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Simulating the Impact of Strategy Development Frameworks on Transportation Infrastructure System Performance

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ABSTRACT

This paper develops, through a simulation model, a deeper understanding of the relationship between transportation infrastructure strategy development frameworks and system performance. A strategy development framework for transportation can be characterized by the infrastructure ownership structures, cross-modal and cross-sectoral linkages, revenue sources, resource allocation decision-making processes, and geographic scales of the organizations responsible for making infrastructure investments. Taking the dimensions of a strategy development framework as inputs, the model simulates investments in an infrastructure network over time—in this paper, the national intercity roadway network of Portugal. The results demonstrate the value of using simulation models of complex transportation systems to inform the decisions of not only planners but also of stakeholders who design strategy development frameworks. Such a tool is particularly important given the ongoing reorganizations of the Portuguese transportation sector, including increasing reliance on concession agreements, highway tolls, and sub-national government participation.

INTRODUCTION

Transportation infrastructure system users, operators, planners, and owners constitute a set of distinct stakeholders, each making strategic decisions and investments toward fulfilling its own objectives for system performance. Ultimately, however, transportation system performance is a function of interactions among and decisions taken by all stakeholders. These interactions complicate efforts at large-scale infrastructure planning (e.g., for metropolitan areas or countries) and prediction of future system characteristics and performance.

For purposes of this research, we call the environment within which interactions and decisions among organizations occur the *strategy development framework*. A strategy development framework for transportation can be characterized by the infrastructure ownership structures, cross-modal and cross-sectoral linkages, revenue sources, resource allocation decision-making processes, and geographic scales of the organizations responsible for making infrastructure investments. While strategy development frameworks can be evaluated to a modest extent by inspection (or by "common sense"), we can more easily measure and evaluate the relative performance of the transportation systems they produce.

This paper develops, through a simulation model, a deeper understanding of the relationship between strategy development frameworks and system performance. Taking the parameters of a strategy development framework as inputs, the model simulates investments in an infrastructure network over time—a network (in this paper, the national intercity roadway network of Portugal) whose simulated performance we can measure. The results demonstrate the value of using simulation models of complex transportation systems to inform the decisions of not only planners but also of stakeholders who design strategy development frameworks. We offer direction for further refinement and development of this simulation approach as well as thoughts on future research in this area.

LITERATURE REVIEW

The identification, definition, characterization, and simulation of *strategy development frameworks* in this research builds upon past efforts to understand complex systems. While complexity has long been present in natural and engineering environments, its formal scientific study moved forward quickly in the mid-20th century. In that era, Simon defined a complex system as one "made up a number of parts that interact in a non-simple way" such that "it is not a trivial matter to infer the properties of the whole" (*1*). Reductionist approaches, therefore, must maintain a holistic view of the system in question.

Nightingale and Rhodes offer *enterprise architecture* as a framework for characterizing and understanding complex systems, comprising eight "views": strategy, organization, information, knowledge, services, products, processes, and policy (*2*). Their framework specifies methods for evaluating an enterprise according to these views, and how to approach transitions to the architecture in pursuit of future desired states, but for a single organization such as a company.

Transportation systems as with other complex systems, however, comprise many organizations and many stakeholders, which introduces evaluative complexity (stakeholders have competing views of "good" performance) and nested complexity (organizational layers and physical layers of a complex system interact in unpredictable ways). Sussman, et al. introduced the notion of Complex, Large-scale, Interconnected, Open, Socio-technical (CLIOS) Systems and applied the CLIOS Process (for representation, evaluation, and implementation of changes to CLIOS Systems) to a number of contexts, including transportation systems (*3*). Although the

CLIOS Process provides a guiding framework for capturing various types of complexity, it is not tied to any particular qualitative or quantitative approaches.

Our approach, an agent-based simulation model, follows the CLIOS Process by relating the organizational layers of a complex system (i.e., the strategy development framework) to the physical layers (i.e., the transportation system). Previous such efforts in the transportation arena are relatively sparse, although agent-based models have been used for a variety of other purposes in transportation, particularly to simulate traffic and to forecast travel demand (e.g., *4*, *5*, *6*). More recently, Xie and Levinson developed a model of infrastructure network evolution that has a similar structure as the model presented here, viewing the network as an emergent outcome of a variety of interactions, including organizations' responses to economic and political forces (*7*). They observed the long-term construction and evolution of a hypothetical network beginning with few links under various frameworks, but considered principally changes in the degree of centralization of investment decision control.

The model presented in this paper builds on past efforts by considering in an integrated fashion the impact of the various parameters that compose a strategy development framework on system performance. Additionally, we execute the simulation using data from the real, largely-built Portuguese intercity highway network. In the following sections we describe the characteristics of a strategy development framework, the simulation model structure, and the results, which help us to understand more clearly the relationship between a framework and system performance.

STRATEGY DEVELOPMENT FRAMEWORK
To allow a more tractable, systematic description of a strategy development framework, we decompose it into seven dimensions as illustrated in Figure 1a. Characterization of a particular instance of a strategy development framework is accomplished by selecting a discrete value or combination of values along each of these dimensions, as shown in the figure and as described below:
- Ownership structure: state-owned enterprise (SOE) and concession
- Revenue sources: general taxes and user fees
- Revenue level: any value selected from a continuous or discrete spectrum (e.g., high-medium-low)
- Resource allocation criterion: net present value (NPV), benefit-cost ratio (BCR), and financial internal rate of return (IRR)
- Geographic scale: link-based, municipal (232 municipalities), national-municipal hybrid, regional (5 regions), and national (note that these geographic scales are specific to the context of Portugal as illustrated in Figure 1b; "national" corresponds to the mainland territory of Portugal)
- Degree of modal integration: uni-modal and multi-modal
- Degree of sectoral integration: integrated and unintegrated

