USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No. 079PY04

Integrated Framework to Capture the Interdependencies between Transportation and Energy Sectors due to Policy Decisions

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DISCLAIMER

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TECHNICAL SUMMARY

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Title

Integrated Framework to Capture the Interdependencies between Transportation and Energy Sectors due to Policy Decisions

Introduction

Currently, transportation and energy sectors are developed, managed, and operated independently of one another. Due to the non-renewable nature of fossil fuels, energy security has evolved into a strategic goal for the United States. The transportation sector accounts for about 30% of the energy consumed by the U.S. As the emergent and strategic linkages between the two sectors are becoming increasingly apparent from a qualitative perspective, there is an evolving consensus that national, regional, and local policy goals may not be achievable completely or effectively by focusing on one sector at a time. For example, the increase in the market penetration of electric vehicle has brought many advantages and challenges along with it on both transportation as well as the energy sector. Such challenges for transportation sector include reduction of highway maintenance budgets due to a reduction in gasoline sales, and that for energy sector include increased power demand during specific times of the day, thereby affecting daily power generation operations. This motivates the need to develop an analytical framework to capture the interdependencies between these two infrastructure systems. This study provides a system-of-systems based infrastructure computable general equilibrium framework for analyzing the interdependencies between the transportation and energy sectors.

Findings

The insights from this study suggest that due to the interactions between the transportation and energy sectors, optimal policy decisions cannot be achieved by designing and evaluating these decisions only one sector at-a-time. This is because the inherent interdependencies between these two infrastructure systems leads to emergence of new equilibrium for each of them which cannot be captured in isolation. The study presents a system-of-systems based analytical framework to evaluate the policy instruments, e.g. subsidizing the electric vehicles. Interactions between these two sectors are captured using substitution effect. For example, electricity will substitute for gasoline usage by transportation sector. This will not only affect the equilibrium of the transportation network but also the operation of the energy sector.

Recommendations

The study findings suggest that the interactions among the transportation and energy sectors need to be captured using an integrated framework. Further, this research suggests that the policy decisions need to be evaluated from a holistic perspective to achieve strategic policy goals. This study presents a system-of-systems based analytical framework capturing the interdependencies between these two sectors to evaluate the performance of policy instruments.

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CHAPTER 1. INTRODUCTION

1.1 *<u>Background</u>*

Currently, transportation and energy sectors are developed, managed, and operated independently of one another. Due to the non-renewable nature of fossil fuels, energy security has evolved into a strategic goal for the United States. The transportation sector accounts for about 30% of the energy consumed by the U.S. As the emergent and strategic linkages between the two sectors are becoming increasingly apparent from a qualitative perspective, there is an evolving consensus that national, regional, and local policy goals may not be achievable completely or effectively by focusing on one sector at a time. For example, the increase in the market penetration of electric vehicle has brought many advantages and challenges along with it on both transportation as well as the energy sector. Such challenges for transportation sector include reduction of highway maintenance budgets due to a reduction in gasoline sales, and that for energy sector include increased power demand during specific times of the day, thereby affecting daily power generation operations. This motivates the need to understand the interdependencies between these two infrastructure systems.

Economists and urban planners usually divide the infrastructure system into two different types: economic and social. For example, "*economic infrastructure is defined as infrastructure that promotes economic activity, such as roads, highways, railroads, airports, sea ports, electricity, telecommunications, water supply and sanitation*." Social infrastructure includes "*infrastructure that promotes health, education, and cultural standards of a population....*" (Hirschmann, 1958). Economic and social infrastructure has also been termed "hard" and "soft" infrastructure, respectively. Infrastructure that is of particular importance to the operations of a society and economy has been termed the *critical* infrastructure. ASCE (American Society of Civil Engineers) Policy Statement 518 defines critical infrastructure as the following: "*Critical infrastructure includes systems, facilities, and assets so vital that if destroyed or incapacitated would disrupt the security, economy, health, safety, or welfare of the public Critical infrastructure may cross political boundaries and may be built (such as structures, energy, water, transportation, and communication systems), natural (such as surface or ground water resources), or virtual (such as cyber, electronic data, and information systems)*" (ASCE, 2012). The importance of critical infrastructure to society has been discussed from many policy and planning perspectives, including but not limited to, defense (PCCIP, 1997; The White House, 2010), economic security, and development (Kessides, 1993; Roeller, L-H. and Waverman, L., 2001; Payne, J., 2010).

In addition to the individual importance of each critical infrastructure, it is increasingly apparent that these infrastructure systems are highly interdependent on one another (Rinaldi et al., 2001). Interdependencies can be *geographic* where infrastructure and facilities share spatial attributes, *functional* where output requires inputs from other infrastructure or industries, *budgetary* where investment comes from shared sources, and/or *market-based* where these infrastructure systems reside as part of an economic system (Zhang and Peeta, 2011). With newly constructed infrastructure, along with new technologies and policies which impact multiple infrastructures simultaneously, these interdependencies are increasing in terms of both magnitude and complexity. In addition to the critical infrastructure, strategic policy goals (e.g., energy security, climate change, national security) are also becoming increasingly complex and interdependent, cross-cutting conventional infrastructure agencies and bureaucratic distinctions. Thus, methods for capturing critical infrastructure interdependencies at both a system-wide and an economy-wide level are necessary to support decision-makers addressing such strategic policy goals involving critical infrastructure in a consistent, comprehensive, and holistic manner. This research focuses on analyzing the interdependencies between the two critical economic infrastructure systems: transportation and energy.

1.2 Motivation and Objectives

Critical infrastructure and its interdependencies have been modeled by both the engineering and the economics community. The perspectives differ in many ways, but predominantly in the perspective of how critical infrastructure is fundamentally interconnected.

In the engineering domain, much research attempts to address infrastructure interdependencies. Despite a plethora of widely diverse of model in this domain, limitations which persist include: (1) methods not general enough to seamlessly integrate additional infrastructure systems (i.e., the models and theories are often designed only for the selected infrastructure systems); (2) analysis which neglects to explicitly incorporate economic and industry responses. Since industries produce goods and services which the infrastructure effectively transports, treating infrastructure and productive industry independently cannot capture the economy-wide implications relevant to policy analysis.

