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Dynamic Adaptive Approach to Transportation-Infrastructure Planning for Climate Change: San-Francisco-Bay-Area Case Study

Thomas A. Wall, A.M.ASCE¹; Warren E. Walker²; Vincent A. W. J. Marchau³; and Luca Bertolini⁴

Abstract: Adaptation of existing infrastructure is a response to climate change that can ensure a viable, safe, and robust transportation network. However, deep uncertainties associated with climate change pose significant challenges to adaptation planning. Specifically, current transportation planning methods are ill-equipped to address deep uncertainties, as they rely on designing responses to a few predicted futures, none of which will occur exactly as envisioned. In this paper, we propose using dynamic adaptive planning (DAP), an emerging general strategic planning method, to account for deep uncertainties by building flexibility and learning mechanisms into plans that enable continuous adaptation throughout implementation. This paper first reviews uncertainty in general, introduces what is meant by *deep uncertainty*, and then introduces DAP. Then, DAP is applied to a case study of the Oakland approach to the San Francisco-Oakland Bay Bridge, which was initially assessed under the 2010–2011 FHWA Climate Change Vulnerability Assessment Pilot program, to illustrate how DAP could be applied as a response to climate change in the context of evolving transportation infrastructure adaptation planning practices in the United States. We conclude that DAP is well suited to account for the deep uncertainties of climate change in transportation and infrastructure planning, and provide suggestions for further research to better apply DAP in this field. DOI: [10.1061/\(ASCE\)IS.1943-555X.0000257](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000257). © 2015 American Society of Civil Engineers.

Author keywords: Adaptation; Climate change; Deep uncertainty; Dynamic adaptive planning (DAP); Transportation infrastructure.

Introduction

A growing body of evidence in the scientific community strongly suggests that the Earth's climate is changing. In 2007, the United Nations' Intergovernmental Panel on Climate Change (IPCC) released its fourth comprehensive assessment report, stating that "warming of the climate system is unequivocal, as is now evident from observed increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC 2007). There remains, however, considerable uncertainty about (Rahman et al. 2008)

- The timing of projected climate change impacts;
- How global changes will manifest as regional impacts; and
- What responses best protect against the adverse consequences of climate change impacts.

The transportation community is becoming increasingly concerned about how these climatic changes may affect various aspects of transportation system planning, operations, management, and

design (Dewar and Wachs 2008; Meyer 2006; Meyer et al. 2014; Savonis et al. 2008; Schwartz et al. 2013; USGCRP 2009). According to the Transportation Research Board (TRB 2008), temperature increases could lead to a softening of road surfaces, thermal expansion of the joints in bridges, rail line deformation, and equipment failures. Further, increases in intense precipitation events could lead to increases in flooding of roads, rail lines, and tunnels; overloading of drainage systems; increases in road scouring, road washout, damages to rail beds and support structures; and increases in soil moisture levels that could affect the integrity of structures.

In response to this, the transportation community's recent focus has been predominantly on adaptation of transportation infrastructure systems to the potential physical impacts of climate change, as evidenced by the numerous infrastructure risk and vulnerability assessment frameworks developed by agencies across the globe [e.g., Federal Highway Administration (FHWA) 2012b; Highways Agency and Parsons-Brinkerhoff 2009; Major and O'Grady 2010; PIEVC 2009; PIEVC and Engineers Canada 2008; TRB 2008]. However, Wilbanks et al. (2012) draw the important distinction when considering infrastructure and climate vulnerability that ultimately "services and not structures are what are important to users and decision-makers." This suggests that, while assessing and adapting the physical vulnerabilities of transportation infrastructure to the impacts of climate change (as is the current focus), it is important to recognize the vulnerabilities of services provided by infrastructure as we develop adaptation policies and plans in the face of uncertain future conditions.

Uncertainty is a common aspect of transportation, often stemming from its derived and interdependent nature, wherein uncertainties external to the transport system itself (e.g., regional economics, politics, land use) can affect transport operations, planning, and policymaking (van Geenhuizen et al. 2007). Numerous approaches to account for uncertainty in planning and policymaking have emerged over the past decades. Methods such as

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statistical modeling, simulation, and scenario planning are commonly used by transportation professionals to quantify and manage uncertainties; many of these methods have also been applied to characterize and explore climate change risks and uncertainties in the transportation and infrastructure sectors (e.g., Bjarnadottir et al. 2013; Khelifa et al. 2013; Lambert et al. 2013; Oswald and McNeil 2013). However, we suggest that: (1) these types of approaches are still not able to adequately address the range and depth of climate change uncertainties with regard to transportation infrastructure; and (2) the current focus in the transportation sector on physical infrastructure vulnerabilities may be improved if turned towards approaches suited to accounting for the broader, cascading impacts (Wilbanks et al. 2012) of infrastructure and service disruptions. The objective of this paper is to explore and illustrate the practical application of an innovative approach called dynamic adaptive planning (DAP) that can aid transportation professionals and infrastructure managers in addressing these two challenges by building adaptive robustness into plans, which allows them to change in response to uncertain developments over time.

In the following section of the paper, we define four levels of uncertainty, and explain that climate uncertainty is a Level 4 (deep) uncertainty. We then examine approaches that are available to deal with deep uncertainty, concluding that DAP is attractive for several reasons. The next sections then describe the steps involved in performing DAP, and then apply DAP in an illustrative case study of the Oakland Approach to the San Francisco-Oakland Bay bridge. This case is based on an evaluation by the Metropolitan Transportation Commission (MTC) as part of the FHWA's 2010–2011 Climate Change Vulnerability Assessment Pilot programs. The case study demonstrates how DAP could be used to design and implement an adaptive response to the deep uncertainties surrounding climate change as a complementary next step to current frameworks that seek to prioritize infrastructure according to vulnerability or risk. The final section provides the paper's conclusions and offers thoughts on future applications should the MTC (or other organizations) choose to pursue DAP for climate change adaptation planning.

Four Levels of Uncertainty

Generally speaking, uncertainty is defined as limited or inadequate information about past, present, or future events (Walker et al. 2013c). Uncertainty can derive from *natural variability* within a system or from *lack of knowledge* (Walker et al. 2003). In civil engineering, these types are commonly distinguished as (1) aleatory uncertainty, and (2) epistemic uncertainty, respectively (Abrahamson 2006; Apel et al. 2004; Der Kiureghian and Ditlevsen 2009; Oberkampf et al. 2004; Ross et al. 2009; Sun et al. 2012). The definition of uncertainty may then be broadened to “any departure from the unachievable ideal of complete determinism” (Walker et al. 2003).