(a)
Geographic scale
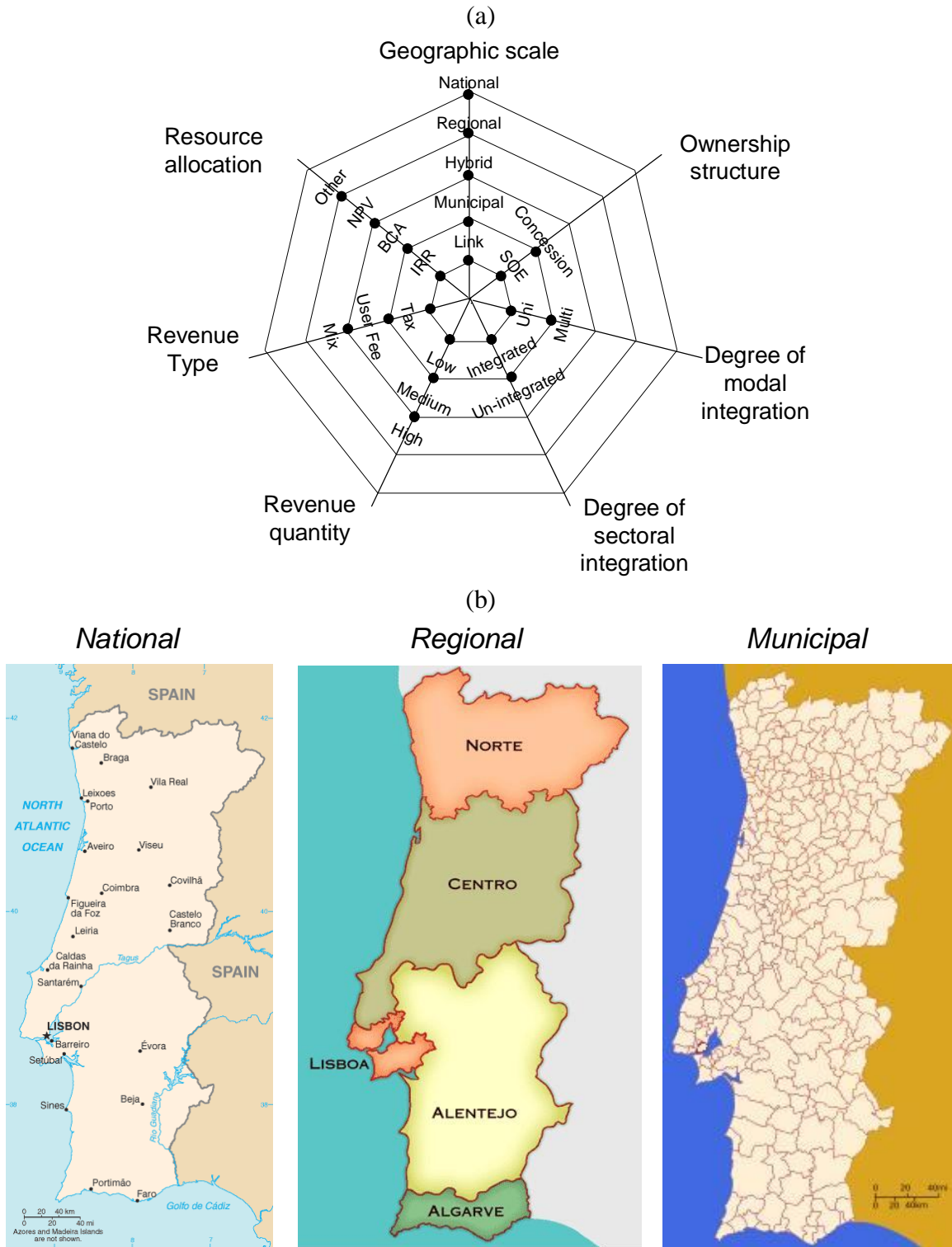

(b)

| *National* | *Regional* | *Municipal* |

FIGURE 1 – (a) Strategy Development Framework and (b) Illustration of Alternative
Geographic Scales in Portugal

By combining all the possible values (and combinations of values) along each dimension, it is possible to characterize several thousand distinct alternative strategy development frameworks. Some of these frameworks approximate those observed in real contexts; however, most are hypothetical, while many are altogether infeasible, either logically or technologically. By making judgments about the logical, technological, and/or practical feasibility of the various alternatives, we down-selected 105 frameworks to study in further detail using the simulation model. The model is described next.[1] *Examples* of the frameworks selected for further examination (8 of the 105) are shown in Table 1.

TABLE 1 – Examples of Strategy Development Frameworks Simulated (8 out of 105)

Geographic Scale	Ownership Structure	Revenue Type	Revenue Level	Resource allocation criterion
National	SOE	Tax	High	BCR
Regional	SOE	Tax-Toll Mix	Low	NPV
Hybrid	SOE	Tax	Low	BCR
Municipal	SOE	Toll	Medium	BCR
Link-Based	Concession	Toll	Low	IRR
National	Concession	Toll	High	IRR
Link-Based	SOE	Tax	High	BCR
Regional	SOE	Tax	High	NPV

SIMULATION STRUCTURE

The simulation model is conceptually an agent-based model, which includes four components: an environment, rules, agents, and outputs (*8*). The simulation comprises five modules as illustrated in Figure 2 and as described below. In agent-based modeling terms, the **environment** is represented by Portuguese population demographics, the physical infrastructure network, and travel demand (modules 1-3), **rules** are reflected in the project evaluation and investment strategy decision processes (modules 4-5), **agents** are defined as the entities (government agencies or private companies) that decide investment strategies (module 5), and the **outputs** include a set of investment decisions (module 5) and an updated infrastructure network (module 2).

1. The **demographic data module** contains population data for each municipality in mainland Portugal for the years 1995-2008.
2. The **network module** is a collection of 375 links (highway segments) and 232 nodes (municipalities) describing the intercity highway network in Portugal.
3. The **travel demand module** assigns trips to each link in the network based on the definition of the network from the network module and population information from the demographic module.
4. The **project evaluation module** determines the benefits, costs, and other impacts associated with various proposed projects based on inputs from the travel demand module.
5. The **investment strategy module** uses information from the project evaluation module together with budget constraints to select projects for implementation.