In the economic domain, computable general equilibrium (CGE) models have been used to capture cross-industry effects (i.e., functional and market-based interdependencies). Beyond some introductory efforts CGE models mostly represent infrastructure in the same fashion as traditional sectors (e.g., agriculture, manufacturing) and fails to explicitly account for infrastructure in the following ways: (1) the models do not explicitly account for the physical infrastructure characteristics (network, capacity, performance, etc.), and (2) the models do not recognize the operators and level of control of the infrastructure. These limitations compromise the ability to adequately address many infrastructural interdependencies, notably geographic and budgetary interdependencies, and as a result, such interdependencies are often overlooked by the infrastructure engineering community.

There is a need to consolidate the strengths of both the engineering and the economic perspective to design a formal, general method for analyzing critical infrastructure planning and policy. As discussed, some engineering-type models attempt to incorporate the strengths of economic models (i.e., a general approach for all infrastructure (firms) and capturing economic and industry responses). Likewise some economic-type models (CGE) models attempt to incorporate the strengths of engineering models (i.e., accounting for unique characteristics of infrastructure and recognition of operator and level of control). However, incorporating the primary capabilities of both remains elusive.

Zhang and Peeta (2011) propose a generalized approach. They use a static computable general equilibrium model with infrastructure systems acting as producers to model the interdependencies in a general framework. Different infrastructure networks are modeled in a multi-layer network with horizontal links for connections within a single infrastructure and vertical links across separate infrastructure. Generalized costs are used in the multi-layer network, which may be problematic for substitution between different infrastructure systems based on price (i.e., the structure of generalized cost for one system may not be comparable to another system). Also, the analysis focuses primarily on interdependencies between critical infrastructure systems for resilience analysis and only casually considers the impact on the economy. Economy-wide analysis is crucial when extending such a framework from the engineering domain to conduct comprehensive and holistic policy analysis.

Therefore, in order to specifically address policymaking considering interdependencies between transportation and energy sectors, it is necessary to: (1) seamlessly integrate the models and theories designed independently for these two infrastructure systems; (2) explicitly incorporate economic and industry responses to capture both the system-wide and economy-wide impacts; (3) explicitly account for the physical infrastructure characteristics (network, capacity, performance, etc.); and (4) explicitly recognize the operators and level of control of the infrastructure. This research utilizes spatial-network general equilibrium as a building-block foundation to specifically address the four needs described above. Synergies from the literature are incorporated to present a formal, general methodology for investigating infrastructure interdependencies. In this way, both system-wide and economy-wide impact analysis can be performed on issues relating to both transportation and energy sectors to support consistent, comprehensive, and holistic decision-making.

This research presents a generalized framework to capture infrastructure interdependencies that includes transportation and energy sectors. It will allow policymakers to explicitly understand the impacts of various policies and/or mandates directed at the transportation and energy sectors for the purpose of addressing strategic goals of security and sustainability. Such understanding from the tool will demonstrate the necessity of a holistic policy approach to infrastructure regulation, operation, and investment strategies.

1.3 Organization

This report proposes an integrated framework to capture interdependencies between the transportation and energy sectors in order to inform holistic policy approaches. A number of past approaches to the problem from both engineering and economic perspectives are reviewed in detail in Chapter 2. Chapter 3 presents a conceptual framework which overcomes the limitations of each perspective and exploits synergies to holistically analyze interdependent critical infrastructure systems using systems of system approach. Chapter 4 presents examples of evaluating the policy instruments using proposed framework. Finally, concluding comments and directions for future research are presented in Chapter 5.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Critical infrastructure and its interdependencies have been modeled by both the engineering and the economics community. The perspectives differ in many ways, but predominantly in the perspective of how critical infrastructure is fundamentally interconnected. While engineering researchers tend to see direct connections between infrastructure systems (see Figure 1), economic researchers tend to see infrastructure as implicit connections which facilitate good movement in an interdependent economy (see Figure 2).

Even within the engineering and economic disciplines methodologies also vary widely. There is no one, all-encompassing method and this research does not intend to provide this. This section identifies important surveys of models in the engineering literature and discusses important efforts in the economics literature. The intent is to look on the landscape of literature to identify general limitations and synergies which may overcome the disparity between engineering and economic models. Where only individual infrastructure is considered, focus is placed primarily on transportation-relevant models since many other infrastructure systems can often be generalized to transportation (e.g., electricity infrastructure transports electrons, pipelines transport energy fuels and water).

2.2 Engineering Literature

In the engineering domain, several research attempts to address infrastructure interdependencies. Rinaldi et al. (2001) describes physical, geographic, cyber, and logical interdependencies, and Rinaldi (2004) follows up with this by describing important types of interdependencies, characteristics of the infrastructure interdependency problem, and classes of models which have been used for this purpose. Pederson, et al. (2006) provides a survey of both U.S. and international research on the infrastructure interdependency modeling. Yusta et al. (2011) also survey many critical infrastructure models from an energy security and vulnerability perspective. They conclude there is a trend toward risk assessment and simulation techniques which attempt to explicitly capture functional connections between infrastructure systems. An example of functional connections between infrastructure systems from an engineering perspective is shown in Figure 1. Simulation-type methodologies which have been explored include system dynamic, agent-based, network, expert analysis, and various combinations of these models (Huang et al., 2014).