In order to manage uncertainty, one must be aware that an entire spectrum of different levels of knowledge exists, ranging from the unachievable ideal of complete understanding at one end of the scale to total ignorance at the other. Policy analysts have different methods and tools to treat the various levels. For purposes of determining ways of dealing with uncertainty in developing plans, one can distinguish two extreme levels of uncertainty (complete certainty and total ignorance) and several intermediate levels (e.g., Courtney 2001; Walker et al. 2003; Makridakis et al. 2009; Kwakkel et al. 2010). Walker et al. (2003) have defined four intermediate levels:

- *Complete certainty* is the situation in which we know everything precisely. It is not attainable, but acts as a limiting characteristic at one end of the spectrum.

- *Level 1 uncertainty* represents the situation in which one admits that one is not absolutely certain, but one is not willing or able to measure the degree of uncertainty in any explicit way (Hillier and Lieberman 2001). Level 1 uncertainty is often treated through a simple sensitivity analysis of model parameters, where the impacts of small perturbations of model input parameters on the outcomes of a model are assessed.
- *Level 2 uncertainty* is any uncertainty that can be described adequately in statistical terms. In the case of uncertainty about the future, Level 2 uncertainty is often captured in the form of either a (single) forecast (usually trend based) with a confidence interval, or multiple forecasts (scenarios) with associated probabilities.
- *Level 3 uncertainty* represents the situation in which one is able to enumerate multiple plausible futures without being able to assign probabilities to them.
- *Level 4 uncertainty* represents the deepest level of recognized uncertainty; in this case, we know only that we do not know. We recognize our ignorance. Recognized ignorance is increasingly becoming a common feature of our existence, because catastrophic, unpredicted, surprising, but painful events seem to be occurring more often. Taleb (2007) calls these events *black swans*. He defines a black swan event as one that lies outside the realm of regular expectations (i.e., “nothing in the past can convincingly point to its possibility”), carries an extreme impact, and is explainable only after the fact (i.e., through retrospective, not prospective, predictability).
- *Total ignorance* is the other extreme on the scale of uncertainty. As with complete certainty, total ignorance acts as a limiting case.

Level 4 uncertainty is often called *deep uncertainty* (Walker et al. 2013b). That is, a situation in which analysts and decision makers do not know or cannot agree upon “(1) the appropriate models to describe the interactions among a system's variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes” (Lempert et al. 2003). These aspects of Level 4 uncertainty are evident in the sources of climate change uncertainty identified by Willows and Connell (2003), as well as the noted challenges in predicting probabilistically many aspects of climate change (Camp et al. 2013). We can, therefore, reasonably speak of climate change in terms of deep uncertainty (Rahman et al. 2008; Haasnoot et al. 2013).

Characterizing climate change with deep uncertainty complicates current approaches to strategic planning in the United States (and abroad). Risk management–based approaches to adaptation planning predominate in the global transportation sector (Wall and Meyer 2013); however, such approaches estimate impacts as a function of likelihood and magnitude of consequences. Reliance on probabilistic likelihood to identify, assess, and respond to uncertain climate change risks is problematic, since the emission scenarios upon which climate projections are based are assigned no measure of likelihood (Nakicenvoic et al. 2000). Thus, expert opinion is frequently used to determine qualitative or subjective probability distributions to describe the likelihood of future events or outcomes (Willows and Connell 2003), which simply “become statements of ‘degree of belief’” (Morgan 2003).

Approaches for Handling Level 4 Uncertainty

There are a variety of approaches and tools that have been developed for dealing with uncertainty in conducting a model-based planning study. Most of these (e.g., sensitivity analysis,

probabilities, statistics, Monte Carlo simulation) deal with Level 1 and Level 2 uncertainty (see, for example, Morgan and Henrion 1990). A few (e.g., scenario planning) deal with Level 3 uncertainty (van der Heijden 1996), and are used to identify a *robust static* plan (where *robust* means that the plan will perform acceptably well in a wide range of plausible scenarios).

Broadly speaking, although there are differences in definitions, and ambiguities in meanings, the literature offers four (overlapping, not mutually exclusive) ways for dealing with Level 4 uncertainty in making plans (e.g., Leusink and Zanting 2009):

- Resistance: plan for the worst possible case or future situation.
- Resilience: whatever happens in the future, make sure that the system can recover quickly.
- Static robustness: implement a (static) plan that will perform reasonably well in practically all conceivable situations.
- Adaptive robustness: plan to change over time, in case conditions change.

The first approach is likely to be very costly and might not produce a plan that works well, because of unanticipated surprises (black swans). The second approach accepts short-term pain (negative system performance), but focuses on recovery. Unlike most approaches for dealing with Level 1 and Level 2 uncertainties, the third and fourth approaches do not use models to produce forecasts. Instead of determining the best predictive model and solving for the plan that is optimal, but fragilely dependent on assumptions (as is done by approaches for dealing with Level 1 and Level 2 uncertainties), in the face of deep uncertainty it may be wiser to seek among the alternatives those actions that are most robust—that achieve a reasonable level of goodness across the myriad models and assumptions consistent with known facts. As shown by Lempert and Collins (2007), analytic approaches that seek robust plans are often appropriate when uncertainty is deep and a rich array of options is available to decision makers.

Identifying static robust plans requires reversing the usual approach to uncertainty. Rather than seeking to characterize uncertainties in terms of probabilities, a task rendered impossible by definition for Level 3 and Level 4 uncertainties, one can instead explore how different assumptions about the future values of these uncertain variables would affect the decisions actually being faced. Scenario planning (van der Heijden 1996) is one approach to identifying static robust plans. This approach assumes that, although the likelihood of various future worlds is unknown, a range of plausible futures can be specified well enough to identify a (static) plan that will produce acceptable outcomes in most of them. It works best when dealing with Level 3 uncertainties.

Many of the risk-based adaptation frameworks based on static robustness used in the transportation sector attempt to address the issues related to uncertainty about the future by complementing static robustness with an iterative approach, under which there is a periodic reidentification, reassessment, and response to new developments over time. Although this may begin to move towards an adaptive approach, it really only periodically updates a static plan, and does not respond to unforeseen events or new developments in real time.

Long-term robust plans for dealing with Level 4 uncertainties will generally need to be truly adaptive—i.e., plans that can be easily changed in response to changing conditions. An adaptive plan is developed with an awareness of the range of plausible futures that lie ahead, is designed to be changed over time as new information becomes available, and leverages autonomous response to surprise. Eriksson and Weber (2008) call one such approach to dealing with deep uncertainty *adaptive foresight*; Quay (2010) calls a similar approach *anticipatory governance*; Lempert et al. (2003) call their approach *robust decision making* (RDM);

Ranger et al. (2013) recently introduced a similar approach, *adaptation pathways*, in the specific context of major infrastructure adaptation planning.

