Transportation Planning, Climate Change, and Decisionmaking Under Uncertainty

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Travel demand forecasting as widely practiced today deals inadequately with uncertainty. Methods currently used to forecast travel at the regional level simplify the world for which they forecast by relying heavily on point estimates. Forecasts are developed through the application of sequences of independent models in which the outputs from one become inputs to others. The current transportation modeling process is demanding in the sense that it employs a great deal of data to a large number of interconnected models having many parameters. The complexity of the modeling process, however, does not extend to the accurate representation of complex economic and social phenomena, and point estimates of many quantities are used that make it difficult to analyze or even to represent the uncertainty that characterizes transportation systems and traveler decisionmaking. After summarizing the major characteristics of travel forecasting procedures and their limited treatment of uncertainty, this paper presents several methods by which forecasting has been done outside the field of transportation that include explicit consideration of uncertainty. Influence trees and influence diagrams, real options, adaptive management, and the use of scenarios in planning and policy making are described and their application to policymaking under uncertainty is explored. Methods that aim to achieve robustness and resiliency rather than to optimize system performance are also described. Such methods would help us try to create transportation systems that perform acceptably under a range of potential future conditions rather than to find a single system design that best meets a set of precisely specified set of evaluation criteria.

Case studies are presented that illustrate the application of methods which incorporate decisionmaking under uncertainty. The applications of these methods that are summarized in this paper deal with cases outside of transportation, including military planning and planning for higher education systems. The cases are indicative of ways in which such methods might be applied in transportation and comments are offered regarding opportunities and difficulties that might be involved if such methods were extended to applications in the field of transportation.

1. INTRODUCTION

Among the concerns facing the U.S. transportation sector, the potential effects of climate change is a relatively new and increasing one. As scientists struggle to understand the potential impact of increasing levels of carbon dioxide and other greenhouse gases in the atmosphere, it is becoming increasingly clear that those potential impacts could have significant consequences for the transportation sector. There are great uncertainties surrounding the eventual effects of

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climate change and the nature of those uncertainties differ in some important ways from the kinds of uncertainty presented by other transportation sector concerns. Although the uncertainties posed by climate change are somewhat new to the transportation sector, other organizations have faced similar uncertainties and there are planning techniques that have proved useful in those conditions. This paper explores the unique uncertainties posed by climate change and means that might be incorporated into transportation planning that would enable the transportation sector to better prepare for the challenges of climate change.

To understand better how the transportation sector might address the threat of climate change, however, it is important to understand how the sector addresses the uncertainties that it confronts today.

The issues associated with climate change only compound and enlarge a problem that transportation officials always face. Transportation planners must plan for the compounding influences of uncertainty and system complexity, yet those with the responsibility to do so always have insufficient knowledge and information with which to do so. The most common approach historically has been to use apparently complex yet relatively simple data sets and concepts to predict average, aggregate traffic flows and then to provide capacity to meet that demand, and to ignore possible wild card fluctuations in conditions. Consideration of climate change and its implications may suggest that paradigm is no longer adequate, and perhaps discussions of new approaches to decisionmaking under uncertainty can contribute to rethinking in general the current modes of analysis and models of decision making.

2. TRANSPORTATION PLANNING TODAY

Federal law requires that monies be spent on the construction or rehabilitation of transportation systems only if the expenditure is consistent with a long-range regional transportation plan, so every metropolitan area has a regional plan that looks ahead twenty to thirty years. Most but not all states also have similar plans that address their interregional travel needs. While regional transportation plans emphasize trips made by walking, cycling, driving, public transit and trucks, statewide plans often also include trips made by air, railroad. Population, economic growth and change, and land use patterns are forecasted to arrive at some sense of where residences, work locations, shopping destinations and recreational activities will be in the future. Of course, there are huge uncertainties involved when predicting future population, economic activity and the location patterns of households and firms. These are largely ignored in the long-range planning process, in large part because they could overwhelm the process of analyzing potential options for the future.

In the 1950s, transportation planning was at the forefront of the use of computerized deterministic models to predict social and economic patterns. The models developed in those days have been updated over time, but the basic approach has not changed. Using population, economic activity and the location of activities as inputs, transportation planners proceed to forecast travel. The metropolitan area is represented as thousands of geographic zones and the transportation system is represented as thousands of nodes connected by thousands of links. A sequence of at least four independent models is used to estimate travel. The outputs from one model become the inputs to another. Very often, there are more than four models in the sequence. Each sequence of models can be run for weekday conditions or a weekend day; for traffic during peak periods (rush hours) or for traffic during off-peak hours; or for total daily traffic. First, trip generation models predict how many trips will start or end in each zone on the basis of social and economic characteristics and land uses in those zones. Next a “trip distribution model,” most often in the form of a gravity model, is used to model how many of the trips originating in each of the origin zones will travel to each destination zone. Then, a separate mode choice model estimates how many of the trips from each origin zone to each destination zone will be made by automobile or train or bus or carpool. Next, in the phase of the analysis known as “traffic assignment,” for trips by each mode such as automobile or transit, an algorithm or procedure is used to estimate how many trips will use each possible path between each origin and destination. Because the quality of traffic service on a link deteriorates when congestion builds up, the algorithms for traffic assignment “balance” flows and performance to rather roughly simulate actual drivers’ choices. Trips are likely to be distributed among alternative routes to the extent that congestion levels influence the flow levels.

While these are the major models that comprise a “chain” of models in which the outputs of each are the inputs to others, the actual chain of models used in particular cases can be far more complex. For example, the mode choice model is often a multinomial logit model in which an influential determinant of mode choice is vehicle ownership. In short, people who own many automobiles are more likely to drive them for most trips, while people who own few vehicles are more likely to use public transit. Thus, many metropolitan areas use a statistical vehicle ownership model to predict one of the most important inputs to the mode choice model. This illustrates the fact that chains of models can often be quite long and complex.

The output of this process is matrices of estimates of flows on particular links in the system that can change in response to the many inputs to the modeling process. Planners can add or delete links in their networks to judge how well the system will perform if new highways or rail lines are built or removed; future traffic can be allowed in the models to attempt to use an existing network to see where overcrowding will be most severe and judgments can then be made as to where to add capacity or to change capacity by adjusting traffic signal timing or by introducing restrictions on travel, such as banning trucks from central city streets at certain hours.

Often, the models just described are used to estimate future passenger flows and then truck traffic is estimated by multiplying passenger flows by some factors. Thus far, only a few metropolitan areas and states have separate and sophisticated models of travel by trucks even though truck traffic is growing more rapidly than trips by people in cars or on public transit.

In metropolitan areas in which there are violations of national air quality standards, federal regulations require that estimates of traffic flow be used in turn to estimate concentrations of several specified air pollutants. Thus, the long string of independent travel demand models provides inputs to similarly complex models that estimate concentrations of several different air pollutants on the basis of vehicle fleet composition, traffic volume, speed, and so on.

The forecasting models just described must be constrained in many ways to insure that their results are in balance with one another. The trips between one origin and all the destinations must add up to the total of trips originating at that origin. The trips between an origin and destination that are divided among the different modes must obviously add up to all the trips. Since travel is sensitive to travel time between an origin and destination, there are feedback loops among the models to insure that the speeds resulting from the traffic assignment in the fourth step are fed back into the trip distribution models that determine how many trips from a particular origin will be made to a particular destination. The feedback loops allow consistency to be achieved among the various models in the sequence by permitting the computer models to "iterate" until they produce consistent and compatible results.

The forecasting tools used by transportation planners appear to be complex because they involve many geographic zones, contain representations of many links, in the transportation system and include multiple travel modes. They also involve computationally complex procedures because modelers need to be sure that various components of the forecasting process are consistent with one another. In part because of the demands of handling many dimensions of interaction between large matrices of numbers and multiple models, the models themselves represent economic and physical behavior through rather simple relationships. This leads to a paradox. Transportation modelers on one hand think they are doing a good job because they are struggling reasonably well to deal with the computational complexity of their systems of zones, nodes, links, modes and independent choice processes. On the other hand, critics of their work from other fields look at the core social and economic relationships in their models and conclude that their forecasting tools are actually insufficiently complex in their representation of social behavior. This critique of travel modeling applies quite well to the ability of the models to incorporate into the planning process many of the issues raised in discussions of global climate change.

In the next sections we will demonstrate that dealing with uncertainty is one dimension of this paradox. Simplifying the treatment of uncertainty is one of the ways in which travel forecasters make compromises in order to manage the almost overwhelming dimensionality of their tasks. And, if they were to try to add concepts of uncertainty much more explicitly to transportation policy analysis using models currently in widespread use, the challenges due to computational complexity would be very demanding ones. This leads to the likelihood that the incorporation of uncertainty into travel demand analysis will demand entirely new approaches to the analytical representation of travel.