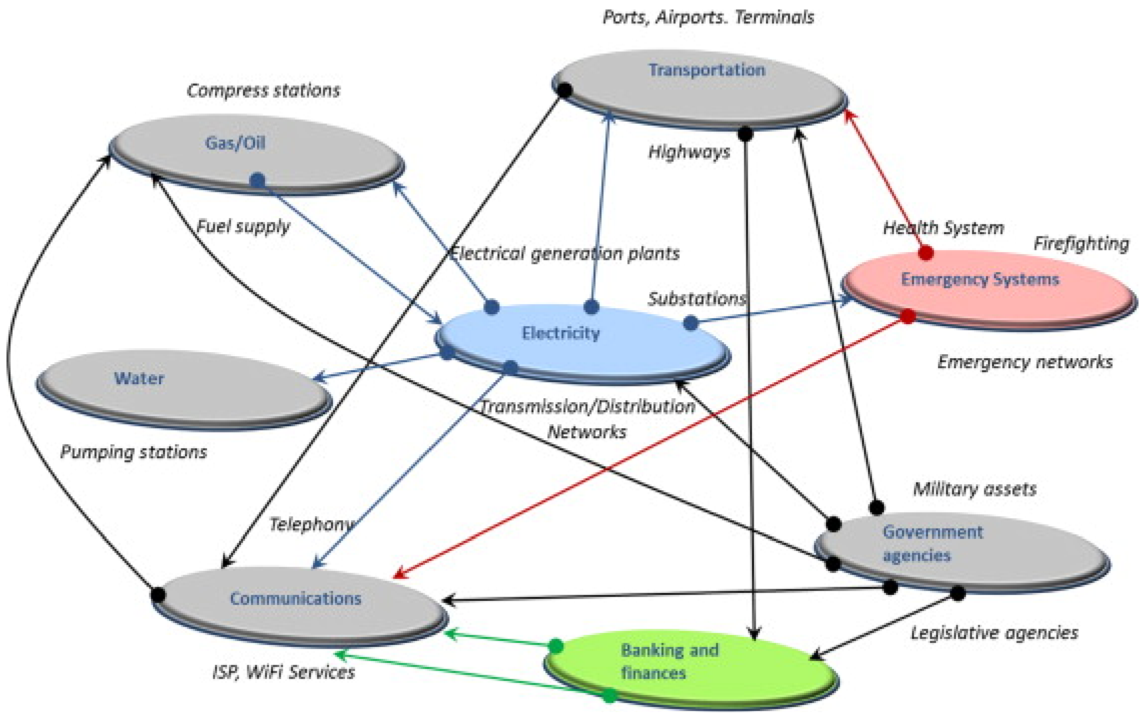

Figure 1: Example of interdependence between energy systems and other critical infrastructure

Source: Yusta et al. (2011)

As mentioned earlier in Chapter 1, there are two important limitations of models in this domain, which include: (1) the models are not general enough to seamlessly integrate additional infrastructure systems (i.e., the models and theories are often designed only for the selected infrastructure systems); (2) analysis neglects to explicitly incorporate economic and industry responses. Since industries produce goods and services which the infrastructure effectively transports, treating infrastructure and productive industry independently cannot capture the economy-wide implications relevant to policy analysis.

2.3 Economic Literature

In the economic domain, computable general equilibrium (CGE) models have been used to capture cross-industry effects (i.e., functional and market-based interdependencies). CGE models, in general, are driven by empirically estimated input-output tables, which detail output in each single industry from input values from all other industries in the economy, and parameters which capture substitutability of inputs (e.g., capital and labor). Isard (1951) introduced interregional input-output models to address problems involving good movement between regions (e.g., tariff and trade policy). Termed spatial computable general equilibrium (SCGE), these models are used to capture transportation and good/service movement within and across borders. One primary purpose is to analyze economy-wide impacts (e.g., regional and sectoral welfare disparity) from policies using comparative statics (Shoven and Whalley (1984; 1992); Kehoe and Kehoe (1995)).

By and large infrastructure systems in CGE (and SCGE) have been and continue to be treated as individual firms or aggregated with other firms (e.g., transport services, energy, or electricity sectors). Many researchers investigate the macroeconomic impacts (e.g., GDP) of infrastructure investments in a CGE framework (e.g., Kim (1998)). The sectors receiving investment in the experiments (i.e., road, railroad, seaport, and airport) are treated as firms, which treats many characteristics of infrastructure systems implicitly (e.g., cost, network, capacity, performance). Similar analysis does not address problems of *how* to invest.

Alternatively, Buckley (1992) introduced transportation cost coefficients to differentiate prices of goods between origin-destination pairs. Also, Conrad (1997) and Conrad and Heng (2002) modify the cost structure for transportation services to account for congestion effects. Although they treat some good movement costs explicitly, most CGE models continue to assume no change in transportation network costs because of research objective and/or computational complexity. Another notable attempt to model good movement relevant to this research is due to Lofgren and Robinson (2002). Here, transportation is treated as a general sector without explicit network costs; however trade between regions is dependent on network connectivity (i.e., rural regions connect to urban regions which connect to the rest of the world). These works make important attempts toward integrating infrastructure systems in traditional CGE frameworks.

The literature in domain reveals that CGE models mostly represent infrastructure in the same fashion as traditional sectors (e.g., agriculture, manufacturing) and have following limitations: (1) the models do not explicitly account for the physical infrastructure characteristics (network, capacity, performance, etc.), and (2) the models do not recognize the operators and level of control of the infrastructure. Under these limitations, CGE models are unable to adequately address many infrastructural interdependencies such as, geographic and budgetary interdependencies. Therefore, CGE models are often overlooked by the infrastructure engineering community.

2.4 Combining Engineering and Economic Perspectives

There is a need to consolidate the strengths of both the engineering and the economic perspective to design a formal, general method for analyzing critical infrastructure planning and policy. As discussed, some engineering-type models attempt to incorporate the strengths of economic models (i.e., a general approach for all infrastructure (firms) and capturing economic and industry responses). Likewise some economic-type models (CGE) attempt to incorporate the strengths of engineering models (i.e., accounting for unique characteristics of infrastructure and recognition of operator and level of control). However, incorporating the primary capabilities of both remains elusive.

Some research has attempted to bridge this gap. In literature these are often termed “top-down, bottom-up” models where “bottom-up” refers to engineering-type models of highly disaggregated systems and “top-down” refers to micro- and macroeconomic linkages between aggregated systems (e.g., input-output analysis, CGE). The research discussed previously can be considered principally “bottom-up” and “top-down" reaching toward the "top" (macroeconomy) or "bottom" (individual infrastructure detail), respectively; the research in this section attempts to provide a more all-encompassing framework.

Kim et al. (2004) uses a minimum distance matrix and an accessibility index between regions derived from proposed highway investment in a transportation model. Investment for the proposed highway is fed into a CGE model to determine economy-wide impacts for cost-benefit analysis. The two models are hard-linked via investment and accessibility. Rutherford and van Nieuwkoop (2011) embed general equilibrium and traffic equilibrium models in a single mixed complementarity problem. These two pieces of work satisfy several elements of both the economic and engineering problem in transportation but lack generality for other infrastructure systems.