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[1] Note that in the simulation model, we consider only uni-modal and sectorally unintegrated strategy development frameworks.
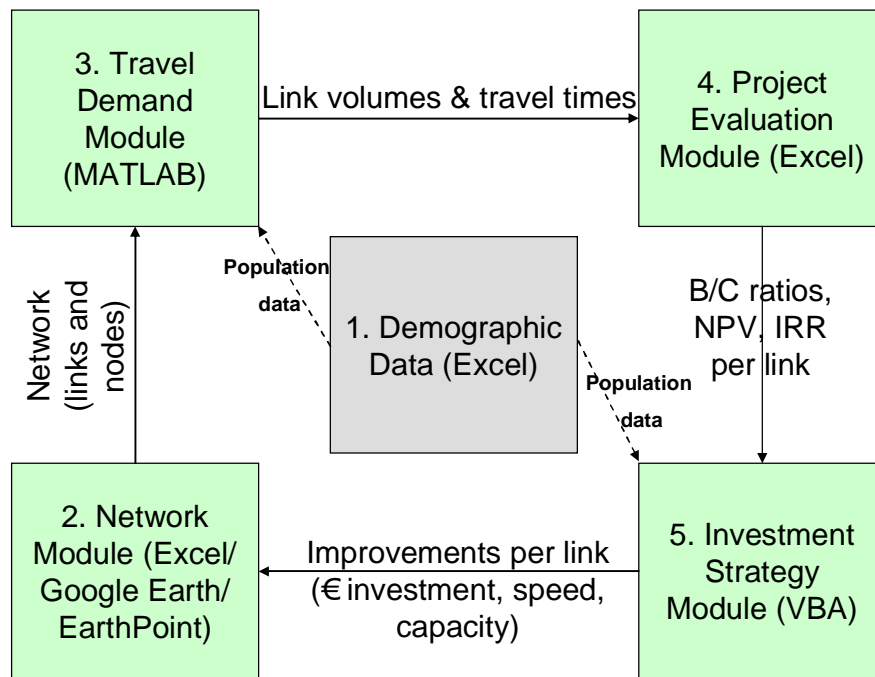
FIGURE 2 – Model Structure

Each run through these modules represents one year in time. Although the simulation could run for any number of years, we chose 14 years based on availability of data. In the following subsections, we discuss each module in detail.

Demographic Module
The demographic module contains population data for each municipality in mainland Portugal for the years 1995-2008. Data were obtained from Portugal's National Statistics Institute, which maintains census data as well as annual population estimates (*9*). In 2008, there were 278 municipalities in mainland Portugal ranging in population from 1,714 (Barrancos) to 494,631 (Lisbon). The average population was 36,443, and the median population was 16,369. For modeling purposes, some municipalities were merged and treated as a single node. In addition, 5 external zones were added to represent municipalities in neighboring Spain with important highway connections to Portugal. After making these adjustments, the demographic module contains 232 municipalities.

Network Module
The network module is a database describing the intercity highway infrastructure network in Portugal. We define the network as the collection of nodes (municipalities) and the links (highway segments) that connect them. For purposes of this modeling exercise, we omit other travel modes. Although rail and air are available in a few intercity corridors in Portugal, highway remains the dominant choice; for the top ten domestic city pairs, only 6% of trips are by rail and less than 1% by air (*10*).

The starting point for the simulation model is 1995, near the start of an era of major infrastructure upgrades in Portugal and three years prior to the publication of the National Roadway Plan (Plano Rodoviária Nacional, or PRN) (*11*). Constructing an accurate

representation of the highway system as it existed in 1995 is based on review of contemporary maps, historical maps, satellite imagery, and official documentation of highway investments from the state-owned highway company *Estradas de Portugal* (EP), concessionaires, and Google's map service (*12*).

The PRN defines three categories of intercity highways in Portugal: principal routes (IPs), complementary routes (ICs), and national roads (ENs). All 9 IPS, all 34 ICs, and a majority of the ENs (90 out of 170) are included in the network module. Each of these highways is broken into segments, or links, drawn to connect municipalities. In all, there are 375 links, 341 of which existed in 1995. The remaining 34 are in the PRN and are represented in the 1995 network as "proposed" links. Each link is two-way and has the following characteristics.

- Terrain. Terrain takes one of the following values: flat, hilly, or mountainous.
- Land Use. Land use takes one of the following values: urban, suburban or rural.
- Length. Length of the path (travel distance) followed between two nodes, measured in kilometers.
- Design speed. Links can have a design speed of 60, 90, or 120 kilometers per hour (kph). Links with a design speed of 120 kph represent motorways (IPs and some ICs); links with a design speed of 90 kph design represent non-motorway ICs; links with a design speed of 60 kph represent ENs.
- Number of lanes. The number of lanes of any link is identical in both directions and takes a nonnegative integer value (unbuilt-but-proposed links have 0 lanes).
- Capacity. The capacity of a link is reflected in passenger cars per hour per lane (pcphpl) in each direction. Capacity is a function of the speed according to the relationship defined in the Highway Capacity Manual (*13*).

Travel Demand Module
The travel demand module predicts the volume of travel on each link in the intercity highway network of Portugal, drawing on data from the network and demographic modules. This is accomplished using a simplified aggregate 4-step model, with trip generation and distribution based on a traditional Zipf gravity function of the form (*14*):

$$T_{ij} = a \frac{P_i P_j}{C_{ij}^b} \text{, where}$$

T_{ij} = total number of trips from municipality i to municipality j.
P_i = number of inhabitants of municipality i
P_j = number of inhabitants of municipality j
C_{ij} = shortest-path free-flow travel cost (including time) between i and j in minutes
a and b are parameters

As previously indicated, all trips are assigned to the highway network, reflecting the dominance of the auto mode for intercity travel in Portugal. Finally, trips are assigned all-or-nothing to the shortest path. The all-or-nothing assignment allows us to see the "desired" routing of users, which is an important input for the next module (project evaluation). More pragmatically, however, our simulation represents intercity links with an average length of 25 km. Few motorists would in reality re-route on long-distance trips in order to avoid congestion. This was verified by comparing the results of the all-or-nothing approach to an incremental trip assignment (which accounts for congestion). Only 7 links out of 375 saw a change in trip volume

of greater than 250 trips per day, all of them associated with a single bottleneck in the Porto metropolitan area. Calibration of the model was conducted using measured vehicle flows available for 45 of the 375 links in the network, obtained from EP's data collection system (*15*).

Project Evaluation Module

The project evaluation module enumerates and evaluates each of the possible improvements to the national highway network. In any year, there is *exactly one project* associated with each link in the network. Project alternatives are: do nothing, add one lane in each direction, or improve design speed one level (i.e., from 60 to 90 kph or from 90 to 120 kph).

For any given time period there are 375 proposed projects (one for each link). For uncongested links with a design speed of 120 kph, the "project" is, by definition, "do nothing." The project evaluation module computes several pieces of information related to each of the proposed projects, broadly categorized as costs and benefits. All cost and benefit values used in the model are in constant 2008 euros.