Uncertainty in Transportation Systems

The extent to which uncertainty exists in the performance of transportation systems and systematic responses to uncertainty in those systems through the planning, decision making, operations, and management processes is an important and complex problem. Urban transportation systems include extensive networks of physical facilities that are massive, immovable and long-lived. The extent, location, and physical condition of the current system in any geographic location are in the short run among the least uncertain of all the elements of the physical environment. Bridges, tunnels, highways, and rail lines are unchanging for decades or centuries and are dominating features of the landscape and their physical characteristics are difficult to alter.

What is important to structure the discussion here is not the stability of the physical transportation network but rather the variability of travel on that network, and consequently the variability and uncertainty of the network's performance under different circumstances. Travel that takes place on transportation facilities is highly variable, flexible and malleable. People and goods use the transportation system rationally, but they employ many and highly individual criteria when deciding how to fulfill varying needs. The complexity of travel decisionmaking by people and firms is fundamentally reflective of social, economic, and cultural patterns that are themselves quite complex, and these are compounded by the complexity of physical flows in transportation networks.

Yet, when society in the aggregate makes all of its travel decisions using many different rational choice processes, the outcome is clear patterns that seem regular and repetitive, and this in turn causes us to think that uncertainty is less important to planning than it actually is. Traffic peaks almost every day at the same times and places; roughly the same numbers of people use public transit versus highways between certain origins and destinations at a certain hour of the day. When looked at by an engineer, traffic on a facility has certain predictable characteristics like volumes, densities, starting times, and concentrations at certain origins and destinations that recur on a predictable, daily basis. But, the engineer looks at the performance of the system and not of the thousands of people who are using it. When looked at as a social phenomenon rather than as traffic flows, trips can be made by different modes, at different times, at different vehicle occupancy rates, for different purposes, from different origins to different destinations and, in at least some cases, they can be postponed or cancelled.

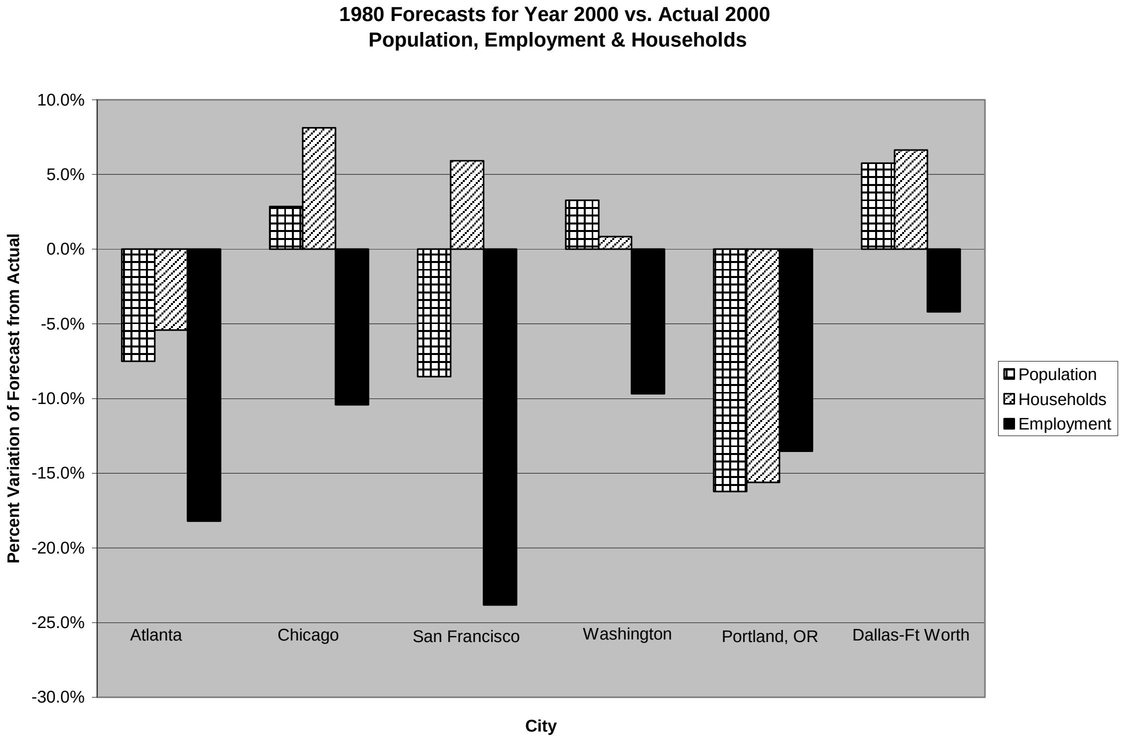
Implications of Travel Modeling for the Treatment of Uncertainty

The urban transportation planning and policymaking process is characterized by many uncertainties, some of which have already been described. But they are of necessity incompletely addressed in the formal long-range planning and modeling process just described. The demand for transportation services is determined by key inputs to policy making processes such as population growth, the distribution of population and economic activities in space, the growth or decline in economic activity, the introduction of new technologies, and so forth. When planning for a transportation system and its operations over thirty or more years into the future, it is certain that planners cannot anticipate with precision all the changes that will occur. Projections and plans depend upon “inputs” that are the products of assumptions and of models or extrapolation procedures whose parameters have depended in turn upon other assumptions. Projections and assumptions are always needed and they are always subject to error. This is a fundamental characteristic of planning. People plan in part because they cannot see the future with certainty, but to plan they must reduce the complexity of the world for which they plan.

A related source of uncertainty very important to transportation planning is the compounding effect of the oversimplification that is broadly accepted in transportation planning and policy making as the result of the use of the institutionalized modeling approaches that were outlined above. That is, in addition to the genuine uncertainty that arises from an inability to know the future, additional uncertainties can be introduced into models because of technical limitations. Data used in travel demand forecasting are based on sampling, and sample values always differ from true population values of variables. In addition to sampling errors there are possibilities that errors are made when data are aggregated, when they are entered into data bases, and so forth. The models themselves suffer from misspecification. Even if they were perfectly specified, their unknown parameters are estimated with sample data and hence are not known with certainty. When models are used for purposes of prediction, additional errors are necessarily introduced because the values of input variables in the future are always estimates and thus subject to error. The parameters of the models themselves, even if initially estimated perfectly, may not remain stable over time. Errors are not avoidable nor do they prevent effective applications of modeling to forecasting and policymaking. It is necessary and appropriate, however, to develop sampling and modeling strategies that are informed by patterns with which errors occur and especially by understanding the ways in which errors are propagated through sequences of models.

Forecasts of future travel begin with forecasts of the underlying social and economic determinants of travel. Most transportation forecasts rely upon exogenous forecasts of population, employment and housing. These descriptors of our future communities are themselves subject to uncertainty, but transportation planners tend to start their planning exercises on the basis of the "best available" forecasts of these quantities rather than by incorporating the notion that they are uncertain. Figure 1 shows that for six major metropolitan areas the deviation between forecast and actual values over a twenty year period were considerable. These deviations seem reasonable in a statistical sense in that models that accommodate uncertainty could deal with differences this large in their inputs. Yet, the impacts of uncertainty in these estimates are generally not incorporated into the modeling process. This may make the resulting plans more vulnerable to the potential ravages of uncertainty than would be necessary if we could somehow do a better job of internalizing that uncertainty.

One of the most persistent unresolved issues in the literature of travel demand forecasting is the propagation of travel demand forecast uncertainties and errors because several models are employed in sequence. Travel demand forecasts are, as indicated above, usually the result of sequences of several models. It is difficult or impossible to know the cumulative effect on the outputs from later models in the sequence of the errors that most certainly exist in the earlier models in the sequence. This problem has been noted in the travel demand forecasting literature for over forty years, yet it is difficult to deal with in practical terms as long as sequences of



Source: Forthcoming Transportation Research Board Special Report: "State of the Practice in Metropolitan Area Travel Forecasting: A Report of the Committee for the State of the Practice in Metropolitan Area Travel Forecasting," early 2007.

FIGURE 1 1980 forecasts for 2000 vs. actual: population, employment, households.

models are employed in travel forecasting. William Alonso wrote in the late sixties that sequences of non-linear models were more likely than linear models to cause errors or uncertainties to multiply and increase in size. Many modelers express the opinion that errors may be just as likely to cancel one another as to expand through sequences of models, but there is little empirical evidence of this. A few researchers have used simulation to test error propagation empirically. Recently, for example, Zhao and Kockelman investigated the stability of contemporary travel demand model outputs by quantifying the variability in model outputs as a function of variations in such model inputs as socio-economic variables and trip generation rates. They used a small model having 25 zones and over 800 links in the transportation network. Running the models over 100 times, they concluded that errors in the early stages of the models do tend to amplify errors in the later stages of the sequence. Equilibrium traffic assignment was found to be capable of counteracting the worst effects of error propagation, but the larger conclusion is that this is a phenomenon that needs further study to be of greater value to practitioners.[2]

Uncertainties and potential errors that result from the modeling and planning process itself should be discussed in the course of normal practice, their influence should be understood and disclosed, and proper account should be taken of the variation that necessarily occurs in the use of models for the purpose of forecasting. Agencies and consultants who apply travel demand models differ widely in their practice with respect to disclosing and analyzing sources and impacts of modeling uncertainties and errors. Rigorous statistical standards would suggest that variances and covariances in model outputs be estimated and analyzed as a function of variations in model inputs. Unfortunately, the standard practice relies primarily upon point estimates of outputs from some models that become the inputs to successive ones, and the transition to practices that emphasize more rigorous statistical error estimation would require a major change in perspective and dramatic augmentation of resources. It is understandable that agencies use point estimates rather than ranges and variances for so many model inputs and outputs. They use so many models as inputs to other models that ranges of inputs in each model would increase the computations needed to an extreme number. But, in the absence of practices that include tracing the ranges of output that result from widely differing ranges of inputs, it is possible that the error terms that would result from such practices would be far greater than the quantities that are modeled. If uncertainties associated with model predictions are as large as or larger than the model outputs, the use of models to produce forecasts for policymaking is itself highly risky. Modelers believe that their efforts are important because they make policymaking more "objective" than decision making by other means such as crass political bargaining over transportation investments. Yet, this objectivity is illusory when the range of possible model outputs due to uncertainty is of the same order of magnitude as the outputs of the models themselves.