Top-down, bottom-up models are increasingly prevalent in the energy economic field (relating to energy and electricity infrastructure). This is likely because energy and electricity consumption is less dependent on specific engineering characteristics (i.e., network, congestion) than the transport sector, fitting more easily in top-down approaches. The MARKAL-MACRO model (Manne and Wene, 1992) combines the engineering detail of the energy sector in the MARKAL model (Loulou, et al. 2004) with a simple general equilibrium from the MACRO model (Manne and Richels, 1992) via exchange of energy output and energy cost variables between the respective models. Similarly, Shaefer and Jacoby (2006) create a single framework by exchanging prices, demand, and modes shares from a CGE model with fuel substitution elasticities from the MARKAL model. Boehringer and Rutherford (2008), similar to Rutherford and van Nieuwkoop (2011) for transportation, describe a complementarity formulation of the energy sector which combines bottom-up technological detail and top-down economic considerations within a single mathematical model. Because of complexity issues which may make the approach intractable, Boehringer and Rutherford (2009) decompose the original complementarity formulation into separate top-down and bottom-up models, which are solved independently, and uses an iterative process to achieve convergence.

Top-down, bottom-up models deal with the general infrastructure and suffer from computational complexity, which limits their applicability for modeling interdependencies of multiple infrastructure systems. The Zhang and Peeta (2011) approach represents an important step toward generalizing an infrastructure model and is used as a foundation for this research. Zhang and Peeta (2011) describe geographic, functional, budgetary, and market interdependencies and use a SCGE model with infrastructure systems acting as producers to model the interdependencies in a general framework. Different infrastructure networks are modeled in a multi-layer network with horizontal links for connections within a single infrastructure and vertical links across separate infrastructure. Generalized costs are used in the multi-layer network, which may be problematic for substitution between different infrastructure systems based on price (i.e., the structure of generalized cost for one system may not be comparable to another system). Also, the analysis focuses primarily on interdependencies between critical infrastructure systems for resilience analysis and only casually considers the impact on the economy. Economy-wide analysis is crucial when extending such a framework from the engineering domain to conduct comprehensive and holistic policy analysis.

2.5 *Identify the Needs*

Therefore, in order to specifically address policymaking considering critical infrastructure interdependencies, it is necessary to: (1) seamlessly integrate additional infrastructure systems (models, theories designed only for a handful of systems rather than for all); (2) explicitly incorporate economic and industry responses to capture both the system-wide and economy-wide impacts; (3) explicitly account for the physical infrastructure characteristics (network, capacity, performance, etc.); and (4) explicitly recognize the operators and level of control of the infrastructure. This research utilizes spatial-network general equilibrium as a building-block foundation to specifically address the four needs described above. Synergies from the literature above are incorporated to present a formal, general methodology for investigating infrastructure interdependencies. In this way, both system-wide and economy-wide impact analysis can be performed on issues relating to critical infrastructure to support consistent, comprehensive, and holistic decision-making.

CHAPTER 3. INFRASTRUCTURE COMPUTABLE GENERAL EQUILIBRIUM FRAMEWORK

3.1 Spatial Computable General Equilibrium Foundation

The model in this report is termed *infrastructure computable general equilibrium* (ICGE). ICGE implies that infrastructure interdependencies (i.e., geographic, functional, budgetary, and market-based) are captured in the formulation, and the infrastructure included in the model are critical in that they are included for a specific objective. This could be considered a subset of SCGE in that infrastructure is also characterized by space and movement of goods and services across this space. There is substantial research in this domain which could serve as a foundation. The formulation of the ICGE problem in this research is built up from a trade-based SCGE formulation presented in Shoven and Whalley (1974; 1992), which serves as an introductory literature to general equilibrium for those who are unfamiliar with the modeling techniques and assumptions. Figure 2 shows a simplified model of the economy; there are consumers and producers in multiple regions (countries, states, localities, or otherwise). Consumers are endowed with various factors of production (e.g., capital, labor, natural resources, land) which they sell to firms in exchange for payment (e.g., rent, wage). Firms use the factors, along with intermediate goods from other firms, to produce goods which are then exchanged with other firms or consumer as expenditures. Goods and factors can be sold within the region or between regions via an interregional market.

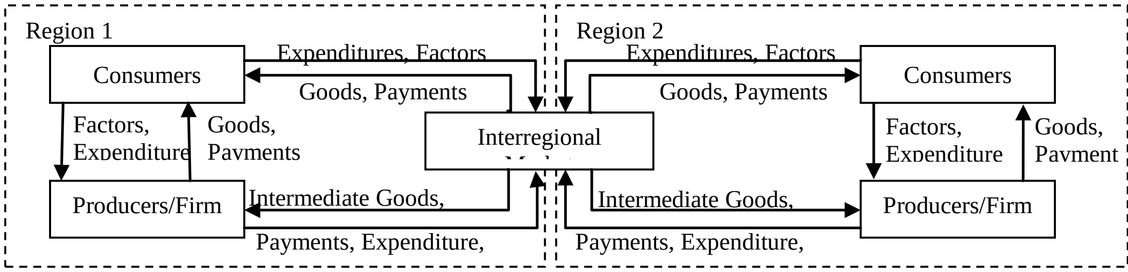

Figure 2: The circular flow of economy with multiple regions.

Although not shown specifically, the exchange of expenditure for intermediate goods can occur regionally and can be thought of as occurring within the Producers/Firms box.

We consider an economy of N goods $(i,...,N)$, F factors of production $(1,...,F)$, R regions $(1,...,R)$, and one aggregate, representative consumer per region. Each good and factor in each region are considered unique so at the world level there are NR goods and FR factors.

Intermediate demands are the input demands for a good in the production of another (functional interdependency). Final demands are the demands for goods by the households (or other end-use). Demands are a function of economy-wide prices and quantities, represented primarily by own-price and cross-price elasticities (substitution effect) and is equal to supply in equilibrium (market-based interdependency). As an example, if final demand for one good increases, demand for the inputs also increases based upon the input share to production and the elasticities in the demand function. Also, if the price of a good increases, the quantity demanded may change based on consumer budget constraints (income effect) or substitution for another good (substitution effect). These are the primary mechanisms in the general equilibrium framework.