Construction cost is calculated as a function of the terrain, land use, and length of the project and is based on approximately 2,000 km of proposed new highway construction cost estimation data in Portugal (*16*), cross-checked against a Washington State DOT survey of construction costs in the U.S. (*17*). Meanwhile, the present value of life-cycle cost is computed as the total discounted cost of ownership, including initial construction costs and discounted annual maintenance costs.

Benefits of each project computed within the model include travel-time savings and, in some cases, revenues. Travel-time savings for each project can result from congestion reduction as well as design speed improvements and are computed over the same time horizon as life-cycle costs. The other potential source of project benefits is toll revenues. Tolls typically represent an intra-jurisdictional transfer from users to the infrastructure provider and should not be treated as a benefit. However, in cases where non-local users are using the facility and contributing toll revenues, then toll revenues can be counted as benefits.

The computation of costs and benefits allows us to construct several metrics: benefit-cost ratio, net present value, and financial internal rate of return (IRR).

Strategy Development Module

The fifth and final module is the strategy development module. Here, agents (infrastructure providers) make investment decisions in each project on the basis of the metrics computed in the project evaluation module, subject to additional rules which include budget constraints and multi-agent negotiations. The outputs of this investment decision-making process are investment decisions for each of the proposed projects.

The type of agents are determined based on the characterization of ownership structure in the strategy development framework. If the ownership structure is a state-owned enterprise, then agents represent governments and select projects on the basis of either benefit-cost ratio or net present value. If, on the other hand, the ownership structure is concession, then agents represent private concessionaires and select projects on the basis of financial IRR. Agents representing the government will make investments until their budgets are exhausted, while agents representing private concessionaires will only make investments with an acceptable IRR.

Agents have resources available to them for investment in the infrastructure network which are a function of the type and level of revenues. Alternative revenue types include general taxes and user fees (or a mixture of the two). However, the allocation of revenues to agents

depends on the number of agents, which is a function of the geographic scale. Alternative geographic scales are summarized as follows:

- National. With a nationally scaled government, there is only one agent making investment decisions for all 375 links across the entire nation.
- Regional. With regionally scaled organizations, there are 5 agents making investment decisions only for the links within their region.
- Municipal. Under this approach, there are 232 agents with decision-making autonomy. Their budgets are limited to whatever they collect in tax revenues from their residents and in tolls from users of incident links. Since each link is shared by exactly two municipalities, any decision to invest in a link must result from a negotiation and agreement between the two municipalities that share it. The negotiation process, described more fully in (*18*), involves an iterative bidding process among municipalities that ensures no municipality bids or pays more than its benefit for any single project and no municipality spends more than its budget on all of its projects.
- Hybrid. The hybrid approach is similar to the municipal approach, except that municipalities share a portion of their revenues equally. Two levels of revenue sharing are simulated: 25% and 50%. The mechanism works as follows: municipalities collect revenues, but contribute a portion (25% or 50%) of their budgets to a national pool; the national pool is then distributed in equal portions to each of the 232 municipalities.
- Link. This approach is perhaps the simplest. Under a link-based approach, the links themselves collect revenues. Toll revenues accrue to a link budget, while tax revenues are derived from the residents of neighboring municipalities. Links accumulate budgets and invest in projects whenever their budget is sufficient to cover the cost of the improvement. Although there are no prospects for this approach in Portugal, it is studied here to illustrate the full range of potential strategy development frameworks and their relative performance.

Simulation Process
One cycle through the five modules represents one year in time. At the end of each year, the model updates the network to reflect the new design speeds and number of lanes on each link; updates the budgets to reflect the amount of money invested as well as any unspent budget that can roll over into next year; and prepares the origin-destination matrix and free-flow travel times for the next year of the simulation. This process repeats for 14 cycles (14 years). Table 2 summarizes the variables employed in the various modules of the simulation model.

TABLE 2 – Values Used in Simulation Model

Module	Variable	Value in model
General	Start Year	1995
	End Year	2008
Network	Design speed – low	60 kph
	Design speed – medium	90 kph
	Design speed – high	120 kph
	Capacity – low speed	1600 pcphpl
	Capacity – medium speed	2250 pcphpl
	Capacity – high speed	2400 pcphpl
Travel demand	*A*	0.005
	B	1.80
Project evaluation	Evaluation time horizon	15 years
	Discount rate	5.0%
	Escalation rate (for value of time and maintenance costs)	1.4%
	Annual maintenance costs as % of construction costs	10%
	Passenger value of time (*21*)	€19.5 / hour
	% of peak-hour traffic in peak direction	65%
	K factor – rural (% of traffic in peak hour) (*12*)	20%
	K factor – suburban	13.5%
	K factor – urban	9.5%
Strategy development	Per capita tax rate – low	€39
	Per capita tax rate – medium	€65
	Per capita tax rate – high	€91
	Toll rate per km – low	€0.0166
	Toll rate per km – medium	€0.028
	Toll rate per km – high	€0.039
	Minimum IRR (*source: Brisa Company, unpublished*)	10%

RESULTS
Each simulation run produces a range of outputs, including a record of the evolution of the highway network over time (i.e., investments, capacity enhancements, and design speed improvements) as well as performance measures such as average network speeds, congestion and delay, number of trips, and accessibility.