At the very least, agencies should mention and interpret in their reports the likely impacts of uncertainties and error propagation on their standard modeling approaches. They should also consciously select approaches, such as equilibrium traffic assignment, which are known to minimize rather than to heighten errors and uncertainty in model outputs. More research certainly is needed on error propagation in sequences of travel demand models.

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[2] Yong Zhou and Kara Kockelman, "The Propagation of Uncertainty through Travel Demand models: An Exploratory Analysis," *Annals of Regional Science,* 36(1), March 2002, pp. 145-163.

Uncertain Events and Daily Travel Patterns

This long-standing approach to predicting transportation patterns introduces an interesting and complex paradox into transportation planning and policymaking. Transportation planning is done to accommodate travel as though it is highly regular and predictable. The paradigm by which the current system plans to accommodate future needs is almost defiant in the extent to which it ignores uncertainty. Despite this, uncertainty arises in the performance of the transportation system every single day. Facilities are planned to meet forecasted average aggregate demands, which are quite predictable and regular, and systems are built to meet that expected demand. But, from time to time the system is challenged by “wild card” events that lie outside of the planning framework. California experienced drastic short-term changes in the system resulting from the Loma Prieta and Northridge earthquakes. In the Gulf States, hurricanes have had similar effects, and in many locations floods can change the characteristics of the system very quickly. In the northeast, blizzards can shut down the entire transportation system for days at a time. And, there have been at least a few terrorist incidents that have changed system performance dramatically. Even more regularly, serious crashes, jackknifed trucks, and spilled loads of lumber unexpectedly close some links in the system, and strikes by transit workers sometimes remove them from service at very short notice. In general, transportation agencies do not include the systematic anticipation of such “wild card” events in the planning or sizing or location of the system or its elements. Yet, something like half of all congestion and delay and almost all deaths, injuries and property damage due to crashes arise from such unplanned intrusions into the planned regularity of transportation system performance.

Even though when looking at data and statistics and curves, travel patterns seem amazingly regular in the aggregate, it is probably the fact that independent travel decisions are made by thousands of people that has saved us from ourselves. People decide whether to travel and by which mode, by which route, and which vehicle, on the basis of current conditions, and their myriad individual decisions provide the mechanism by which the transportation system responds to uncertainty. During the Northridge earthquake in Los Angeles – on a holiday – the collapse of a highway overpass closed one critical freeway. The very next day – a work day – the ridership on a parallel commuter rail line grew to more than twenty times its normal daily average.[3] Similarly, when the heaviest traffic corridor in the San Francisco Bay Area, the Oakland-San Francisco Bay Bridge, was closed for months due to earthquake damage, the use of BART, buses, ferries, parallel bridges, and telecommuting meant that few people missed work. When an accident closes one of New York’s East River bridges, people use alternate modes and routes. When possible, they decide to defer their trips to another time and hastily form carpools instead of driving alone.

The current “strategy” for dealing with many uncertainties has consisted of allowing people to make thousands of individual decisions that they perceive to be in their own interest. Of course, system managers can and do use radio traffic reports and computerized information on current conditions and traveler information telephone numbers that travelers call to better inform their decisionmaking. Yet, the fundamental point is that the ability to respond to rather major uncertainties arises from the fact that thousands of independent agents optimize according to their own criteria when unexpected circumstances arise. People and their vehicles adapt to uncertain events, sometimes in ways that planners have hardly anticipated, and that quite often

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[3] Nabil Kamel, Dulce-Marie Leon, and Martin Wachs. *Transportation Decision Making Under Disaster Conditions*. Institute of Transportation Studies, University of California, Los Angeles, February 1996.

overcomes failures to adequately prepare for uncertainty when planning centrally for the entire system. Sometimes, but only rarely, do their adaptations fail or become inadequate, for example when traffic jams extended over hundreds of miles as people tried to evacuate cities in the path of oncoming hurricanes. It would seem that these failures arise from having too little information or too few choices rather than from the lack of a clear set of directions from a central authority.

Despite enormous uncertainty in future travel on particular facilities or by particular groups of people, planners practically assume away much of that uncertainty in the planning of the physical networks. Yet, to some extent planners manage to create systems that operate under a wide variety of unanticipated conditions because the individual travel decisions that people make respond to uncertainties far more effectively than do the systems themselves.

Planners' Assessments of Forecast Performance

Despite the fact that long-range forecasts in support of planning do not take account of the many uncertainties in the model inputs and fail to address the many sorts of uncertainties discussed above as "wild cards," regional planners seem surprisingly satisfied with their methods.[4] A recent national survey of hundreds of regional planning agencies - to which there was a very high response rate - revealed that the vast majority of the agencies rated their performance as acceptable and their models as adequate or better. A few regional agencies and states have applied their models to scenarios in which emergencies have been simulated by removing key links from their systems or have been stressed by assuming huge and irregular fluctuations in traffic flows in some corridors, and when such tests have been performed the outcomes have provided a great deal of fodder for criticism of the methods.

Travel demand modelers constitute an important intellectual community. Technical committees, annual conferences, and a rich literature consisting of journals and technical reports address the tools and techniques of transportation forecasting. Analysis of that literature reveals widespread acceptance of the fact that uncertainty is not adequately represented in travel demand models. While the literature takes note of the fact that uncertainty is always inherent in projections of travel demand, widely shared priorities for improvement of the craft of forecasting travel clearly lie elsewhere. Proposals for major advances in travel demand modeling are numerous, but for decades they have emphasized improvements other than improved representation of uncertainty. Many have argued, for example, that models should become more disaggregate in that individual travelers or households should become units of analysis in place of zones. Others have urged that individual trips from origin to destination should become less important in the models, while "tours" or sets of trips from the time travelers leave home through their return to home should be the basis of modeling. Some of these changes might make it more feasible than others to incorporate uncertainty into travel modeling, but the improved representation of uncertainty has rarely been a motivation for suggested improvements in travel forecasting.

A possible explanation for the widespread belief by modelers that travel models are adequate despite their poor representation of uncertainty in a world that is filled with it is that the models may be contributing to the reduction of uncertainty to some extent by becoming self fulfilling prophecies. That is, land use and economic activity locate in space in response to the

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[4] The survey, conducted by BMI-SG, Inc., is summarized and results are presented at: http://www.trb.org/publications/reports/BMI-SG-Sept2005-Draft.pdf.

accessibility provided by the transportation network, and travelers choose modes and routes in response to the performance of the network. If the network is built on the basis of assumptions about the future or faulty models of choice, the resulting transportation investments influence travel patterns to become more like those that were assumed or modeled. Consistency between forecast results and system behavior may often be observed because planners to some extent are confounding their assessment of cause and effect. The models may be adequate because they have determined, rather than correctly forecasted, transportation system behavior. And, consistency between forecast and observed travel in the aggregate does not mean that the system as built is, under normal circumstances, the most effective, efficient, or equitable system possible. Nor does that consistency mean that the performance of the network is anywhere near optimal when uncertain conditions occur. This leaves open the prospect that better models and methods, dealing more effectively with both transportation behavior and uncertainty could produce far more satisfying and effective outcomes.

In summary, transportation planners would be well-served to adopt more recent techniques for addressing uncertainties that they currently downplay or ignore. That said, it still makes sense to discuss how uncertainties from possible climate change might be handled, because even if transportation planners did a better job of handling the uncertainties they currently confront, the uncertainties posed by possible climate change are of a different character. There is a great deal of uncertainty about climate change, including how quickly it could become significant. Most indications today suggest that climate change will come upon us gradually over a period of years to decades with the ultimate effects quite uncertain at this point. This makes the effects of climate change: 1) of very low near-term probability, 2) of possibly catastrophic and long-lasting effect, and 3) of national (quite possibly even global) extent. Of the wild card scenarios that transportation planners currently face, none is quite like this. Weather events, with the possible exception of Hurricane Katrina in New Orleans, are near-term, unpredictable, and of reasonably short-term duration. Earthquakes are unpredictable, possibly catastrophic, but localized. To the extent that there are methods aimed at wild cards with the attributes of climate change, it is worthwhile adding those to the list of methods that transportation planners might use in improving their approach to uncertainty.