Walker et al. (2001) have specified a generic, structured approach for developing adaptive plans for practically any policy domain, which they call dynamic adaptive planning (DAP). This approach allows implementation to begin prior to the resolution of all major uncertainties, with the plan being adapted over time based on new knowledge. It is a way to proceed with the implementation of long-term plans despite the presence of uncertainties. DAP makes adaptation explicit at the outset of plan formulation. Thus, the inevitable changes become part of a larger, recognized process and are not forced to be made repeatedly on an ad hoc basis. Under this approach, dealing with significant changes in the system would be based on an analytic and deliberative effort that first clarifies system goals, and then identifies plans designed to achieve those goals, and ways of modifying those plans as conditions change. Using DAP, individual actors would carry out their activities as they would under normal policy conditions. But planners, through monitoring and corrective actions, would try to keep the system headed toward the original goals. McCray et al. (2010) describe it succinctly as keeping plans “yoked to an evolving knowledge base.” DAP appears to be a robust, efficacious, and cost-effective way of dealing with Level 4 uncertainties (Kwakkel et al. 2012b; Yzer et al. 2014). It provides a promising and viable means by which to account for climate change uncertainties and broader impacts in transportation planning and infrastructure management by building upon existing practices, and integrating greater flexibility and learning mechanisms into management plans.

The following section describes the steps in DAP. The next section will then illustrate DAP using a case study that addresses adaptation planning for transportation infrastructure in the San Francisco Bay area. The infrastructure considered in this example was originally part of a study conducted by the Metropolitan Transportation Commission (MTC), called *Adapting to Rising Tides* (ART) (Nguyen et al. 2011b), which piloted the Federal Highway Administration’s Conceptual Risk Assessment Model for climate change adaptation (FHWA 2012c). Examining the ART study enables an explorative discussion of DAP’s contribution within current transportation planning practices, in particular within the context of the evolving transportation adaptation practices in the United States. In the final section, the efficacy of DAP for transportation infrastructure planning in the face of climate change is discussed, and some suggestions are offered.

Dynamic Adaptive Planning (DAP)

DAP was first outlined by Walker et al. (2001), and made more concrete by Kwakkel et al. (2010) and Walker (2011). DAP has been explored in various applications, including flood risk management in the Netherlands in light of climate change (Rahman et al. 2008) and policies with respect to the implementation of innovative urban transport infrastructures (Marchau et al. 2008), congestion road pricing (Marchau et al. 2010), intelligent speed adaptation (Agusdinata et al. 2007), and magnetically levitated (Maglev) rail transport (Marchau et al. 2010). Central to DAP is the acknowledgement of uncertainty: that “in a rapidly changing world, fixed static policies are likely to fail” (Kwakkel et al. 2010). As new information becomes known over the life of a policy or plan, it should incorporate the ability to adapt dynamically through learning mechanisms (Kwakkel et al. 2010; Walker 2011; Walker et al. 2013a).

In brief, DAP involves developing a basic plan, identifying the vulnerabilities of the plan (i.e., how it might fail), developing a

series of actions to guard against these vulnerabilities, and establishing a series of signposts to monitor the uncertain vulnerabilities. During implementation, if the monitoring program indicates that one or more of the signposts reaches predetermined critical levels, predetermined adaptive actions are taken to ensure that the basic plan stays on track to meet its goals and objectives. The basic plan, monitoring program, and planned adaptations remain in place unless monitoring indicates that the intended outcomes can no longer be achieved, or if the goals and objectives of the basic plan change. In these instances, the adaptive plan is then reassessed. The elements of flexibility, adaptability, and learning enable DAP to adjust to new information as it becomes available, and therefore to deal with deep uncertainty (Marchau et al. 2010).

DAP occurs in two phases: (1) a design phase, in which the dynamic adaptive plan, monitoring program, and various pre- and post-implementation actions are designed, and (2) an implementation phase, in which the plan and the monitoring program are implemented and adaptive actions are taken, if necessary. The five steps of the design phase are shown in Fig. 1. Once the basic dynamic adaptive plan is established through the five design steps shown, the plan is implemented, and monitoring commences.

Step I (Stage Setting) and Step II (Assembling a Basic Plan)

As a foundation for the plan, the goals and objectives that are important to the planners and stakeholders are defined, as is what constitutes a successful outcome. Planning constraints are identified and a series of basic options are analyzed. In Step II, the basic plan that meets the goals and objectives is assembled from the options that have been identified. The necessary conditions for success are outlined (e.g., physical, political, economic, or other conditions necessary for the plan to succeed). It is important in this step to identify a full range of necessary conditions for success, as these are used in later steps to identify vulnerabilities, signposts, and triggers. For this reason, it is important to involve managing agencies, as well as other stakeholders from local and regional communities.

Step III (Increasing the Robustness of the Basic Plan)

The static robustness of the basic plan is increased through a series of actions taken in direct response to vulnerabilities and opportunities. Vulnerabilities that can diminish the success of the basic plan, and opportunities that can increase the success of