As an illustration of the model outputs, Figure 3 shows four maps. Figure 3a is notional map of the Portuguese intercity road network as it existed in 1995. Figure 3b is a map of the 2008 network predicted by the simulation under the *actual* strategy development framework in Portugal, characterized by a nationally scaled state-owned enterprise using a mix of taxes and tolls to make investments prioritized by NPV. Figure 3c is a map of the 2008 network predicted by the simulation under a *municipal alternative* framework that is similar to the *actual* framework, with the major exception that it is municipally scaled rather than nationally scaled, meaning investments are decided by 232 independent municipal agents rather than a single national agent. For comparison, Figure 3d shows the highway network that existed in reality in 2008.
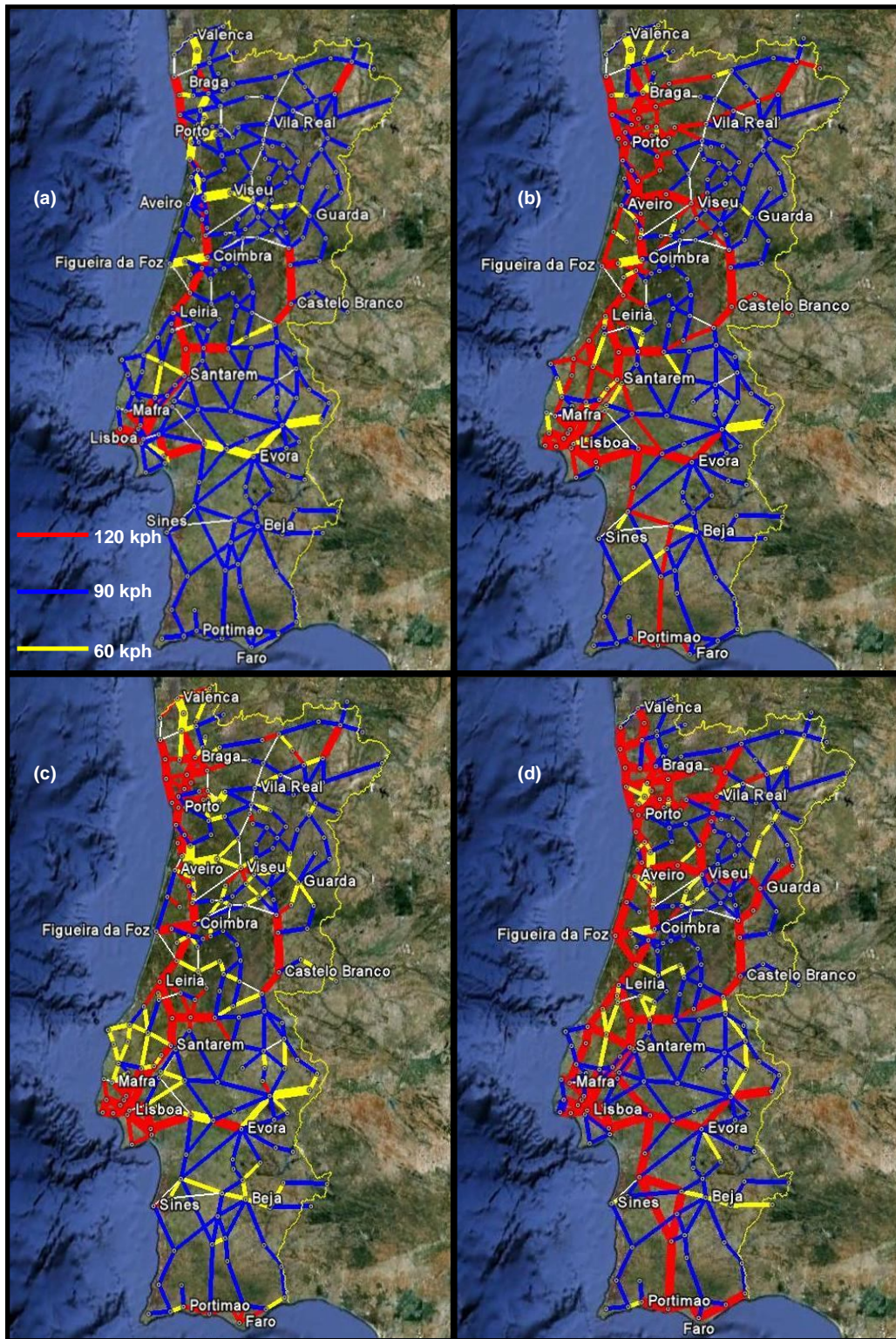
FIGURE 3 – (a) 1995 network, (b) model prediction of network under *actual* framework, (c) model prediction of network under *municipal alternative* framework, and (d) actual 2008 network

Several distinctions can be observed by visual inspection. Several high-speed corridors emerge in Figure 3b under the *actual* framework, including a new parallel high-speed route between Lisbon and Porto, a complete high-speed corridor from Lisbon to Faro, as well as several corridors in the northern interior, one linking Porto to the east with Spain, one linking Aveiro with Viseu, and a third extending from Santarém to Spain. In reality, each of these corridors was improved to motorway quality between 1995 and 2008. In addition, there were numerous capacity expansions in the Lisbon and Porto metropolitan areas as well as in and around several smaller metropolitan agglomerations between Lisbon and Porto. Between 1998-2000 the simulation constructed a second crossing of the Tagus River (a high-speed link with 2 lanes in each direction), connecting Lisbon with the suburbs to the south in Alcochete/Montijo. This link represents the Vasco da Gama Bridge, which in reality was completed in 1998. Overall, 89% of the links predicted in the simulation of the *actual* framework conform with the links observed in reality according to both design speed and capacity. By contrast, the network produced by the *municipal alternative* framework shown in Figure 3c sees no long-distance corridors, but rather some locally concentrated improvements in the major metropolitan areas and some midsized cities in the interior.

Table 3 summarizes several key performance metrics for the 2 frameworks (*actual* and *municipal alternative*) shown in Figures 3b and 3c, including financial metrics, traffic metrics, system performance metrics, equity, and others. In addition, we can compare some of these metrics with the metrics for the build-nothing scenario. For example, under the *actual* framework, there were 32.6 billion VKT in 2008, a 46% increase over the number of VKT in the build-nothing scenario. The *actual* framework resulted in higher levels of spending than the *municipal alternative* (€10.7 billion compared with €4.7 billion) over the 14-year simulation period. Not surprisingly, the *actual* framework also resulted in a network with less delay in 2008, higher peak and offpeak speeds, more stable spending year to year, and higher levels of accessibility both in constant terms and relative to the build-nothing scenarios. On the other hand, the *municipal alternative* framework provides more *cost-effective delay reductions*, a closer match of spending relative to population, and a smaller increase in low-speed (highly congested) VKT.