The equilibrium is defined as the set of prices $P=(\pi,R)$ for the set of goods $(\pi_{11},..., \pi_{N1},..., \pi_{1r},... \pi_{1R},..., \pi_{NR})$, value-added factors of production $(\pi_{(N+1)1},.. \pi_{(N+F)1},...\pi_{(N+1)r},...,\pi_{(N+1,R)},...\pi_{(N+F)R})$, and tax revenue $(R_{11},...,R_{(N+F)1},...,R_{1r},...R_{1R},...,R_{(N+F)R})$ such that supply and demand equalities hold for all goods and factors where π_{ir} is the price of good i in region r and $\pi_{(N+f)r}$ is the price of factor f in region r. That is to say that at these prices are such that the market clearance, zero profit condition, and income balance hold. These three general equilibrium conditions for the case with regional trade are as follows:

$$(1) \qquad G_i^r = \sum_{j=1}^{N}\sum_{e=1}^{R} H_{ije}^r + \sum_{s=1}^{R} X_{ir}^s$$

where G_i^r is the gross output of good *i* in region *r*, H_{ije}^r is the amount of good *i* supplied by region *r* used in producing good *j* in region *e*, and X_{ir}^s is the final (consumer) demand for good *i* from region *r* in region *s*. This characterizes the clearance of the goods market where the gross output of each good in each region is equal to the economy-wide intermediate and final demand for the good.

$$(2) \qquad \sum_{i=1}^{N} V_{fi}^r = \sum_{s=1}^{R} \overline{V}_f^{sr}$$

where V_{fi}^r is the total amount of factor *f* used for production of good *i* in region *r*, and $\overline{V}_f^{sr}$ is the total amount of factor *f* used in region *r* from region *s* (owned by consumer in region *s*). Similar to the goods market, this characterizes the clearance of the factors market. The combination of equations 1 and 2 is known as the market clearance condition.

$$(3) \qquad \pi_{ir} G_i^r = \sum_{i=1}^{N}\sum_{e=1}^{R} \pi_{ie} H_{ijr}^e + \sum_{f=1}^{F} \pi_{(N+f)r} V_{fi}^r$$

Equation (3) is known as the zero-profit condition. This condition is an artifact of an assumption of free-entry and exit by firms which drives profits to zero in the long-term. Zero-profit can alternatively be understood as residual profits returning to consumers (e.g., residuals do not accrue to a firm, but rather accrue to persons (households) via payments to labor). Here the value of the produced good is equal to sum of the value of the intermediate inputs and the value of the factors used to make the good.

$$(4) \qquad \sum_{i=1}^{N}\sum_{s=1}^{R} \left(\pi_{ir} + \tau_i^r\right)\left(1 + t_i^r\right) X_{is}^r = \sum_{f=1}^{F}\sum_{s=1}^{R} \pi_{(N+f)s} \overline{V}_f^{rs} + \sum_{i=1}^{N} R_i^r$$

where τ_i^r and t_i^r are the specific tax and ad valorem tax on consumption of good *i* in region *r*, respectively. R_i^r is the revenue generated from taxes on good *i* in region *r*. The equation above is related to the income of the representative consumer in each region. The value of total consumption net taxes is equal to the sum of the value of consumers' endowments and the tax revenue from consumption (budgetary interdependcy). This is known as the income balance condition. Alternatively, we can write (5) to show income balance for government and consumer expenditures in region *r*, respectively.

$$(5) \qquad \sum_{i=1}^{N}\sum_{s=1}^{R}\left(\tau_i^r + \pi_{ir}t_i^r + \tau_i^r t_i^r\right)X_{is}^r = \sum_{i=N}^{N} R_i^r \text{ and } \sum_{i=1}^{N}\sum_{s=1}^{R}\pi_{ir}X_{is}^r = \sum_{i=1}^{N}\sum_{s=1}^{R}\pi_{(N+f)s}\overline{V}_f^{rs}$$

This formulation, based on trade with tariffs, serves as an ideal platform to discuss how to incorporate critical infrastructure in general equilibrium models because it concerns the movement of factors and goods across space. An infrastructure good or service (e.g., electricity generation, transport services) can be incorporated as an additional good in the set of goods. The formulation captures the economy-wide responses (geographic, functional, budgetary and market-based interdependencies) through the final bundle of *N* goods. However, it does not explain *how* goods move and *who* moves them. Thus there are needs to address the engineering features of the critical infrastructure problem in this formulation by capturing physical infrastructure characteristics (*how*) and operational/operator and level of control (*who*) within this framework.

3.2 Incorporating Infrastructure Networks

It is first necessary to distinguish infrastructure *firms* from the infrastructure *networks*. Many industrial sectors (e.g., agriculture, manufacturing) purchase infrastructural goods (e.g., electricity) as inputs to production. Industrial sectors also purchase transportation services (e.g., freight trucking) to move their intermediate inputs for production and/or good to the market or directly to consumers. In this context, the electricity good and transportation services sectors are infrastructure *firms*. These infrastructure firms operate on their respective infrastructural *networks* and incur the network costs directly as part of the production of their good and service.

Physical infrastructure is generally characterized by critical nodes of activity and the flow of activity between the critical nodes via links in the form of a network. In this context, a region of economic activity is represented as a node, and the transport path of good is represented as a link. Important attributes of any infrastructure network for this research are the connectivity between nodes, the rate of flow on links, link capacity, link cost, and any restrictions on link flow (capacity 0 for certain goods). This can be represented mathematically by a finite digraph, a source and sink node, a cost function for each link, and a capacity function (Even and Even, 2012).

In the context of most SCGE models, regions are defined as critical nodes of economic activity and all regions are linked to one another through some transport cost for goods or through the purchase of transport services as a distinct sector. This is a reasonable assumption for many applications; however, its validity is questionable in problems where the flow itself is important. This is especially evident in regional cases where goods must be physically transported between regions via other regions and when there may exist limitations in the movement (e.g., disaster, defense, capacity constraints, geographic barriers). Buckley (1992) and Lofgren and Robinson (2002) introduce a spatial-network general equilibrium model with a finite digraph between regions for a transportation network. Conrad (1997) and Conrad and Heng (2002) incorporate a congestion function on links between regions to represent cost and capacity. Consistent with the objective of this research, the ICGE model requires the extension of spatial-network general equilibrium to incorporate transportation and energy infrastructures seamlessly.

While the above research has focused on a single infrastructure system or with exogenous transportation costs (e.g., Buckley, 1992), Zhang (2010) and Zhang and Peeta (2011) elegantly combine the SCGE elements with a multi-layer infrastructure network flow problem by introducing an endogenous generalized cost function. The representation of the multilayer infrastructure network is shown in Figure 3.