The following section briefly summarizes a variety of methods that have been used to address some or all of the uncertainties that climate change poses for the transportation system. The section following that provides three case studies that address aspects of the challenge that climate change poses for transportation planners. The final section contains some opinions about how transportation planning ought best to proceed.

3. METHODS FOR DEALING WITH ISSUES LIKE CLIMATE CHANGE

Unique Challenges Posed by Climate Change

Since "climate" is the long-term average of weather, climate change is ultimately about changes in the weather. The transportation sector is well-practiced in dealing with weather and weather extremes. In addition, the sector faces other challenges from natural events such as earthquakes, volcanoes, and from man-made events , both benign (e.g., demographic changes) and malign (e.g., acts of terrorism). Some of the uncertainties posed by climate change are similar to those inherent in these other challenges. There are, however, some challenges posed by climate change that the transportation sector hasn't seen before.

One such challenge is a potential for more extreme weather events than the transportation sector has heretofore faced. These more extreme events include the potential for individual weather events more extreme than we've ever seen (such as a record-breaking hurricane), a greater number of extreme weather events (such as more heavy rainstorms), and weather events in places where such events are currently rare (such as snowstorms in the southern states). All of these effect the ability of the affected locations to cope with these events. Even more importantly, because they are outside of past climate patterns, they can require changes in the building and operating standards of the transportation sector locally, regionally, and even nationally.

The second unusual challenge posed by climate change is the possibility of significant, long-lasting effects on transportation infrastructure. Roads, rail facilities, and airports in low-lying areas, for example, may be permanently overtaken by rising sea levels due to climate change. Manmade and natural events, such as accidents and earthquakes, can cause significant changes to transportation infrastructure, but those tend to be local and temporary. Climate change presents the possibility of requiring changes that are widespread and permanent.

It is not just the ability of climate change to wreak significant changes in the transportation sector, but also the great uncertainty that accompanies the possibility of these changes that presents the greatest planning challenges. Earthquakes, for example, can cause great damage but the uncertainties tend to be not in where or whether they will cause damage, but when. With climate changes, the uncertainties are where, whether *and* when (while we tend to think that climate change will happen slowly over the coming decades, there are plenty of opportunities for tipping points and non-linear interactions to cause some effects much more quickly than we anticipate).

Low-probability (or unknown probability), high-consequence events pose challenges in many other areas than transportation and there has been work done to help deal with such events in the planning process. There are several such formal methods and this section presents a brief survey of the most relevant of those methods along with a brief discussion of their strengths and weaknesses and where they might be used in transportation planning.

Decision Trees and Influence Diagrams

"Decision analysis" refers generally to a structured technique to aid decision-making under conditions of uncertainty. While the name "decision analysis" generally refers to the overall field of using analytic techniques in support of decisionmaking, decision analysis is also more commonly thought of as that set of techniques that generally uses decision trees or influence diagrams in assisting decisionmaking.

A decision tree is a structure composed of nodes and arcs or connections between nodes laid out in a tree-like fashion with a root node and branches. For a given decision, the tree starts with the basic options as branches from the first node. Each of these options rests on uncertainties and subordinate decisions. From each node representing subordinate decisions, the analyst draws out lines that represent options. From each option, the analyst draws out possible outcomes from that decision. This diagram continues until all important subordinate decisions and all relevant options are diagrammed in the tree structure.

The evaluation of a decision tree begins with assigning a score that represents the benefits of the final node of each branch of the tree (in product development, this would be the expected sales of the product). The next step is to assign probabilities at each of the nodes representing uncertainty. The total probability of a given branch times its score is the final "benefit" of that branch. The cost of each branch can then be computed for a cost/benefit ratio for each branch.

For problems that are less quantitative, influence diagrams are used in a similar fashion. Influence diagrams represent the main structural features of a situation and the important influences that exist among those features. Unlike the arrows in a decision tree, the arrows that represent the influences of one box on another in an influence diagram can point in both directions. Influence diagrams are thus an abstraction of decision trees, but otherwise work in much the same way for handling uncertainty.

The main challenge with decision trees or influence diagrams is estimating in terms of exact probabilities. For something like climate change, that is associated with very low probabilities and potentially devastating consequences, this is a significant challenge. Nonetheless, the discipline that decision trees and influence diagrams bring to thinking about decisions can be helpful.

For actually developing decision trees or influence diagrams there is software such as Analytica that can automate the process. Using these methods to assist decisionmaking on something like climate change is probably best left to someone with a great familiarity with decision trees and influence diagrams.

Real Options

Real options come from the finance world and represent capital investment options rather than financial options. A real option is the right, but not the obligation, to make a capital investment. It is an approach to private investment when there is considerable uncertainty about the net cash flow profile of a proposed project. When the net cash flow profile can be confidently predicted, decisions are usually made on the basis of Net Present Value (NPV) computations. Particularly when there is uncertainty over the life of a project, NPV often significantly misestimates the value of the project. Although transportation infrastructure decisions do not rest heavily on such value considerations, the real option approach focuses attention on identifying sources of uncertainty and forces decisionmakers to consider the question of whether a proposed project has flexibility in its development.

Decisionmakers have been making capital investment decisions for centuries, but "real options" are associated with a more analytic approach to those decisions. The real options approach begins with NPV computations and extends those calculations to consider the intertemporal opportunity costs associated with making an immediate irreversible capital investment or waiting. NPV calculations require making precise predictions of future cash flow profiles for a project over its entire duration. Real option calculations, while more complicated, allow for the exploration of various cash flow profiles in the future. Particularly in conjunction with something like exploratory modeling, this allows decisionmakers to look at the NPV of a project over a wide variety of future cash flow profiles. This could be helpful in an arena in which investment decisions about significant transportation infrastructure changes/additions could be tested against plausible future funding profiles that depend on better understanding of the threat from climate change.

Real options are calculated similarly to NPV calculations and, in areas in which the value of projected infrastructure investments is an important consideration, they offer greater flexibility in the face of uncertainty. Real options can be thought of as decision tools for dealing with greater uncertainty than is usually acceptable in NPV calculations. Particularly in regions where climate change could lead to significant alterations in the transportation infrastructure, such as the relocation of roads, railroads, or airports, real options offers a methodology to deal with investments related to the relocation of facilities in the face of significant uncertainty about whether the resiting will be required.

Adaptive Management

Adaptive management is an approach to managing ecosystems under the threat of abrupt change. Adaptive management treats policies as experiments. That is, near-term policy choices are conceived as a set of hypotheses to be tested against the experience of implementation (Holling 1978, Walters 1986, Lee 1993). By designing monitoring and other means of measurement, it becomes possible to gain information about which hypotheses are disconfirmed by experience. This approach to policy design and implementation assumes that policy is problematic from the outset -- that the assertions about causal relationships may be flawed, and that the flaws may be detected with suitable measurements. Adaptive management thus supports an iterative policy process, in which learning from experience is perceived as crucial to determining the best policy choice. The adaptive management cycle is: assess, design, implement, monitor, evaluate, adjust. The assessment includes making sure the objectives are clear, identifying alternative management actions that balance risk and opportunities for learning, identifying metrics for assessing the achievement of objectives, identifying the uncertainties involved, and hypothesizing about the potential effects of alternative actions.

On its face, adaptive management would seem to be ideally suited for ecosystem managers (and perhaps transportation system planners) faced with uncertainties about the impact of climate change. An adaptive approach should prove useful whenever the costs of detecting and correcting erroneous hypotheses are low. In the natural resource management realm, policies impose human-designed disturbances in ecosystems. The response of ecosystems to disturbance is only partially understood, but it is clear that the abundance of species valued by humans can be substantially and indirectly affected. For example, the application of pesticides can, over time, select pest populations resistant to those pesticides, increasing harm to crops as pest populations cease to be suppressed. By treating pesticide use as a series of runs within an experimental design, the dynamics of the ecological response can be studied. As understanding of the process is gained, more effective protocols and methods of using pesticides can be devised.

Adaptive management is a promising approach, but has been adopted infrequently in natural resource management and successfully implemented even less often. Experience suggests two obvious barriers to implementing this potentially promising experimental paradigm – controversy from competing interests and the cost of information.

Policy-makers find it hard to advocate controversial policies while admitting that they may not work. Once a policy is adopted, its managers are likely to be held accountable for the outcomes that ensue. Even if learning-by-doing is an explicit aim, any failure of a policy to deliver other promised results will likely outweigh any new knowledge in stakeholders' perceptions -- particularly if a policy's aims are or become controversial.

The cost of information is often neglected during policy design, and it can be hard to estimate in advance. But adaptive management emphasizes information collection, thus making the cost of information more prominent. It also raises administrative cost and complexity compared to policies whose outcome is believed to be certain. In addition, the need for a statistically valid experimental design may require a baseline, no-treatment phase in which the monitoring scheme is calibrated. This may require delaying or denying any perceived benefits of the policy to politically powerful groups. For these and other reasons, an adaptive approach can be attacked as technocratic, and politically unresponsive.