TABLE 3 – Performance metrics for baseline and municipal alternative frameworks

Performance metric		*Actual* framework: Value (Change from build-nothing, where applicable)	*Municipal alternative framework:* Value (Change from build-nothing, where applicable)
Total spending, 1995-2008 (€billions)		10.7	4.7
Average annual spending (€millions)		761	336
Total VKT in 2008 (billions)		32.6 (+46%)	28.6 (+28%)
Lane-km built, 1995-2008		714	365
Average peak speed (kph), 2008		100.6 (+29%)	91.2 (+17%)
Average offpeak speed (kph), 2008		118.1 (+21%)	114.4 (+17%)
Total delay (millions hours), 2008		10.7 (-88%)	29.1 (-69%)
€spent/hours delay reduced, 1995-2008		130	74
€spent/hour delay reduced per 1 billion VKT, 1995-2008		2,790	1,501
Total spending relative to population, 1995-2008	Urban	-9.7%	-0.8%
	Suburban	-2.0%	+2.2%
	Rural	+11.7%	-1.4%
Peak capacity utilization, 2008		88% (-31)	101% (-40)
Offpeak capacity utilization, 2008		24% (-14)	30% (-15)
VKT < 45 kph (millions), 2008		220 (+7%)	200 (+2%)
Year-to-year spending variability, 1995-2008		10%	45%
Number of trips (millions), 2008		957 (+42%)	908 (+34%)
Average trip length (km), 2008		34.1 (+3%)	31.5 (-5%)
Average peak trip travel time (minutes), 2008		20.3 (-20%)	20.7 (-19%)
Average offpeak trip travel time (minutes), 2008		17.3 (-15%)	16.5 (-19%)

The performance metrics presented in Table 3 are representative of the 78 total metrics available, while the *baseline* and *municipal alternative* frameworks are but two of the 105 total alternative frameworks tested. The full modeling results consist of a matrix of 78 metrics by 105 alternative frameworks and, in examining the total set of results, several trends become clear (refer to *18* for complete results). In the next section, we derive a more tractable set of results from these complete results that can be more easily interpreted for evaluating the alternative frameworks.

EVALUATION
In evaluating the 105 alternative strategy development frameworks, we face not only a range of metrics, but also a variety of stakeholders who value each metric in distinct ways, increasing the potential for conflict. In order to evaluate a complex system, then, we must consider this *evaluative complexity* (*19*). Judgment of the quality of any particular framework depends upon the values of the stakeholder through whose lenses the outcomes are viewed.

Determining which among the 105 alternative strategy development frameworks is "best" could be straightforward if we were interested in only a single metric, or if the views of only one stakeholder were important. For example, the *municipal alternative* framework described above

performs best out of the 105 frameworks tested if we are only interested in measuring the match between revenues and expenditures in urban areas. Alternately, we can combine more than one outcome of interest into a single metric. For example, the *municipal alternative* framework ranks 62nd out of 105 when measured by cost-effectiveness of peak hour speed improvement.

In the face of this complexity, we created 7 evaluation perspectives, each designed to reflect a unique stakeholder perspective:

- *Mobility*. Facilitate intercity travel and trade within Portugal.
- *Environmental protection*. Preserve the environment by limiting travel and minimizing infrastructure development.
- *Economic stimulus*. Invest in infrastructure as a means of providing jobs in the short-term and enabling economic growth in the long-term.
- *Territorial cohesion*. Provide broad access to high-speed intercity travel infrastructure.
- *Urbanization*. Relieve urban congestion by providing high-speed, high-capacity intra-metropolitan linkages to encourage metropolitan growth.
- *Fiscal equivalence*. Ensure a distribution of revenues that is equal in proportion to the population.
- *Fiscal austerity*. Reduce indebtedness by limiting spending in the infrastructure sector.

For each perspective, a unique set of weights was developed for each performance metric, as demonstrated by Brusilovskiy and Hernandez (*20*). The matrix of performance metric values is converted to a matrix of rankings, as shown in Figure 4a. Next, we apply a weight to each rank. For example, Figure 4b illustrates the weights for the mobility perspective and the rankings for the *actual* framework (peak speed is weighed 10.5%, and the peak speeds resulting from simulation of the *actual* framework rank 37th out of 105). Next, a weighted-sum ranking is computed for each framework (45.1 in the example in Figure 4b). Finally, we can determine which strategy development frameworks perform best for each perspective by comparing their weighted-sum rankings. For example, Figure 4c shows the top 10 frameworks for the mobility perspective. All are either regionally or nationally scaled, while most call for taxes, and all call for a medium or high level of revenues.

(a)

Framework \ Metric	Framework 1	Framework 2	…	Framework 105
PM 1	$V_{1,1}$	$V_{1,1}$	…	$V_{1,105}$
PM 2	$V_{2,1}$	$V_{2,2}$	…	$V_{2,105}$
…	…	…	…	…
PM 78	$V_{78,1}$	$V_{78,2}$	…	$V_{78,105}$

(b)

Performance metric	Weight	Framework Rank
Peak-hour speed	10.5%	37
Offpeak speed	10.5%	21
Peak-hour delay reduction	10.5%	58
Offpeak delay reduction	10.5%	38
Reduction in VKT <45 kph	10.5%	87
Increase in number of trips	10.5%	11
Accessibility improvement	21%	24
Cost-effectiveness of speed improvements	5%	89
Cost-effectiveness of delay reduction	5%	76
Cost-effectiveness of induced trips	5%	88
Capacity utilization rate	0	93
…	…	
Average trip length	0	26
Total	100%	**45.1**

Framework \ Metric	Framework 1	Framework 2	…	Framework 105
PM 1	$R_{1,1}$	$R_{1,1}$	…	$R_{1,105}$
PM 2	$R_{2,1}$	$R_{2,2}$	…	$R_{2,105}$
…	…	…	…	…
PM 78	$R_{78,1}$	$R_{78,2}$	…	$R_{78,105}$

(c) Top-performing framework for *mobility* perspective

Framework \ Performance	Geographic Scale	Revenue Type	Revenue Level	Decision-Making Criterion	Owner-ship Structure
17.2	Regional	Tax	High	BCR	SOE
19.4	National	Tax	High	NPV	SOE
19.7	Regional	Tax	High	NPV	SOE
19.8	National	Tax	Medium	BCR	SOE
21.0	Regional	Tax	Medium	BCR	SOE
25.2	National	Tax	Medium	NPV	SOE
25.9	National	Tax-Toll	High	BCR	SOE
28.0	National	Tax	High	BCR	SOE
28.3	Regional	Tax	Medium	NPV	SOE
28.8	National	Tax-Toll	High	NPV	SOE

FIGURE 4 – (a) Conversion of performance metrics to ranks, (b) example implementation of rank-weight procedure, and (c) top performers for mobility perspective

Similar computations were made for each of the 7 perspectives, and the top performing framework in each is summarized in Figure 5a. Determining a top single performer across all perspectives is difficult, given the evaluate complexity, overlap of constituent performance metrics across perspectives, and loss of some information in converting performance metric values to ordinal ranks. However, we can gather some understanding of the relative value of each framework by measuring performance across all 7 perspectives in several ways and by reporting the top several performers. In Figure 5b, we show the top 5 frameworks according to their *average* performance across all 7 perspectives. By contrast, in Figure 5c, we show the top 5 frameworks according to their *best "worst ranking"* for any single perspective. Interestingly, the same framework (nationally scaled, tax revenues, low level of revenues) was ranked as the best in both cases. Next, we discuss some of the key implications of these results.