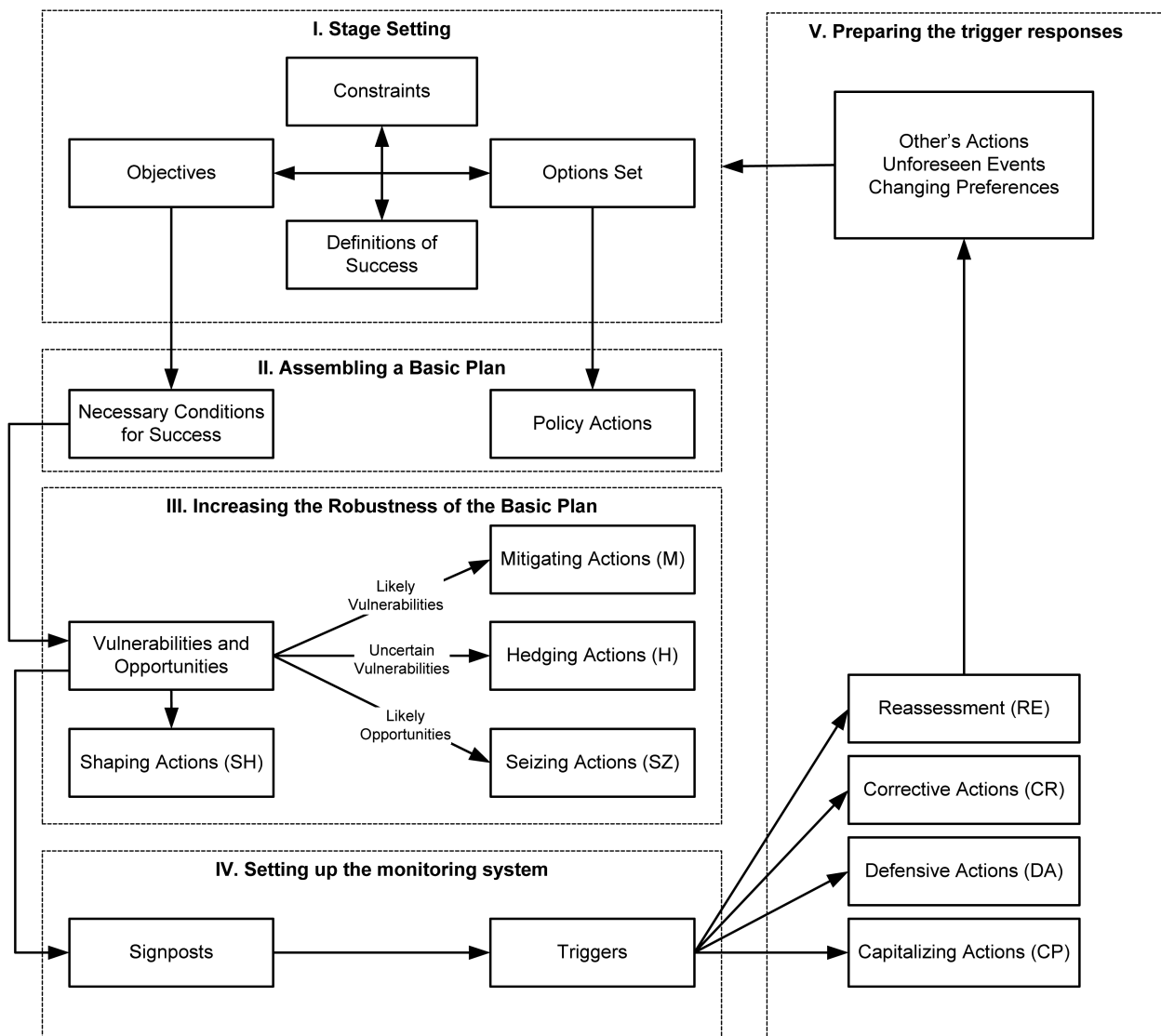


Fig. 1. Five-step process of dynamic adaptive planning (adapted from Walker 2011)

the basic plan, are first identified. Analytical tools, such as exploratory modeling and analysis (EMA) (Bankes et al. 2013) or scenario analysis (van der Heijden 1996) may be used to investigate plausible future conditions to ensure that relevant vulnerabilities, particularly uncertain vulnerabilities, are identified. An approach based on EMA, called scenario discovery (Bryant and Lempert 2010; Kwakkel et al. 2012a), can be used to identify the scenarios in which a plan would perform poorly. These scenarios highlight the vulnerabilities of the plan. Then, actions can be specified to protect the plan from failing if these scenarios occur.

Four types of actions can be taken immediately upon implementation of the plan to address these vulnerabilities (and opportunities). These four types of actions are (Kwakkel et al. 2010):

- Mitigating actions (M): Actions that reduce adverse impacts on a plan stemming from *likely* vulnerabilities.
- Hedging actions (H): Actions that reduce adverse impacts on a plan, or spread or reduce risks that stem from *uncertain* vulnerabilities.
- Seizing actions (SZ): Actions that take advantage of opportunities that may prove beneficial to the plan.
- Shaping actions (SH): Actions taken proactively to affect external events or conditions that could either reduce the plan's chance of failure, or increase its chance of success.

Step IV (Setting up the Monitoring System)

A monitoring program is developed that will identify and initiate responses to new conditions over the course of the plan. This constitutes the learning component that gives DAP the flexibility to adapt to new conditions over time. This introduces the element of adaptive robustness, which makes DAP able to deal with Level 4 uncertainty, in comparison to other approaches that are based on responding to a single or small set of hypothesized futures to achieve static robustness. The monitoring program consists of signposts and triggers. *Signposts* specify the types of information and variables that should be monitored to show (1) whether the basic plan is achieving its goals, and/or (2) whether the vulnerabilities and opportunities identified in Step 3 are impeding the plan from achieving its goals. *Triggers* are the critical signpost levels or events that, when they occur, signify that actions should be taken to ensure the basic plan remains on course to achieve its specified goals.

Step V (Preparing the Trigger Responses)

A series of trigger-event actions are developed prior to implementation to allow the plan to adapt to new conditions if a trigger-event occurs over the life of the plan, further contributing to the plan's adaptive robustness. Preparation of these actions may include carrying out studies, engineering design work, or developing supporting political and financial plans. The results of these efforts are then saved for use if trigger events occur after the actions in Steps II and III have been implemented. Kwakkel et al. (2010) describes the four types of adaptive trigger-event actions that can be taken:

- Defensive actions (DA): Actions taken *after the fact* to clarify the plan, preserve its benefits, or meet outside challenges in response to specific triggers, but that leave the basic plan unchanged.
- Corrective actions (CR): Adjustments to the basic plan in response to specific triggers.
- Capitalizing actions (CP): Actions taken *after the fact* to take advantage of opportunities that further improve the performance of the basic plan.

- Reassessment (RE): A process initiated when the analysis and assumptions critical to the plan's success have lost validity (i.e., when unforeseen events cause a shift in the fundamental goals, objectives, and assumptions underlying the basic plan).

DAP Implementation and Adaptation

The dynamic adaptive plan is then implemented. The basic plan identified in Step II is implemented; the mitigating, hedging, seizing, and shaping actions developed in Step III are taken; and the monitoring program developed in Step IV commences. If one of the signposts' trigger events occurs after implementation of the basic plan, one or more of the adaptive actions developed in Step V is executed. If the original objectives of the plan and constraints on it remain in place upon occurrence of the trigger event, then defensive or corrective actions will be taken. If the monitoring program encounters an opportunity, then capitalizing actions will be taken. If the monitoring program indicates a change that invalidates the basic plan's goals, objectives, or intended outcomes (e.g., vulnerabilities exist or evolve beyond those considered during the Step III—for example, the occurrence of a black swan event), then the adaptive plan is reassessed. Reassessment does not mean completely starting over, as the knowledge of outcomes, objectives, measures, and so forth learned during the initial DAP process would accelerate the new planning process (Kwakkel et al. 2010).

Case Study Illustrating DAP

To show how DAP could be used to deal with climate change uncertainties in transportation infrastructure planning and management, this section applies DAP to an infrastructure vulnerability study conducted in the San Francisco Bay area. DAP serves as an extension of the climate change vulnerability study by providing a framework to develop and implement an adaptive response plan.