Scenarios

Scenarios are in widespread use in planning circles for a variety of purposes. When specifically used in connection with planning under uncertainty, planners are confronted with several scenarios (usually 3-5) and asked to prepare for each. Even at this level of generality, the use of those preparations can vary. In risk-averse organizations (such as the military), the materiel and plans required for each of the scenarios can be used to develop an overall capability to handle any of the presented scenarios. This use of scenarios is for worst-case planning. More often, the preparations for any given scenario provide insight into the kind of equipment and operations that would be required if that scenario were to develop. This generally permits an organization to monitor whether or not the given scenario is developing and to anticipate the kinds of equipment and operations that will be needed if the scenario continues to develop.

The preparation of scenarios is more art than science. Four aspects of scenarios deserve particular attention in thinking about climate change: direction, credibility, details, and relation to other scenarios. Scenarios are constructed in two basic *directions* – backward and forward: either starting with where you want the scenario to wind up and working backward to today or starting with today and working forward to the desired scenario. In thinking about climate change it is more useful to concentrate on specific climate changes and work backward toward today to think about how we might see them coming and what we might do (and when) to accommodate those changes.

Credibility is important in scenarios, particularly those that are most unlike today and most negative. Decision theory suggests that people consider such scenarios as less likely to occur than more benign or familiar scenarios. This suggests extra attention needs to be paid to establishing a credible logic in the scenarios that would represent significant climatic changes at a future time. More *detail* in the scenarios can help with credibility, but there are dangers in too many details. A scenario described in exquisite detail opens up the possibility of weak links in the story, and a particularly weak link in an otherwise strong causal chain can cause an entire scenario to be dismissed as incredible.

Ideally, each scenario should be judged separately, but if several scenarios are used, a given scenario will be judged in *relation to the other scenarios*. If one scenario stands out among a group, it is more likely to be either dismissed as incredible or accepted as the most likely.

Scenarios have been used in long-range transportation planning. For example, in its report *Assessing State Long Range Transportation Planning Initiatives in the Northeast for Climate and Energy Benefits*[5], the BBG Group studied 15 Long-Range Transportation Plans

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[5] Burwell, David, "Assessing State Long Range Transportation Planning Initiatives In the Northeast for

(LRTPs) and found some that used scenario planning for the purpose of allocating limited state resources among various demands for transportation services. They reported that none, however, used alternative land use scenario planning as a process tool for developing the LRTP. Another example comes from New Zealand where scenarios are used for strategic transportation planning.[6] Further examples can be found in the Department of Transportation's Toolbox for Regional Policy Analysis[7] where several case studies detail the use of scenarios to address transportation policy issues. Where further use of scenario planning techniques might best augment current transportation planning is in long-range infrastructure planning. Exploring scenarios in which significant transportation nodes are permanently removed (because of potential climate change effects) would better hedge long-range plans in the face of climate change uncertainties. That is, climate change needs to be considered at the very earliest stages of transportation planning in terms of potential scenarios. More detailed planning models can then be used to help think through the potential consequences of these scenarios.

Robustness and Resilience Methods

Human decisionmakers often approach the solution of a complex problem by developing a strategy that will be robust against uncertainties about the future. While these are generally *ad hoc*, subjective approaches to robust decisions, interest in more explicit approaches to identifying robust, as opposed to optimum, strategies has been growing over the last two decades. This interest has been fueled in part by increasing realization by decision makers that the world is less predictable and more surprising than they might have believed, by advances in the psychology of decision making which show the traditional expected utility framework is not the way skilled human decisionmakers often approach reasoning under uncertainty, and by the advance of new computer capabilities which has made possible new quantitative decision frameworks. The Robust Decisionmaking (RDM) approach developed at RAND is an example of this emerging field and demonstrates the distinctive features of seeking robustness rather than optimality in the face of uncertainty of the type that climate change threatens.

The RDM approach uses computers to create a large collection of plausible future scenarios, where each scenario represents one guess about how the world works and one choice among many alternative strategies people might adopt to influence outcomes. The approach then uses computer visualization and search techniques to extract information from this collection of scenarios that is useful in distinguishing among alternative decision options. The second case study below gives a detailed example of the approach.

Four key elements or principles govern the form and design of an RDM analysis:

1. Consider *ensembles* of large numbers of scenarios. Such ensembles should contain a set of plausible futures that is as diverse as possible in order to provide a challenge set against which to test alternative near-term policies. Scenario ensembles can represent a wide range of different types of information about the long-term future. They can also facilitate group

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Climate and Energy Benefits: Final Report," BBG Group, December, 2005. See also, http://climate.dot.gov/papers.html#bbg.

[6] See, for example, the recently completed North Wellington Public Transport Study at http://www.gw.govt.nz/section1705.cfm.

[7] See http://fhwainter.fhwa.dot.gov/planning/toolbox/index.htm.

processes designed to elicit information and achieve buy-in to the analysis from stakeholders with very different values and expectations about the future.

2. Seek *robust*, rather than optimal, strategies that do "well enough" across a broad range of plausible futures and alternative ways of ranking the desirability of alternative scenarios. Robustness provides a useful criterion for policy analysis because it reflects both the normative choice and is the criterion that many decisionmakers actually use when facing complex problems and deep uncertainty.
3. Employ *adaptive* strategies to achieve robustness. Adaptive strategies evolve over time in response to new information. Near-term adaptive strategies seek to influence the long-term future by shaping the options available to future decision-makers. That is, the near-term strategies are explicitly designed with the expectation that they will be revisited in the future as new information becomes available.
4. Use computer tools designed for *interactive exploration* of the multiplicity of plausible futures. Humans cannot track all the relevant details of the many scenarios. But working interactively with computers, they can discover and test hypotheses that prove to be true over a vast range of possibilities. Thus, computer-guided exploration of scenario and decision spaces can help humans, working individually or in groups, discover adaptive near-term strategies that are robust over large ensembles of plausible futures.

Robustness methods are an improvement on any method aimed at sensitivity analysis. Transportation planners do, in some cases, explore the sensitivity of plans to alternative values for variables such as demography and the performance of alternative travel modes. Because of the run times of transportation models, however, few go beyond using something like "low, medium, and high" values. Particularly with the nonlinearities inherent in transportation models and the uncertainties surrounding climate change, such rudimentary low-medium-high sensitivity analyses may hide important system responses at intermediate values. Robustness methods can explore automatically over a wider range of values and increases in the speed of computers and in running parallel computations will decrease the time required to run additional cases.

Understanding Underlying Assumptions

A study done in 1999[8] noted several instances in which large companies suffered significant downturns due to situations they could easily have foreseen had they done a better job of planning. Specifically, the study pointed out assumptions in each case that the companies made that failed, causing the downturn. In the cases noted, had the companies paid more attention to the assumptions they made in their planning, those downturns might have been avoided. That study went on to recommend a variety of techniques for ensuring that planners are aware of their important assumptions and plan accordingly. Assumption-Based Planning (ABP), developed at RAND, was one of the techniques mentioned and serves as a good example of the techniques for paying attention to planning assumptions.

Assumption-Based Planning was developed in the 1980s as a tool for improving the robustness of plans. Its main purpose is to expose the important assumptions underlying a plan – particularly those assumptions that planners don't realize, or have forgotten, that they are making. Planning for the future requires making assumptions about what the future will be like.

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[8] *Proceeding in Daylight: Frontier Practices for Challenging Strategic Assumptions*, Corporate Strategy Board, Corporate Executive Board, Washington, DC, 1999. See also, http://www.executiveboard.com.

Some of those assumptions are pretty likely to come true; others are more vulnerable to uncontrollable and unforeseen events; still others may be quite unlikely. Some of the assumptions are likely to be very important to the success of the plan; others will be more peripheral. ABP is primarily a “post-planning” tool (recognizing that planning is an iterative process) that concentrates on the assumptions in an already-developed plan that are most important to the plan’s success and that are most uncertain. Specifically, ABP works to decrease the risks that assumptions represent.

The driving force behind ABP is the view that it is important to confront, explicitly and honestly, the uncertainties facing an organization and its planners. There are five basic steps in Assumption-Based Planning. The first step is to identify the assumptions in the plan. This is the most crucial step in ABP and there are several methods for identifying as many of the assumptions as possible that underlie a given plan. Many of a plan’s assumptions will be explicitly spelled out and easy to identify. The primary purpose of this step is to uncover assumptions that are implicit or have been ‘forgotten’ in the planning process.

The next step in ABP is to identify the assumptions upon which the success of the plan most heavily rests--the “load-bearing” assumptions--and the assumptions that are most vulnerable to being overturned by future events. Assumptions that are both load-bearing and vulnerable are the most likely to produce nasty surprises as the plan unfolds.

To deal with potential surprises, ABP produces three things in the final three steps: signposts, shaping actions, and hedging actions. *Signposts* are warning signs that can be used to monitor those assumptions that are most likely to produce surprises. Signposts are events or thresholds that, if detected, signify that a vulnerable assumption is broken or dangerously weak and that management or planning action is called for.