(a)

Perspective \ Framework	Geographic Scale	Revenue Type	Revenue Quantity	Decision-Making Criterion	Owner-ship Structure
Mobility	Regional	Tax	High	SOE	BCR
Environmental Protection	Link	Toll	Low	Concession	IRR
Economic Stimulus	National	Tax	High	SOE	NPV
Territorial Cohesion	National	Toll	High	SOE	NPV
Urbanization	Link	Toll	Low	SOE	n/a
Fiscal Equivalence	Regional	Tax	Low	SOE	NPV
Fiscal Austerity	Link	Toll	Low	Concession	IRR

(b)

Avg. Performance Rank \ Framework	Geographic Scale	Revenue Type	Revenue Level	Decision-Making Criterion	Owner-ship Structure	Worst Performance Rank
22.9	**National**	**Tax**	**Low**	**BCR**	**SOE**	**34**
23.4	Regional	Tax	Low	BCR	SOE	66
32.4	Regional	Tax	Medium	NPV	SOE	70
34.1	National	Tax	Medium	NPV	SOE	79
34.4	Regional	Tax	Low	NPV	SOE	90

(c)

Worst Performance Rank \ Framework	Geographic Scale	Resource Type	Revenue Level	Decision-Making Criterion	Owner-ship Structure	Avg. Performance Rank
34	**National**	**Tax**	**Low**	**BCR**	**SOE**	**22.9**
56	Municipal	Tax	High	NPV	SOE	40.4
57	Hybrid	Tax	Medium	NPV	SOE	47.0
60	National	Tax-Toll	Low	NPV	SOE	45.4
62	Municipal	Tax-Toll	High	NPV	SOE	44.1

FIGURE 5 – (a) Top frameworks for each perspective, (b) overall top frameworks measured by average performance, and (c) overall top frameworks measured by highest low rank[2]

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[2] In Figures 5b and 5c, the "average performance rank" is the average rank of each framework across all 7 perspectives. The "worst performance rank" is the lowest rank of a framework for any of the 7 perspectives. This explains the decimal value in the average (far left) column and the integer value in the "worst rank" (far right) column. In Figure 5b, frameworks are ranked by their average rank, while in 6c they are ranked by their highest worst rank.

Geographic scale
Overall, as the geographic scale shrinks (that is, toward smaller decision-making units), the level of total investment likewise shrinks. Concurrent with that lower level of investment are more modest improvements in such performance metrics as speed, congestion reduction, and accessibility. At the same time, however, the restricted investment of decentralized frameworks leads to a closer, fairer match of revenues with expenditures (geographically) as well as more *cost-effective* overall investments with regard to congestion reduction, accessibility improvements, and travel time savings. Investments in the inter-urban and rural areas do not offer the same value along these metrics as investments concentrated in metropolitan areas.

For the more centralized frameworks (national and regional scales), increases in the toll and/or tax rates for revenues lead to a relatively substantial subsequent increase in transportation investment. By contrast, the more decentralized frameworks (link-based, municipal, and hybrid) are relatively insensitive to increases in toll and/or tax rates. Small, modestly capitalized jurisdictions are often unable to overcome the high costs of infrastructure investment even with substantial increases in revenues; meanwhile, relatively wealthy jurisdictions can afford to make all the improvements available to them with a substantial amount of revenues leftover. Moreover, relatively wealthier jurisdictions such as those in the Lisbon metropolitan area have a high percentage of pass-through traffic and, particularly in un-tolled frameworks, have no local interest in making investments to improve the network. As a result, adding resources to the decentralized frameworks (by increasing the tax and/or toll rates) does not necessarily increase the amount invested in transportation by the same proportion.

Non-intuitively, along these lines, strong performance among large geographically scaled frameworks (national and regional) is associated with a low rate of revenues, while strong performance among small geographically scaled frameworks (link, municipal, and hybrid) is more likely to occur with a high rate of revenues. As rates are increased, more jurisdictions are able to accumulate the funds necessary to afford infrastructure investments. However, it is unlikely that small jurisdictions would be able to tolerate the political cost associated with the high tax rates necessary for local infrastructure in modestly populated areas, and the high toll rates necessary to generate revenues for infrastructure enhancement would drive away traffic and revenue. Indeed, remote jurisdictions with little pass-through traffic stand to benefit most from larger geographic scales, while highly populated jurisdictions will see a net transfer of revenues to other areas.

This raises an interesting dilemma for the urban and metropolitan portions of the network. Under more decentralized frameworks, urban and metropolitan regions are able to invest extensively in inter-urban connections, resulting in some long-distance corridors along heavily populated areas such as between Lisbon and Porto. However, because they do not have to share excess revenues with other regions, they have more revenues available to devote to other areas of need, including internal transportation systems (e.g., high-capacity urban transit).

Ownership structure
Along the ownership structure dimension, substantial differences are observed between the SOE- and concession-based frameworks. Concession frameworks, by design, select only those projects with an acceptable predicted financial return for the investor, and do so using direct user fees (tolls) as the only revenue source. Simulation of concession-based frameworks replicates major portions of the actual real-toll concessioned network in Portugal, particularly the Brisa Main

Concession (the most extensive) but also the metropolitan concessions of Lisbon and Porto. If the government restricted itself to these investments, the network of motorways in Portugal would be much smaller and more concentrated in and around the populated areas than it is today, with the only long-distance corridor connecting Lisbon and Porto and, according to the model, with a likely extension to Faro in the south.

SOE frameworks, on the other hand, aggregate revenues through direct user fees and general taxes to select projects with acceptable social benefits, regardless of financial return. Naturally, the SOE frameworks invest much more extensively than concession frameworks, across all geographic scales, due to the lower barrier that social benefits (i.e., travel time savings) represent relative to the financial rate of return criteria during project evaluation.