In 2010, the United States Federal Highway Administration sponsored a series of five Climate Resilience Pilot Studies (FHWA 2012a) to implement and offer feedback on their Conceptual Risk Assessment Model for climate change adaptation (FHWA 2012c). One of the studies, *Adapting to Rising Tides* (ART) (Nguyen et al. 2011b), was conducted by the Metropolitan Transportation Commission (MTC), which is the metropolitan planning organization (MPO) for San Francisco. ART focused primarily on the impacts of sea level rise (SLR), and the compounding effects of storm surges and wave action, on coastal infrastructure in Alameda County (from Emeryville south to Union City, along the eastern shore of the San Francisco Bay). The Adapting to Rising Tides (ART) pilot study addressed multiple transportation infrastructure types (roads, bridges, tunnels, an airport) and multiple transportation modes (roads, transit, bike/pedestrian). The ART pilot study also involved Bay-area stakeholders in addition to the MTC, including the San Francisco Bay Conservation and Development Commission (BCDC), the California Department of Transportation (Caltrans), Bay Area Rapid Transit (BART), and multiple local agencies and municipalities. Thus, ART provides a good platform upon which to explore DAP's application in the context of local and regional development concerns.

In this case study, we examine the transportation link between San Francisco and Alameda County. To better and more clearly illustrate the application of DAP in such planning exercises, the case study's focus is limited to one specific element of the transportation infrastructure system that was evaluated in ART: the Oakland approach to the San Francisco-Oakland Bay Bridge (also called the Oakland Touchdown), as shown in Fig. 2. The Bay

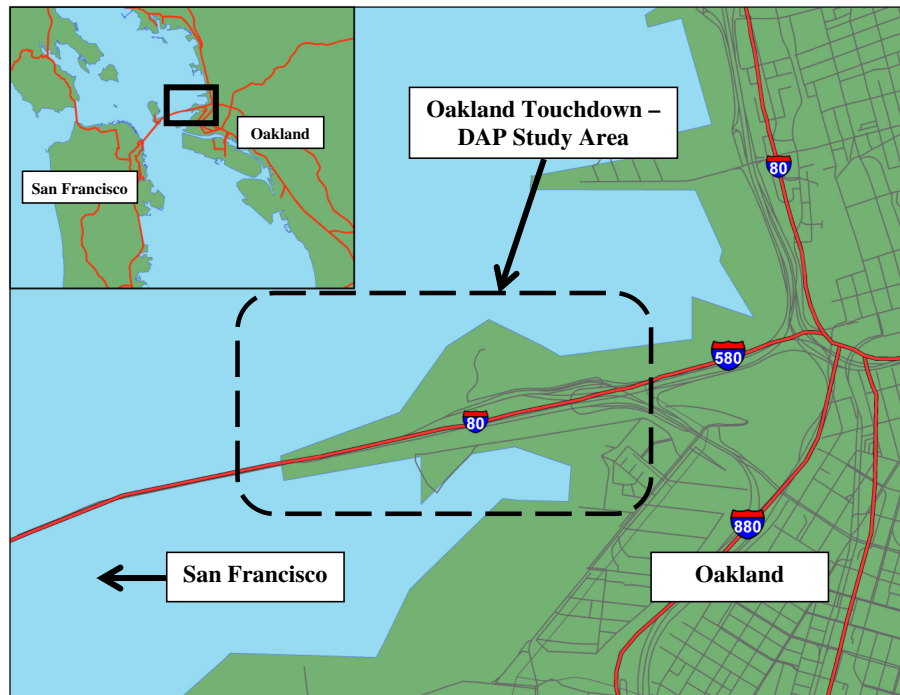


Fig. 2. DAP San Francisco/Oakland case study area (data from Metropolitan Transportation Commission in San Francisco and the U.S. Department of Commerce)

Bridge spans were outside of the scope of the ART study's analysis and, due to their elevation, are not as susceptible to SLR. Therefore, this case study focuses on the Oakland approach (as analyzed in ART) as a means of providing *access* to the bridge, assuming that if access is disrupted, the entire Interstate 80 link across the bridge is disrupted. Additionally, given the discussion in Wilbanks et al. (2012) that the services provided by infrastructure, and not infrastructure itself, are more important to users and decision makers, we consider that the Bay Bridge provides both roadway and transit services (i.e., bus) to users in complement to other cross-bay facilities and modes (e.g., BART, San Francisco Bay Ferry).

The primary sources of uncertainty related to the success of the Bay Bridge as a transportation link between San Francisco and Alameda County are: (1) the uncertainty of sea level rise and storm surge inundation sufficient to disrupt roadway and toll-plaza operations; (2) the uncertainty of changes in long-term travel and land use patterns in the East Bay due to climate change and due to social, economic, and technological developments; and (3) the uncertainty of financial and/or political support for climate change adaptation measures. Although a broad range of concerns and vulnerabilities are considered, it should be understood that we are using this example to illustrate DAP and that it is not exhaustive in its treatment of plausible future conditions.

It is particularly important to consider the impacts of climate change and other developments on population, land use, and travel demand. Future temperature extremes and extreme weather may influence gradual, long-term shifts in population centers or land use patterns, which could lead to significant changes in travel demand. The impact of these climate changes will also be compounded by and interact with social, economic, and technological developments in unpredictable ways. The compounding impact of numerous uncertain, unpredictable, interacting systems (economic, social, technological, climatologic) that affect land use and travel demand leads to a characterization of this as a situation of planning under deep uncertainty.

Case Study: Defining the Problem

There are several sources of uncertainty relating to the Oakland approach. The primary climate uncertainties are the extent and timing of impacts. The ART project considered regional climate changes that include sea level rise (SLR), storm surge, and related coastal flooding. These climate impact concerns are consistent with those outlined by the U.S. Department of Transportation for coastal locations (Savonis et al. 2008). The ART vulnerability analysis (Nguyen et al. 2011a) incorporated scenario analysis to explore plausible future conditions. The uncertainty associated with timing was explored by considering two sets of SLR scenarios: midcentury impacts and end-of-century impacts. Within these two sets of scenarios, the uncertainties associated with the extent of impacts were explored by evaluating mean higher high water (MHHW), 100-year still-water elevations (SWEL), and a 100-year SWEL plus wind scenario. Thus, a total of six climate impact scenarios were considered. ART scenario analysis projected inundation depths ranging from 0 to 1.52 m (0 to 5 ft) (Nguyen et al. 2011a).

In addition to the physical impacts of climate change, other related uncertainties exist that should be addressed in DAP. Specifically, changes in land use and the broader societal context may cause travel demand to (1) exceed the capacity of the existing crossing, or (2) drop below levels that justify continued investment in the operation and maintenance of the crossing. Additionally, financial and stakeholder support are uncertainties that could impact the design and implementation of the plan itself, and therefore must be considered when developing the basic plan and action sets. These uncertainties were not explicitly considered in ART, but are incorporated in this case study of DAP.