Shaping actions are intended to help shore up uncertain assumptions, and thus to control the future to the extent possible. Planners generally know how they would like an assumption to play out. Shaping actions are designed to help the assumption play out to the planners’ liking.

Hedging actions better prepare for the possibility that an assumption will fail, despite efforts to shore it up. Hedging actions typically come from thinking through a plausible scenario in which an assumption collapses and asking what might be done now to prepare for that scenario.

A planner using Assumption-Based Planning cannot hope to identify all the possible ways in which a plan could fail, nor hope to prepare a plan for any eventuality. There is any number of events that could intervene to disrupt any plan. The primary aim of ABP is to ensure that a plan is cognizant of and responsive to major uncertainties inherent in the assumptions that underlie it. Many of the assumptions upon which the plan rests are voluntarily made by the planners. Those voluntarily made assumptions should be most explicitly recognized and dealt with. Surprises from the failure of those assumptions should be most avoidable.

Any transportation plan could use the kind of assumption scrubbing that techniques such as ABP offer. With respect to climate change, however, there is one area where it is crucial to scrub for underlying assumptions – in the models used in the transportation sector to do long-range planning. Those models have been used for years – sometimes for decades – and the assumptions that underlie them may be inappropriate in a climate-changed world. Particularly susceptible to inappropriate assumptions are likely to be land use models that have not taken into account limits on future land development that will arise because of climate change. Also susceptible are mode choice and traffic assignment models because particular facilities included in such models may be far more vulnerable to climate change than others. Testing the assumptions of these models would need to be done either with someone very familiar with them or following careful documentation of the models.

4. CASE STUDIES

To lend more practical understanding of the techniques above, this section takes a look at examples of two of the most promising techniques above. One takes place at the national level and the other at the state/local level. The case studies were selected for their long-range perspective and their similarities with the issue of climate change that is facing the transportation planning community.

Air Force 2025 and Scenarios (National Level)[9]

The long-range planning task of the U. S. Air Force is to ensure that the Air Force has the proper capabilities to meet the nation's security threats today and in the future. When it comes to planning, the task facing the U. S. Air Force is similar to that facing transportation planners – particularly as it relates to the uncertainty of climate change – in two important aspects. First, both must take a risk-averse approach. That is, unlike private companies that are allowed to fail, both the U. S. Air Force and transportation system planners must put safety above opportunity – they must be prepared for the worst case scenario. As will be explained further below, this is an ideal situation for scenario planning.

The second similarity is that both the U. S. Air Force and transportation infrastructure planning require long lead times in making significant changes to the *status quo*. Advanced military equipment requires 15-30 years to go through a complex cycle from research to design to prototype to testing to production to fielding. While the process of making changes to transportation infrastructure is different, the lead times for significant changes are similarly measured in decades. This requires that both Air Force and national transportation planners look several decades into the future. (In the case of the national transportation infrastructure and climate change, the climate change problem itself is one that will play out slowly over the coming decades).

The Air Force faced a serious planning problem in the aftermath of the Cold War that added a third similarity with transportation planning that takes climate change into account Air Force equipment had been optimized to face the challenges of the bipolar Cold War World. With the collapse of the Soviet Union, the national security challenge – and its associated required equipment – changed dramatically. While it was clear to the Air Force that the situation had changed, exactly how it had changed was not clear. Their new worst case was going to be very different than it had been during the Cold War. In the transportation sector it is not entirely clear that climate change has altered the transportation situation, but it is relatively clear that the worst case scenarios that the transportation sector faces with climate change are significantly different than the worst cases they faced a decade or more ago. The way in which the Air Force faced its altered worst case scenario is instructive in thinking about how transportation infrastructure planners might face the challenge of climate change.

In 1995 the Air Force undertook a study designed to look 30 years into the future "to identify the concepts, capabilities, and technologies the United States will require to remain the

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[9] Details of this case can be found at http://csat.au.af.mil/2025/index.htm.

dominant air and space force in the 21st century." A fundamental aspect of their approach used "alternative futures" or scenarios to help them "envision an array of future worlds in which the U.S. must be able to survive and prosper in the year 2025." A large research team developed six alternative futures and from those futures they developed military capabilities and systems concepts for dealing with all six of the alternative futures. From the capabilities and concepts, they identified a list of high leverage technologies. That study had an important impact not only on the R&D portfolio of the Air Force, but on the shape of the Air Force today.

The title of the section on scenarios in the Air Force 2025 report (hereafter AF2025) is Alternative Futures for 2025: Security Planning to Avoid Surprises. As further explained in the section that describes the purpose of the scenarios, "The problems encountered by most long-range planners are the difficulties of thinking "outside the box" and the pitfalls of simply using projections from today to predict the future. As a result of these problems, the common tendency is to create future operating environments that are similar to those of today. This constrained planning space … can lead to "rude surprises" as trends and events vary from the expected … the key objective for the study was avoiding surprise. The Alternative Futures team achieved this by employing a process specifically designed to create a complete and robust set of planning environments."[10]

This emphasizes the failsafe nature of Air Force planning and the desire to avoid "rude surprises." A similar approach would be prudent in thinking about the potential impact of climate change on national transportation infrastructure.

The process by which the Alternative Futures team created the alternative futures is instructive and similar to methods found elsewhere. In its essence, there are four steps:

- select the drivers of the future
- define the drivers
- create the strategic planning space
- name and select the worlds of interest

To the Alternative Futures team, a driver was "a factor determined to be an important contributor to change affecting the future. Drivers should be beyond the control of the customer, as independent as possible from each other, and relevant to the customer."

To produce the driver candidates, a combination of scientific and nonscientific methods was used. "The scientific methods involved analyzing various trends, conducting research on various topics, interviewing respected futurists and scientists, and completing affinity diagrams. The nonscientific methods involved creative thinking techniques such as brainstorming, "exploring," and "artistry.""[11]

The Global Business Network (GBN), perhaps the premier scenario planning organization, defines drivers similarly, but uses various stakeholders of an institution to identify candidate drivers as part of a day-long scenario planning exercise. In the GBN approach, the next step is to reduce the driver candidates to two main drivers (that could be combinations of driver candidates) that are independent and whose extreme values are defined. In the AF2025 exercise, they reduced the driver candidates to three main drivers, as shown in Figure 2. The American Worldview described the U.S. perspective of the world and ranged from a focus on internal problems to a global view in which the U.S. would seek a world leadership role. ΔTeK

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[10] Air Force 2025 report, http://csat.au.af.mil/2025/a_f.pdf, pp.1-2.

[11] *Ibid*., p. 9.

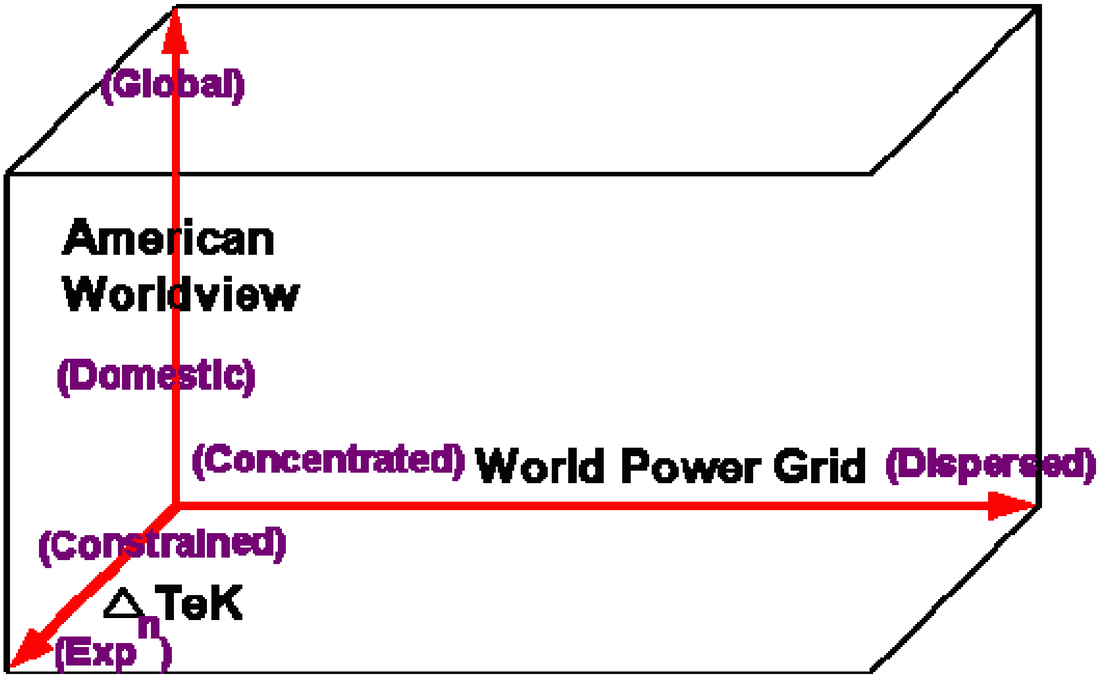

FIGURE 2 Air Force 2025 strategic planning space.

described the ability to employ technology, ranging from a constrained world in which technology advances at an evolutionary rate and few actors can exploit the advances to an exponential technology world in which many actors can exploit revolutionary breakthroughs in technology. The World Power Grid described the distribution of "power" throughout the world and ranged from a high concentration of power amongst a few actors to a widely dispersed world where thousands of actors (even individuals) had the ability to affect the rest of the world.