A generalized cost for each individual infrastructure is used to create equilibrium in multiple infrastructure networks simultaneously and can take the form of cost, time, or risk of disruption. This fully represents network characteristics and works well in their problem context, namely system risk and robustness where they bound the economy to infrastructure and test effects of different levels of interdependence via the elasticity of substitution. However, this may be problematic in an economy-wide application.

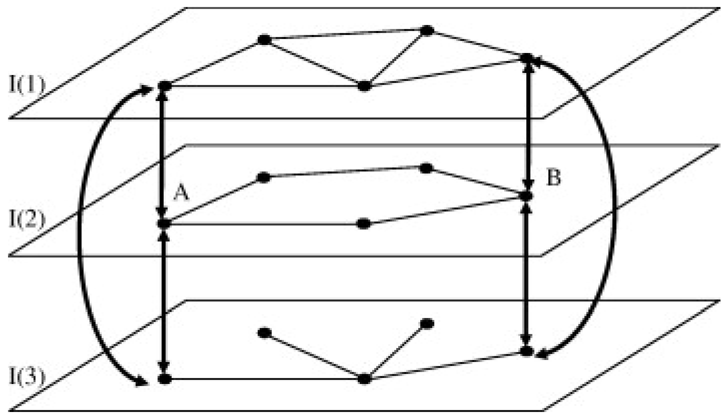

Figure 3: Multilayer infrastructure network (MIN) framework.

Source: Zhang and Peeta (2011)

In Figure 3, I(i) represents infrastructure network i. Horizontal links represent linkages in a single infrastructure network and vertical links represent inter-infrastructure linkages.

Typically in SCGE models, the mechanism for substitution between goods and services is price (or relative price) difference. It is unclear how generalized costs of different infrastructure with unique physical characteristics and unique provision of needs to the firms or consumer can be used in this context (i.e., relative generalized costs between infrastructure systems are not comparable). Substitution based on generalized costs may require a great deal of finesse in estimating parameters, much of which are not readily available in literature. Also, it is unclear how generalized (not actual) costs impact income to consumer and firm budgets.

Also, Zhang and Peeta (2011) use elasticities of substitution between infrastructure systems. This implies that one infrastructure *network* (e.g., transportation) is directly substitutable for another (e.g., electricity). In reality, a firm seeking to minimize cost (maximize profit) will purchase infrastructure goods/services from other infrastructure *firms*. Elasticity of substitution should be based on relative infrastructure good/service prices from *firms,* not the *network* price/cost itself.

The remedy for the application in this research is straightforward. First, the actual cost is used in lieu of a generalized cost. Second, the cost structure of firms represented by an input-output table is based on goods and services input prices (function of network cost) from other firms. This substitutes explicit interdependencies between infrastructure systems for implicit interdependencies resulting from economic structure. The cost structure discussed heretofore seamlessly integrates with SCGE models where firms act as profit maximizers; other decision-making components are treated implicitly and transmitted via prices. Infrastructure firms which may not act as profit maximizers is discussed in the following section.

3.3 Recognition of Network Operators

Differentiating from many industrial sectors, infrastructure systems (e.g., electricity, transportation) are often operated fully or in part by governmental organizations. Which infrastructure system is controlled by private firms and which is controlled by public firms vary greatly from region to region. It is necessary to specifically separate government sectors and government-controlled infrastructural firms from private firms to acknowledge the difference in operative control for a particular region and study. As an example, in the United States energy production and distribution, and transportation services are privately owned and operate as profit maximizers, in general. This fits seamlessly in SCGE assumptions. However, transportation networks (e.g., highways) are operated by the government and other transportation (e.g., railroad, aircraft) and energy networks are regulated by the government. Operation and regulation (i.e., investment and control) may not follow profit maximizing behavior. Assuming profit maximizing behavior (e.g., tax collection on links) may explain some behavior on part of government operated networks; however, this may not be plausible in the real world context. This research treats operation and regulation of partly or wholly government operated infrastructure networks (in terms of investment, control, tax, and other policies) exogenously to investigate how an economy responds endogenously.

Another dimension important in the policy context is the regional bureaucratic landscape. Using the United States transportation network as an example, regional departments of transportation (DOTs) are responsible for roads in their region (namely, state). They accrue a budget via taxes on various goods and services within the region as well as grants from the federal DOT. The federal DOT accrues a separate budget via taxes on various goods and services and provides funding to state DOTs for interstate investment as well as other regional and interregional projects. Both the method of accumulating a budget and investment behavior of regional and interregional government agencies can be significantly different. To fully reflect budgetary interdependencies of the problem, regional and interregional government must be distinguished.

3.4 Putting It All Together

ICGE tracks the circular flow of the economy between regional households, firms, government, and infrastructure as well as the between regions via interregional infrastructure. Similar to traditional CGE models, households receives payments (e.g., income) from firms in exchange for factors of production (e.g., labor, capital). Households expend incomes in exchange for goods and services from firms. Firms exchange goods and services with other firms, as well. The government receives factors, goods and services, and taxes from households and firms in exchange for governmental goods and services and subsidies.

Different from traditional CGE models, infrastructure networks are identified explicitly. Infrastructure firms, a subset of firms in the economy, incur cost (expenditure) to facilitate movement of their goods across space. This becomes an explicit portion of the cost share represented in an input-output table. The expenditure is distributed to appropriate firms (e.g., fuel, power loss as function of distance) and governmental receipts (e.g., tax). Regional infrastructure is also subject to investment and control from regional government. A portion of the regional government budget (from receipts from households, firms, and infrastructure) is allocated to regional infrastructure. Investment and control directly connects with the link existence, capacity, and cost function. Households' infrastructure use provide expenditures to regional infrastructure in exchange for personal mobility (e.g., transportation, telecommunication).

Regional infrastructure links to interregional infrastructure which links it to other regional economies. A firm in region *s* must make expenditures to region *s* infrastructure, interregional infrastructure, and region *r* infrastructure to move goods and services between regions *s* and *r*, provided there is a connected digraph between the regions. Interregional (e.g., federal) government may receive receipts from interregional infrastructure or even regional households, firms, and governments, and are redistributed in the regional economies. Here, firms in each region choose the least cost (or profit maximizing) path for their production, explicitly accounting for spatial differences and network effects. The path may change due to policy shocks (e.g., investment, tax) on the regional and interregional infrastructure networks.