The exploration of future climate vulnerability scenarios provides the foundation upon which the basic plan can be constructed and provides insight into potential signposts for monitoring. The scenarios also aid in developing sets of additional actions to be taken immediately upon implementation (time = 0), and adaptive

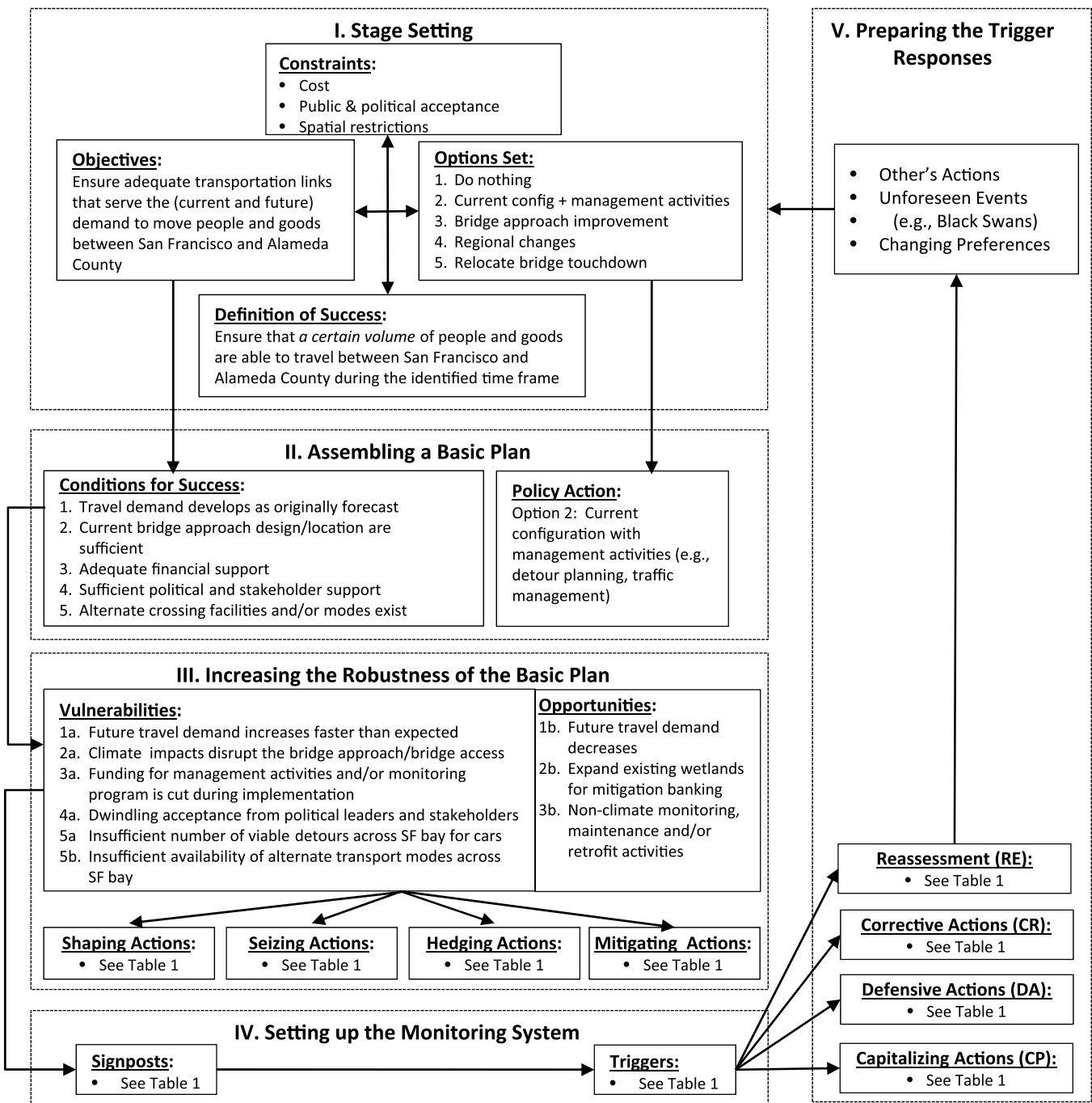


Fig. 3. Dynamic adaptive planning process for Oakland approach case study

actions that are taken during the implementation of DAP (time > 0) in response to trigger events. The inputs and steps of the DAP process specific to this case study, which correspond to the generic steps shown in Fig. 1, are outlined in Fig. 3, and are discussed in detail throughout this section.

Case Study: Step I (Setting the Stage)

In setting the stage for DAP, it is important to consider the broader regional development goals, in addition to the infrastructure itself, and how the infrastructure affects those goals. In this case, regional visioning or planning efforts, such as *Plan Bay Area* (Association of Bay Area Governments and Metropolitan Transportation

Commission 2013a, b) provide valuable insight for setting the stage for DAP. For example, the preferred transportation visioning scenario for the Plan Bay Area focuses 86% of its funding to operate and maintain the existing transportation network. The preferred land use visioning scenario focuses on job and housing growth in priority development areas (PDAs), which are primarily in the region's core. Job growth (in number of jobs) from 2010–2040 is projected to be greatest in San Francisco (~190,000 jobs), whereas 2010–2040 population growth is projected to be greatest in Alameda County (~2 million).

These development goals underscore the vital need for a viable transportation system connecting San Francisco with Alameda County, of which the Bay Bridge (the focus of this case study)

is one component. They also reflect the region's commitment to infrastructure investments to maintain the viability of such links (this will become particularly important in identifying plan constraints and vulnerabilities). Considering the regional development vision, a reasonable goal for this step in DAP may simply be the following:

Objective: To ensure adequate transportation links that serve the (current and future) demand to move people and goods between San Francisco and Alameda County.

Definition of Success: To ensure that *a certain volume* of people and goods are able to travel between San Francisco and Alameda County during the identified time frame.

Constraints: There are numerous constraints on possible options. Nguyen et al. (2011a) identify constraints and other criteria for option selection in four general thematic areas: economy, ecology, equity, and governance. For this illustrative case study, we simply consider:

1. **Cost:** It is unlikely that funds are immediately available to undertake large-scale infrastructure modification, new construction, or land use changes.
2. **Public and political acceptance:** The political climate and public attitude will influence, among other things, the degree to which action can be taken and the willingness to support roadway and crossing improvements.
3. **Spatial restrictions:** Such restrictions may limit the amount, breadth, and types of physical actions that can be taken.