The Alternative Futures Team then explored the eight extreme corners of the scenario planning space shown in Figure 1 and identified four corners of particular concern. They gave those areas of the planning space names and developed the details of worlds with those characteristics. The four worlds, *King Khan*, *Zaibatsu*, *Gulliver's Travails*, and *Digital Cacophony* are shown in Figure 3. After review with senior Air Force leaders, two additional intermediate scenarios were added – *2015 Crossroads* and *Halfs and Half-Naughts* – as shown in Figure 3. With the worlds described, the team then created plausible histories for each world as a means of checking the plausibility of the worlds and paths that might lead us to those worlds.

The six alternative worlds and their histories then formed the framework for quantitative and qualitative evaluation of Air Force systems and concepts identified by other teams in the study. The six worlds were used to help identify systems and concepts "which promise a high leverage capability applicable to many or all of the alternative futures."

With the six scenarios in hand, subject matter experts assessed potential technologies, systems and operational concepts that would – to the extent possible – handle all six of the planning scenarios. Technology planners looked at the types of technologies that were in the laboratories to find promising candidate technologies for addressing the challenges of each of the six planning scenarios. Similarly, weapons systems engineers looked at the types of systems that

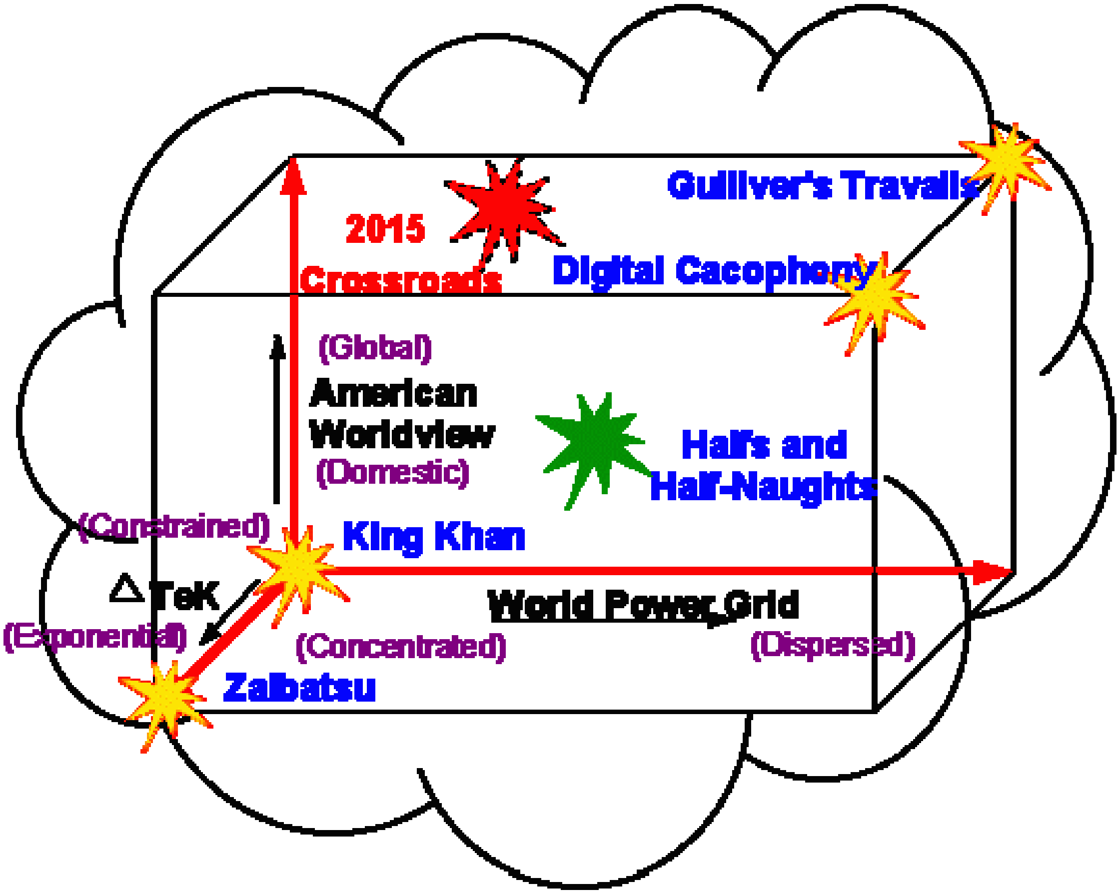

FIGURE 3 Six Air Force 2025 planning scenarios.

could be fielded that would address challenges of the planning scenarios and doctrine experts looked at the challenges of putting systems together to address the operational challenges of the planning scenarios.

In much the same way that transportation planners would develop detailed, quantitative plans, Air Force planners took these scenarios and developed the materiel and budgets that would be required to handle the six alternative worlds using their typical Planning, Programming and Budgeting System (PPBS) tools. With detailed plans and budgets, the analysts then looked across the six worlds for systems that best handled all six worlds and were able to develop an overall Research and Development plan aimed at the year 2025.

The final report detailed a variety of technologies (e.g., unmanned aerial vehicles), systems (e.g., space information systems), and operational concepts (e.g., information integration) that have become part of the Air Force of today. The scenario exercises involved a large segment of the Air Force planning community and generally changed the nature of the debate within the Air Force from one involving what the future was going to look like to one involving which systems would be most appropriate for the Air Force to develop regardless of what the future looked like.

While the transportation sector arguably doesn't face a "climate-changed" world, the uncertain threat from climate change makes it prudent to plan as though the future transportation sector *will* face a climate-changed world. This puts the transportation sector in the same situation that the Air Force faced in 1995. The primary question is, "what should transportation infrastructure look like (e.g., in a region) given the uncertain threat of climate changes?" This suggests separately planning transportation networks for a (small) number of extreme climate-changed scenarios and looking across them for network elements that are robust against the uncertainties.

Higher Education and Robustness Methods (State/Local Level)[12]

Since 1960, California's higher education system has operated on the principle that all California residents who could benefit from a college education would receive one. The system that was erected to fulfill that guarantee was widely admired and emulated. By the mid 1990s, however, it was clear that three highly uncertain trends threatened future access to the state's higher education system. First, there was a surging baby "boomlet" that threatened to swamp the education system in the future. Second, the fraction of state resources devoted to higher education had been falling for several years. Third, the costs of higher education had been rising faster than inflation over the previous 35 years.

While these trends were generally agreed upon, their effect on the future of California higher education was contentiously debated among a wide variety of stakeholders. At one end of the spectrum, for example, there were predictions that state funding for higher education would show healthy growth over the succeeding two decades as the state economy grew and the fraction of state funding going to higher education remained constant. At the other end of the spectrum, there were predictions that state support for higher education would drop precipitously as increased state spending on corrections would cut the fraction of the state general fund allocated to higher education in half. Similarly, there were many different projections of the precise number of students who would seek higher education.

It is common for education planning to be fought out in the political arena. This can be seen in the recent battles about the teaching of science in Kansas, where fundamental decisions are made by the Board of Education on ideological grounds and are overturned by changes in the ideological commitments due to shifts in the composition of the Board. Those debates are often informed by scientific studies, but such studies rarely settle fundamental issues. Arguments generally revolve around different assumptions with each group defending its assumptions against those of the other groups. Exploratory modeling is an emerging field that attempts to "level the playing field," by utilizing models that encompass everybody's assumptions and look for policies that are robust – do reasonably well – under all of the competing assumptions.

The uncertainties involved in long-range planning in education are of a different nature than the uncertainties involved in climate change in the transportation sector. Nonetheless, the uncertainties in both cases lead to the possibility of a variety of worlds that are sufficiently different that the appropriate policies to prepare for each of those worlds are incompatible with one another. Further, the issues are sufficiently complex that testing policies against just a few possible future worlds can leave significant ambiguity about the best policy in the face of the uncertainties. This suggests the exploratory modeling approach that looks across hundreds or thousands of possible future worlds.

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[12] Details of this case can be found at http://www.rand.org/pubs/monograph_reports/MR971/index.html.