Figure 4 shows an illustrative depiction of the connections, circular flow and interdependencies in the ICGE model. *Physical* interdependencies are captured in each region. If infrastructure is impaired in a particular region, it can be modeled by adjusting the network digraph or regional infrastructure cost functions and capacities appropriately. *Functional* interdependencies are captured via elasticities of substitution between goods and services which utilize independent infrastructure. Similarly, *market-based* interdependencies are captured in the circular flow of value between consumers, firms, and government. *Budgetary* interdependencies are captured in the distribution of regional and interregional government receipts to individual regional and interregional infrastructure.

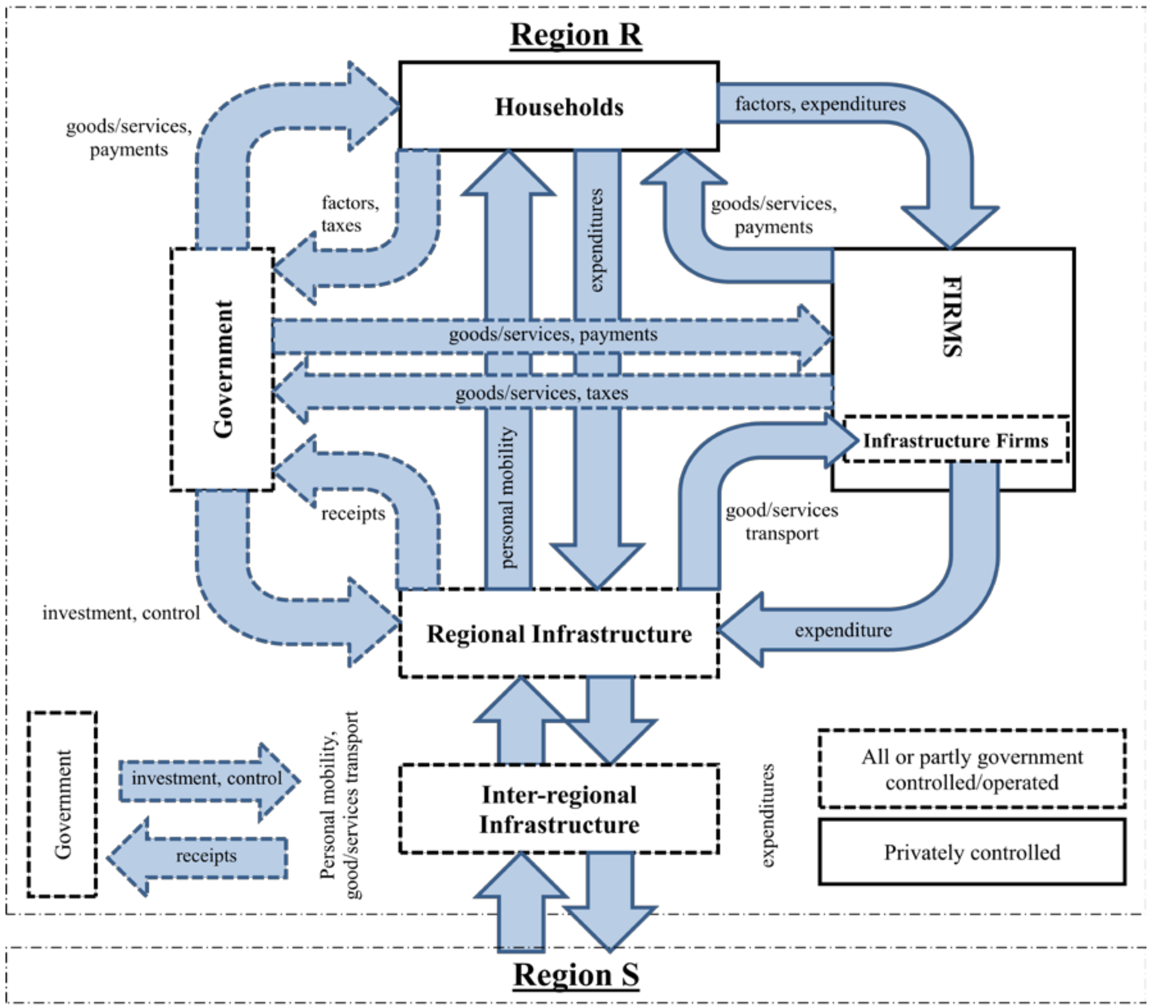

Figure 4: Circular flow of economy in ICGE

3.5 Analyzing energy and transportation

The proposed integrated system-of-systems based analytical framework (as shown in Figure 5) combines the engineering and economic approaches for modeling the interdependencies between energy and transportation sector. It also captures the effect of various types of policy instruments on these two sectors.

This framework consists of three layers; policy instrument layer, individual infrastructure layer and interdependent modeling layer. The individual infrastructure layer consists of two infrastructure systems, namely energy and transportation. The interactions between these two systems are captured by ICGE model in the interdependent modeling layer. The objective of the policy instrument layer is to evaluate policy instruments like regulatory, operational, subsidy and fiscal based on a performance metric (e.g. GHG emissions) provided by ICGE model.