Options set: The options provided in this case study are not meant to be exhaustive. Although the goal and the definition of success are framed in the broader context of transportation between San Francisco and Alameda County, the scope of this case study has been limited to examine only those options directly related to the Bay Bridge. Thus, the options set excludes other transportation options such as building a tunnel, an additional bridge, or implementing new ferry or transit systems. *Adapting to Rising Tides* developed an extensive options set for the Bay Bridge to achieve the stated goal. These options, originally developed by Nguyen et al. (2011a), have been rearranged here, and two additional options (numbers 1 and 5) have been defined.

1. **Do nothing:** Maintain the current approach configuration with existing operations and maintenance plans;
2. **Current configuration + management activities:** Temporary closures due to inundation and extreme events could be managed with detour planning and the provision of alternate modes (e.g., BART, ferries); this option is likely to be acceptable only if disruptions are rare;
3. **Bridge approach improvement:**
 - a. **Improve drainage:** Disruption of the freeway and toll plaza could potentially be shortened by allowing for more rapid drainage of flood waters if storm/high-tide inundation occurs;
 - b. **Retrofit:** To increase resilience to inundation, toll plaza electrical systems/wiring could be raised; buildings, entrances, and toll booths could be made more water-proof;
 - c. **Raise approach road surface:** The roadway surface and toll plaza could be raised above the projected inundation elevations (this is more applicable to the lower, mid-century projections); and
 - d. **Build new causeway:** The roadway surface and toll plaza could be raised above the projected inundation elevations (this is more applicable to the higher, end-of-century projections).
4. **Regional changes:**
 - a. **Create berm:** Inundation or incursion from rising tides could be prevented with a berm along the freeway

perimeter, and near the off-ramps and on-ramps (this is more applicable to the mid-century scenario);

- b. **Construct levees:** A levee could be constructed and the roadway could be placed along its top (this is more applicable to the end-of-century projections); the levee could also be built as an addition to the berms in the previous option;
 - c. **Construct floodwall:** Wave overtopping and flooding of the roadway could be prevented by a perimeter floodwall, although this would require modification of existing roadway drainage; this floodwall could be reconstructed/modified over time to track with flooding impacts; and
 - d. **Support wetland growth:** Storm surge and wave action could be absorbed by increased growth of the existing wetlands, thus reducing inundation at the roadway surface and toll plaza.
5. **Relocate the bridge touchdown:** Due to spatial constraints, the location of the bridge span itself, and the recent investment in new bridge spans, this option is very unlikely to be needed; however, in other infrastructure applications, relocation may be a valuable option, and is considered here for logical consistency.

Case Study: Step II (Assembling a Basic Plan)

In this step, the basic plan is selected from the options outlined in Step I, and the necessary conditions for success are identified. Basic plan selection is heavily influenced by the constraints identified. In this illustrative case we speculate that the deep epistemic uncertainty surrounding the timing and extent of future climate impacts [ART projected inundation anywhere from 0 m up to 1.52 m (5 ft) across multiple scenarios and time frames (Nguyen et al. 2011a)] suggests that Options 3 through 5 are likely to be too risky, as they require significant up-front capital investment to put in place systems that may or may not be adequate given potential future impacts, or conversely may not be necessary at all. However, the ART climate impact analysis suggests that, across multiple scenarios and timeframes, some level of climate impact will occur, and thus some amount of proactive planning is appropriate; this indicates that Option 1 (do nothing) is likely to be insufficient. Thus, we select Option 2 (current configuration + management activities) as the basic plan.

Basic plan: Option 2 will use the existing bridge approach configuration, but will also implement various management strategies. Examples of management strategies include bypass/detour planning, alternate crossing mode planning (e.g., increased BART and ferry service during disruptions), traffic management, and travel demand management. The management strategies would encompass both the planning and, as needed, the installation of additional signage, information systems, or other roadway assets to facilitate their implementation.

Conditions for success: The conditions necessary for the basic plan (Option 2) to succeed derive from the goal and definition of success identified above, as well as from the constraints, to form the practical criteria for success. These conditions are:

1. **Travel demand develops as originally forecast:** This demand is (1) sufficient to justify the bridge, and (2) the roadway capacity is sufficient to meet the travel demand, but (3) the demand does not exceed the capacity of the bridge.
2. **The current design and location of the bridge approach are sufficient:** The physical design is capable of withstanding the projected sea level rise and storm surge scenarios at the current location.

3. Adequate financial support: Sufficient funding exists for the continued support of the basic plan, monitoring program, and adaptive actions.
4. Sufficient support from political leaders and other stakeholders: Sufficient societal support exists to support the basic plan.
5. Alternate crossing facilities and/or modes exist: Viable alternate travel modes and cross-bay links exist within the network to support traffic management, travel demand management, and mode-shift.

Case Study: Step III (Increasing the Robustness of the Basic Plan)

To increase the robustness of the basic plan, vulnerabilities and opportunities are identified based on the conditions for success necessary for the basic plan to meet its stated goal. Actions are then specified to guard the success of the basic plan from these vulnerabilities and to capitalize on opportunities. Table 1 shows how the conditions for success are linked to the vulnerabilities and opportunities, and how these are then linked to the actions. The actions (hedging, seizing, shaping, and mitigating) shown in Column 4 of Table 1, are then executed upon implementation of the basic plan (i.e., at time = 0) to increase the robustness of the plan.

The vulnerabilities and opportunities of the basic plan are shown in Column 2 of Table 1. Vulnerabilities and opportunities are either (fairly) certain or uncertain. This characteristic of the vulnerabilities and opportunities is shown in Column 3 of Table 1. For example, one *certain* vulnerability of the plan is that there are no reliable bypasses/detours as alternative routes. This would be good to know well in advance. Studies identifying and investigating the viability of alternate routes could begin to be made at the time the basic plan is implemented (given the importance of the existing bridge, it is likely Caltrans has already carried out this action) to avoid the need to do this at the last minute. For the purposes of this case, the most important *uncertain* vulnerability is the extent to which local climate changes will affect the bridge approach operations and/or its drainage system. To protect the basic plan from failure, an environmental monitoring and approach disruption monitoring program should be implemented to hedge against this vulnerability.

The opportunities that exist are primarily concerned with identifying synergies between existing management practices and the adaptive actions to be designed in Step V. For example, the asset management program may already contain provisions for monitoring the physical condition of the approach as part of the bridge inventory and taking preventive actions as needed. The adaptive plan could easily be combined with this effort, thereby spreading the cost. Huq and Reid (2004) assign the label mainstreaming to actions that incorporate “potential climate change impacts into ongoing strategies and plans.”

Another opportunity is related to the expansion of existing wetlands near the bridge approach. Wetland expansion at the Oakland Touchdown site could be treated as a wetland mitigation bank in compensation for other Caltrans project sites where wetland encroachment is an unavoidable impact of construction or expansion.