Revenue type
The simulation results generally suggested that taxes represent a preferred method of revenue generation. There are several reasons for the emergence of general tax revenues as preferential to tolls. First, tolls discourage travel, thereby reducing aggregate travel demand between municipalities. This has the effect of reducing the total number of trips, which reflects poorly under evaluation perspectives driven by economic development. Moreover, since toll-based frameworks reduce travel and congestion, improvements to the highway network are less cost-effective with regard to congestion reduction (i.e., there is less congestion to reduce).

That said, toll frameworks do perform well under several perspectives, including fiscal austerity, urbanization, and environmental protection. In part, the strong performance of tolling under these perspectives is due to its coupling with concession-based ownership structures.

Other dimensions
Increasing the level of revenue had a predicable impact on system performance: it increased investments. Under geographically decentralized frameworks, the increase in spending was not proportional to the increase in revenues. Meanwhile, under larger geographically scaled frameworks, increases in revenue led to higher investments, but with diminishing returns (i.e., as congestion was reduced and speeds increased, there were fewer benefits to be gained).

The investment decision-making criterion (NPV vs. BCR) did not impact the results in a meaningful way. It was expected that NPV would direct more resources to more costly projects (e.g., those in urban areas), and while this was the case, the magnitude of the difference between NPV and BCR frameworks was negligible.

CONCLUSIONS AND FUTURE WORK
The results confirm that it is feasible to simulate—using real data describing an intercity transportation system and an agent-based approach—the emergence and performance of infrastructure investments as a function of the strategy development framework. The model approach and results to date show promise for informing decision-makers about the consequences for transportation infrastructure system performance of strategic decisions related to the structure of organizations, collection of resources, and decision-making processes. Such a tool is particularly important given the ongoing reorganizations of the Portuguese transportation sector, including increasing reliance on concession agreements, highway tolls, and sub-national government participation.

The results tell a useful story with insights such as those noted in previous sections. Nonetheless, a range of refinements and improvements can be made, including a more

sophisticated demand forecasting module, a wider range of investment decision-making criteria, and a more complete physical network that includes competing modes such as conventional intercity and regional rail, air, and a proposed high-speed rail system. In addition, there are some phenomena that the model does not currently capture (e.g., multi-modal investment criteria and explicit consideration of freight traffic) and others that are not strictly quantifiable (e.g., politically negotiated investment decisions, competency of organizations at varying scales to participate in infrastructure strategy development at all). These considerations are perhaps best addressed through supplemental qualitative analysis such as case and stakeholder analysis (see *18* for further elaboration). Meanwhile, the quantifiable results of the modeling exercise presented here have generated a number of results with relevance and applicability to Portugal's current situation as well as to practitioners facing similar questions elsewhere.

ACKNOWLEDGEMENTS

REFERENCES
(1) Simon, H. (1962). "The Architecture of Complexity," *Proceedings of the American Philosophical Society*, Vol. 106, No. 6, pp. 467-482.
(2) Nightingale, D. and Rhodes, D. (2007). Architecting the Future Enterprise, Presentation, Lean Aerospace Initiative Knowledge Exchange, 12 June.
(3) Sussman, J., Sgouridis, S., and Ward, J. (2005). "New Approach to Transportation Planning for the 21st Century: Regional Strategic Transportation Planning as a CLIOS Process," *Transportation Research Record 1931*, National Academy Press, Washington, DC.
(4) Zhang, L. and Levinson, D. (2004). "An agent-based approach to travel demand modeling: an exploratory analysis," *Transportation Research Record 1898*, 28-38.
(5) Dia, H. (2002). "An agent-based approach to modeling driver route choice behavior under the influence of real-time information." *Transportation Research Part* C, Vol. 10, 331-349.
(6) Resnick, M. (1994). *Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Microworlds*. Cambridge, MA: MIT Press.
(7) Xie, F. and Levinson, D. (2009). "Jurisdictional control and network growth." *Networks and Spatial Economics*, Vol. 9, No. 3, 459-483.
(8) Gilbert, N. (2008). "Agent-Based Models," *Quantitative Applications in the Social Sciences*, SAGE Publications, Vol. 153.
(9) Instituto Nacional de Estatística (National Statistics Institute, or INE) (2009). Population data extracted from www.ine.pt, 31 Dec.
(10) Steer Davies Gleave (SDG) (2007). *Modelo Integrado de Procura de Passageiros* (Integrated Passenger Demand Model). Report to RAVE (Portuguese High Speed Rail Authority).
(11) EP (2000). *Plano Rodoviária Nacional* (Portuguese National Roadway Plan, or PRN).
(12) Google (2009). Map of Portugal, maps.google.com, retrieved October 2009.
(13) Transportation Research Board (TRB) (2000). *Highway Capacity Manual* (HCM), Washington DC.
(14) Wirasinghe, S. and Kumarage, A. (1998). "An aggregate demand model for intercity passenger travel in Sri Lanka," *Transportation*, Vol. 25, 77-98.
(15) Estradas de Portugal (EP) (2008). Sistema Integrado de Controlo e Informação de Tráfego (Integrated System for Traffic Control and Information, or SICIT), telematica.estradasdeportugal.pt/pls/alqueva/f?p=105:1:3964472390693753, retrieved October 2008.
(16) Ministério das Obras Públicas, Transportes e Comunicações (Ministry of Public Works, Transportation, and Communication, or MOPTC) (2009). New highways website, www.novasestradas.pt, retrieved August 2009.
(17) Washington State Department of Transportation (WSDOT) (2002). *Highway Construction Cost Comparison Survey*, Final Report.
(18) Dunn, T. (2010). The Geography of Strategy: An Exploration of Alternative Frameworks for Transportation Infrastructure Strategy Development, MIT Department of Civil & Environmental Engineering, Doctoral Thesis.
(19) Sussman, J. (2003). "Collected Views On Complexity In Systems," MIT Engineering Systems Division Symposium. Working Paper Series ESD-WP-2003-01.06-ESD.

(20) Brusilovskiy, P. and Hernandez, R. (1997). "Rankings and multi-criteria evaluation of alternatives: usage of objective data, subjective measurements, and expert judgment." Proceedings of NorthEast SAS Users Group Conference.

(21) Deloitte (2009). *Estudo de Impactes Económicos Globais da Subconcessão do Baixo Tejo* (Study of Global Economic Impacts of Baixo Tejo Subconcession). Report to Estradas de Portugal, January 2009.