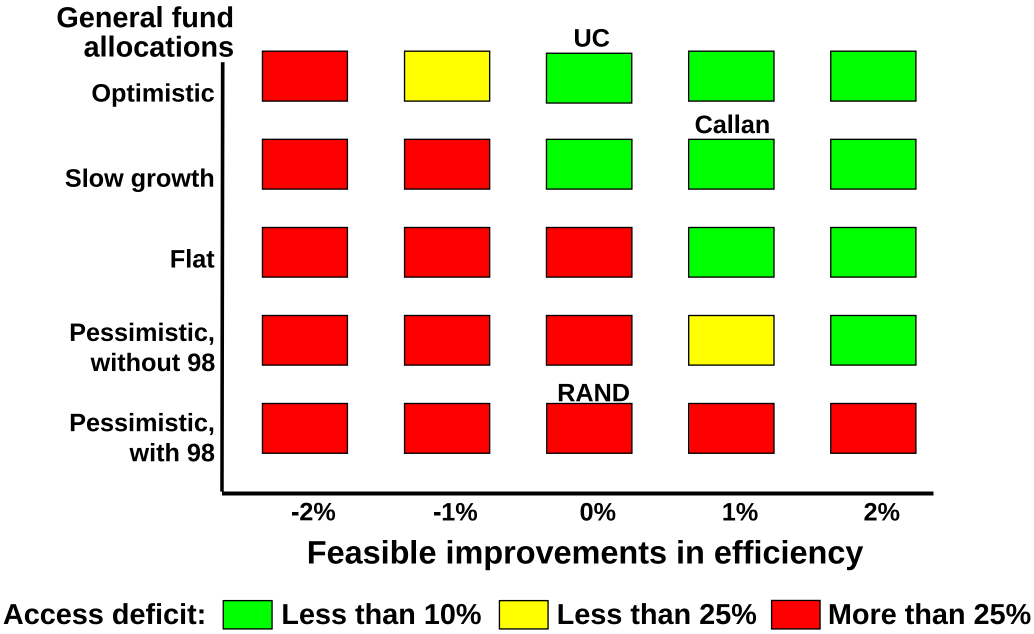
RAND applied exploratory modeling to problems in higher education in four states, California, Nevada, Kentucky, and Texas. The California case provides an instructive example of this type of analysis.

In 1997, RAND was commissioned to examine the issue of preserving access to higher education in California through the year 2014 – a span of 17 years. A typical approach to the issue would have been to adjudicate amongst the various conflicting predictions and improve on the predictions. The significant uncertainties of what policies would be adopted in the future, however, mitigated against such an approach. Instead, RAND took an exploratory modeling approach. In this case, instead of doing a complete robust decisionmaking exercise, the research focused on the first step of a robust decisionmaking approach – creating landscapes of plausible futures for California higher education and using the landscapes to identify those uncertainties and trends that were most salient to the choices of decisionmakers. That step should be instructive to transportation planners as they contemplate plausible climate change worlds.

The research team developed a simplified model focusing on three exogenous factors affecting the California higher education system: (1) increasing demand for higher education due to a growing population and increased participation rates among traditionally underrepresented demographic groups, (2) potential constraints on state funding for higher education, and (3) the degree to which productivity improvements could feasibly offset rising costs for higher education and decreasing revenues. In this way, by choosing a range of estimates for each of these factors, the predictions of each of the major stakeholders could be represented in the model.

The research considered three simple measures of the performance of the higher education system: (1) access deficit – the number of individuals who wanted to enroll, but could not be accommodated, (2) the number of first-time freshmen – a better measure of student population during a time when the time to graduation was changing significantly, and (3) bachelor's degrees awarded – a rough measure of the output of the higher education system.

The one "policy variable" used in the research was student fees. A full robust decisionmaking exercise would have tested a wide variety of policy options, but the use of a single policy lever in this case was sufficient to illuminate important uncertainties and trends. The model was run dozens of times, varying the internal parameters representing different assumptions about the future. This exercise, by itself, brought out an important point about the projections of various stakeholders. The model, by being able to reproduce the results of the other studies, showed that those varying projections were not caused by differences in data or analytic methodology, but by having used fundamentally different assumptions about the future. Figure 4 is an example of an output from the exploratory modeling exercise that allows the stakeholders to "locate themselves" in the output landscape. In some cases, this type of output can change an ongoing debate from one of arguments on data and methodologies to one of arguments on assumptions about the future. In Figure 4, for example, it becomes clear why the "UC" and "Callan" projections came to different conclusions than the "RAND" study did. Their assumptions put them in the green or "less than 10%" access deficit, while RAND's assumptions – using the same model – put them in the red or "more than 25%" access deficit. Further, one can see things in this view suggesting a very unstable situation, such as that the boundary line between <10% deficits and >25% is quite sharp.



General fund allocations	-2%	-1%	0%	1%	2%
Optimistic	🟥	🟨	UC 🟩	🟩	🟩
Slow growth	🟥	🟥	🟩	Callan 🟩	🟩
Flat	🟥	🟥	🟥	🟩	🟩
Pessimistic, without 98	🟥	🟥	🟥	🟨	🟩
Pessimistic, with 98	🟥	🟥	RAND 🟥	🟥	🟥

Feasible improvements in efficiency

Access deficit: 🟩 Less than 10% 🟨 Less than 25% 🟥 More than 25%

FIGURE 4 UC access deficits under different assumptions.

The more important use of exploratory modeling, however, is to find policies that do well across large areas of the output landscape. These policies are said to be robust to the uncertainties about the values that model variables will take in the future. By varying parameters in the model that represent policy options, one can watch how the “colors” in graphs such as Figure 4 change and all stakeholders can come to a better appreciation for the kinds of policies that are most robust across uncertainties about important variables such as general fund allocations and improvements in efficiency.

The outcomes of the robust decisionmaking analyses in the four states were different. Although in all four cases, the RDM analysis altered the nature of the debate (as expected), the overall effects varied with state, client, and question asked. It was in Nevada that the outputs of robust decisionmaking analysis had the greatest effect. In that case, the questions were how to manage higher education in the face of an exploding population. The analysis (done in 2001) explored issues such as mission differentiation, how many 4-year colleges would be required, and where they should be located. The analysis formed an important part of Nevada’s strategic plan for higher education and is mentioned in their University and Community College System of Nevada Master Plan.[13]

Experience suggests that to run an effective analysis of this type requires four basic conditions: (1) a situation that can be rendered into a computer model, (2) the ability to run the model dozens to hundreds of times, (3) the exploratory modeling software to interpret the results, and (4) a client who cares about the answer and can make decisions based on the analysis. In the case of transportation planning, the first condition holds, and the second condition could hold if

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[13] State of Nevada, *University and Community College System of Nevada Master Plan*, February, 2005. http://system.nevada.edu/News/Publicatio/UCCSN-Mast/UCCSN-Master-Plan-Revised_0205.pdf.

enough computational power were dedicated to the research (and that kind of computational power continues to improve with time), the third condition holds,[14] and the fourth, while crucial, can be controlled in the selection of the problem to be analyzed.

5. CONCLUSIONS

We believe that the tools and models currently used by transportation planners do an incomplete job of addressing uncertainty and that major flaws in the current planning methods are not widely acknowledged by their users. Transportation planning is done on the basis of point estimates (forecasts) of the future. They are likely to be wrong in their particulars, but perhaps close enough to right to be useful. Furthermore, the inadequacies of the system that flow from these flaws is to some extent offset by the adaptive behavior of millions of individual decisionmakers who use the system. Even current uncertainties could unmask those flaws by way of breakdowns to which those independent decisionmakers are unable to adapt. Climate change is a new and different challenge to the transportation network that adds to the likelihood that flaws in that network will be unmasked.

There are several methods that transportation planners could use to address the unique challenges posed by climate change. None is perfect for the job – there is no way at this point to analytically deduce the optimal means of addressing the challenges posed by climate change. These methods could, however, assist transportation planners in thinking about the very real possibility that climate change could seriously affect the adequacy and survivability of the nation's transportation sector. In addition, each of the methods could be used to explore other uncertainties in transportation planning. Most of the methods described in this paper address uncertainty by developing more than one future. Used in the context of transportation planning, a multiplicity of futures would allow planners to address the sensitivity of the transportation system to uncertainty about the future. For example, if two or more general land use regimes are plausible in the future, scenarios for each general land use regime could be run through full travel modeling runs to assess the impact of those regimes. An approach that uses multiple scenarios is particularly important in thinking about the potential effects of climate change. If, in New Orleans for example, land-use planners decide that climate change will cause too large a threat for low-lying areas, they might adopt land-use measures that would forbid building in low-lying areas. This would obviously affect the transportation system. It is not certain that such land-use restrictions will (or could, in the case of New Orleans) be adopted, but transportation planners could study the effects of land uses that would accommodate both possibilities. It may be that a different transportation infrastructure would handle both situations equally well – making the transportation system more robust to the potential effects of climate change.

The cost and time needed to assemble data and to run long sets of models will dampen enthusiasm for use in regular practice of methods that blend today's forecasting models with methods that employ multiple scenarios. The utility of scenario methods will need first to be demonstrated in research applications. If they show promise, in all likelihood they will lead to the development of modified methods of forecasting travel demand.

It is important that transportation planning address uncertainties more appropriately than it now does. This will require a rethinking and reworking of the entire transportation planning

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[14] At this point, the exploratory modeling software used at RAND is a proprietary product that is available for lease, but such exploratory modeling environments continue to evolve and emerge.

system. Methods that would be useful for addressing the challenges of climate change should be integrated into a revised planning system that handles current uncertainties plus those posed by climate change.