, "Standardization, Compatibility and Innovation," RAND Journal of Economics, Vol. 16, 1985, pp 70-82.

[54] P.A. David and S. Greenstein, "The Economics of Compatibility Standards: An Introduction to Recent Research," Economics of Innovation and New Technology, Vol. 1, 1990, pp 3-41.

[55] T.W. Jonsbraten, R.J.B. Wets, and D.L. Woodruff, "A Class of Stochastic Programs with Decision Dependent Random Elements," Annals of Operations Research, Vol. 82, 1998, pp 83-106.