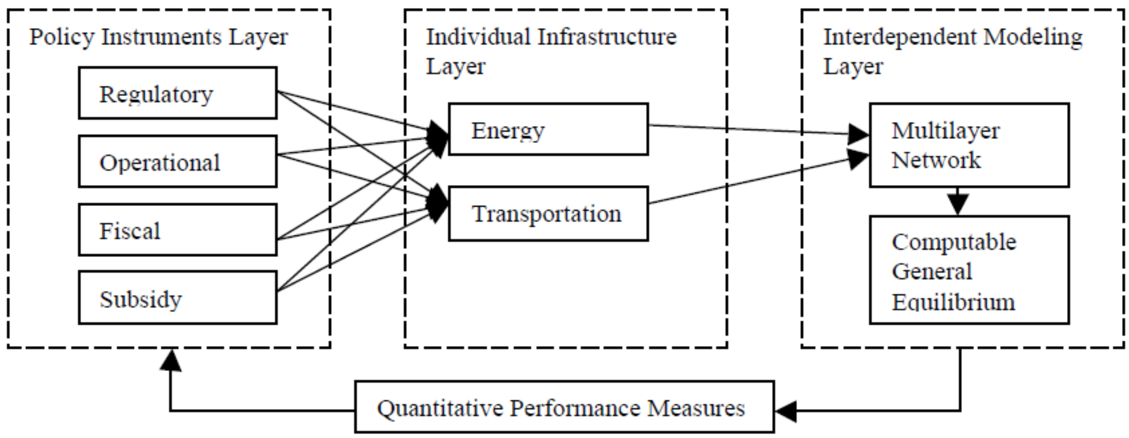

Figure 5 Three layers of interconnected SoS-based analytical framework

CHAPTER 4. EXAMPLE OF INTERDEPENDENT INFRASTRUCTURE PROBLEMS

4.1 Introduction

Currently policy goals of the government agencies are focused on one sector at a time. As such, the policy instruments are evaluated by the government agencies based on the performance metrics targeted towards the energy and transportation sectors separately. These policy decisions may be sub-optimal as they fail to capture the emergent general equilibrium that evolves due to the inherent interdependencies between these two sectors. In this chapter, two examples are presented to explain the system-of-systems based analytical framework as illustrated in Section 3.5. These examples evaluate subsidy and regulatory policy instruments, the former being directed at transportation sector and the latter at energy sector.

4.2 Example 1: Subsidy for electric vehicles

This example evaluates the subsidy instrument adopted by the government in the form of subsidizing electric vehicles (EVs). In effect, more households will be encouraged to use EVs. This will lead to increase in EV market penetration and hence, decreased conventional vehicle usage. This will result into a new equilibrium state for the transportation infrastructure. Due to apparent interdependencies between energy and transportation infrastructures, an increase in electricity demand as well as decrease in gasoline demand is expected. The increased electricity demand will necessitate elevated electricity generation by power generating firms. This will increase the demand for using transportation infrastructure to satisfy the higher demand for required raw materials (e.g. coal) by power generating firms. Increase in electricity demand will also require improvement in energy infrastructure (e.g. transmission capacity). At the same time, decrease in gasoline will decrease the need for transportation of gasoline. The reduced gasoline consumption will also lead to reduced tax collection which will affect the highway maintenance fund. All these interactions will evolve into a new equilibrium that can be modeled using ICGE framework.

4.3 Example 2: Dynamic electricity pricing

Government desires to evaluate the regulatory policy instrument in the form of dynamic electricity pricing scheme. According to this policy the electricity distribution firms are advised to implement different electricity pricing for day-time (peak hour) and night-time (off-peak hour). In effect, EV users are encouraged to charge the vehicle battery during night-time. This will lead to increase in electricity consumption during off-peak hours and thereby balance the load factor for electricity generating firms. This will result in decrease in operating cost for EVs which can affect travel demand pattern in the long run. This will lead to new equilibrium for transportation infrastructure. Due to interdependencies between the energy and transportation infrastructures, this will result in change of electricity hourly usage pattern, thereby changing the operations of the energy sector (in particular energy generation and distribution firms). All these interactions will evolve into a new general equilibrium.

These two examples illustrate how the proposed framework can be utilized for making optimal policy decisions.

CHAPTER 5. CONCLUDING COMMENTS

5.1 Summary and Conclusions

This report discussed a formal and general framework for analyzing interdependent critical infrastructure. By adding engineering detail into a spatial computable general equilibrium model, we can (1) seamlessly integrate additional infrastructure systems (models, theories designed only for a handful of systems rather than for all); (2) explicitly incorporate economic and industry responses to capture both the system-wide and economy-wide impacts; (3) explicitly account for the physical infrastructure characteristics (network, capacity, performance, etc.); and (4) explicitly recognize the operators and level of control of the infrastructure. A SoS framework is presented for analyzing the interdependencies between the transportation and energy sectors. It can act as valuable tool for policymakers for designing policy strategies using holistic approach.

5.2 Remaining Problems

This research presents a holistic framework for modeling the interdependencies between the transportation and energy sectors. Extensive computational experiments are required for evaluating the proposed framework. Due to lack of data the computational experiments could not be performed.

In addition, several theoretical issues persist including time dynamics, tractability, and solution methods. The CGE framework also allows for a straightforward extension to time dynamics; however computational time has not been explored and may entail computational tractability issues. This is especially true when introducing additional infrastructure networks (e.g., translating a general transportation network into highway, non-highway, rail, air, and marine networks where investments are made). Also, currently there is no explicit consideration of opportunity cost. For instance, one route may be cheaper, but slow. There is no tradeoff between time and cost in the model since it considers the long-run. This could be remedied via a discounting factor in a dynamic model. Zhang and Peeta (2011) presented a generalized cost function to elucidate tradeoffs between many decision variables beyond cost. Another theoretical issue is whether the non-linearity introduced with networks in the system of equations will have a unique solution.

SCGE models primarily use multiregional input-output tables and elasticities to describe the global economy. Input-output tables describe the current circular flow of goods in the economy. The values of inputs from each input sector are tabulated in the rows of each end-use sector output column. A production structure describes how values of different inputs can be substituted. A commonly used method is the constant elasticity of substitution (CES). Other data such as emission per unit of production are easily integrated for post-processing. In addition to the SCGE data, ICGE requires network data (finite digraph, link capacities, and cost function) for each infrastructure (e.g., transportation, electricity, energy pipeline) and identification of private versus government operators.

The potential key limiting factor in implementing this framework is related to empirical data availability (or lack thereof). Regional general equilibrium models exist; however, as discussed before, infrastructure is treated implicitly. Data necessary to disaggregate infrastructure costs from the existing input-output tables is not always readily available and inevitably requires "educated guesswork" on behalf of the decision-makers. Similarly, elasticities of substitution are often not directly measurable and require careful calibration. Also, capacity and cost functions of infrastructure networks are not always directly commensurate with available data. This may introduce uncertainty in the model.

5.3 Future Research

Potential future directions are as follows. First, an explicit mathematical representation of the network and operator features should be developed and relevant solution methods should be explored. Second, the construction of necessary input data from existing input-output tables informed by engineering data is necessary. An on-going study by the authors seeks to evaluate the performance of transportation sector due to the increase in the market penetration of electric vehicles.

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