Case Study: Step IV (Setting up the Monitoring System) and Step V (Preparing the Trigger Responses)

In Step IV, a monitoring program is established to keep track of whether the program is on course to achieving its desired outcomes, requires actions beyond the basic plan to ensure that it achieves its goals, or requires reassessment. This is accomplished

by identifying signposts for the uncertain vulnerabilities and opportunities defined in Step III, and identifying trigger events for each signpost, the occurrence of which indicates that some adaptive action is required to achieve adaptive robustness. Note that certain vulnerabilities (Table 1) do not require monitoring, since their conditions are known during the design phase, and actions have been taken at the time the basic plan is implemented to mitigate their effects.

The identification of signposts and trigger levels requires a detailed engineering analysis of the infrastructure asset itself (in the case of physical vulnerabilities), as well as the engagement of stakeholders from various planning, funding, community, and development agencies concerned with the bridge to discuss important non-design-based vulnerabilities (e.g., changes in funding or land use). These analyses and discussions are necessary to identify the correct and mutually agreed upon signposts to be monitored (based on the perspectives and interests of the various stakeholders), and also to provide the opportunity to gauge levels of risk-sensitivity. A detailed understanding of risk- or impact-sensitivity is useful in setting appropriate trigger levels. For example, the MTC, Caltrans, and community groups could identify several frequencies and durations for roadway disruption (see Vulnerability 2a in Table 1) to associate with multiple trigger levels (e.g., 1 disruption in 10 years may be *low*, 1 in 5 years may be *mid*). Relevant engineering studies of the infrastructure, and knowledge of return period-based design practices based on these trigger levels, could then inform the appropriate design of various adaptive actions.

The adaptive actions taken in response to trigger events (e.g., corrective actions, defensive actions, capitalizing actions, or reassessment) that occur after the basic plan’s implementation (i.e., time > 0) are developed in Step V. For example, the adequacy of the current approach roadway and toll plaza drainage system is an uncertain vulnerability. Step IV establishes a drainage system monitoring program and a critical facility disruption frequency/duration condition (i.e., trigger level) based upon stakeholder input and engineering analysis. In Step V, a drainage system retrofit is designed, but not yet implemented, that would increase drainage capacity or otherwise improve the system in response to the critical disruption frequency trigger event established in Step IV. The monitoring program details (i.e., signposts and trigger events), and corresponding sets of adaptive actions are shown in the right-most columns of Table 1. Note that each corresponds directly with one or more of the vulnerabilities and opportunities identified in Step III.

Case Study: DAP Implementation

The dynamic adaptive plan is then implemented. That is, at time = 0, the basic plan from Step II is implemented; the mitigating, hedging, seizing, and shaping actions from Step III are taken; and the monitoring program from Step IV is initiated. The basic plan remains in place and the monitoring program continues as long as the signposts signify that the plan is on course to achieve its intended outcomes (Kwakkel et al. 2010). If at some time over the life of the plan (i.e., at some time > 0) a trigger event occurs for any of the signposts being monitored, the predesigned adaptive actions (i.e., corrective, defensive, capitalizing, or reassessment actions) are taken to ensure that the plan stays on track to meet its goals. For example, if stormwater drainage monitoring indicates that the system has exceeded capacity (i.e., a certain number of occurrences within a specified time frame), the corrective actions are triggered to retrofit the drainage system and increase its capacity. Note that the corrective actions have been designed (in Step V)

Table 1. Vulnerabilities and Opportunities in the Basic Plan and Related Actions

Condition for success	Vulnerability(V)/ opportunity (Op)	Certain/ uncertain	Actions taken at time = 0 (increase basic plan robustness)	Signpost monitoring (begins at time = 0) and trigger events	Actions taken at time > 0 (adaptive actions)
1. Travel demand develops as originally forecast	V a. Future travel demand increases faster than expected	Uncertain	(H) Develop alternate traffic management plans for increased demand scenarios (e.g., tolling, public transit, or telecommuting incentives) above those planned for in the basic plan	<i>Monitor</i> bridge traffic volume Trigger: if average daily volume exceeds upper threshold, take CR actions <i>Monitor</i> updated land-use and travel demand forecasts, regional visioning scenarios for new developments that incorporate climate-related factors Trigger: if available and forecasts differ significantly from those available at basic plan implementation, take RE action <i>Monitor</i> bridge traffic volume Trigger 1: if volume drops below lower threshold, take CP-1-action Trigger 2: if volume remains below threshold for predetermined amount of time (e.g., several years), take CP-2 action	(CR-1) Implement additional traffic management plans (e.g., increased tolling) in case those developed as part of the basic plan become insufficient (CR-2) Retrofit toll plaza to increase throughput capacity (RE) Reassess the plan
2. Current bridge approach design and location are sufficient	Op b. Future travel demand decreases	Uncertain	(SZ) Conduct analysis of alternate uses of bridge roadway facilities (e.g., transit facilities, bicycle facilities, touristic facilities)	<i>Monitor</i> storm water drainage system Trigger 1: if drainage volume exceeds capacity for a specified number of incidents per year, take CR-1 <i>Monitor</i> frequency of roadway operations disruption Trigger 1: if disruption frequency exceeds low threshold, take CR-2 action Trigger 2: if exceeds mid threshold, take CR-3 action Trigger 3: if exceeds high threshold, take CR-4 action Trigger 4: if exceeds critical threshold, take RE action <i>Monitor</i> bridge approach embankment for erosion/deterioration due to storm surge/wave action Trigger 1: if any occurs to a specified level, take CR-3, CR-5 <i>Monitor</i> state/regional-level climate change projection development Trigger 1: if new climate (sea level rise) projections become available that differ significantly from current scenarios, take RE action <i>Monitor</i> area transportation projects where wetlands may be necessarily disturbed for construction Trigger 1: if project exists, take CP-action	(CP-1) Implement revised traffic management plans (e.g., adjust tolling to decreased volumes) (CP-2) Implement alternate uses of portion of the bridge (e.g., bicycle facilities, touristic facilities) (CR-1) Improve/retrofit storm water drainage system to increase capacity and allow for more rapid drainage of floodwaters (CR-2) Retrofit/waterproof toll plaza electrical systems, toll booths, and related buildings to increase resilience to inundation (CR-3) Construct berm to protect roadway and toll plaza from mid-century flooding projections (CR-4) Construct levee (or expand berm, if CR-2 is taken) to elevate the approach roadway surface above end-of-century projections (CR-5) Install armoring material (e.g., rip-rap) to protect embankment from further erosion (RE) Reassess the plan
	Op b. Expand existing wetlands for mitigation banking	Uncertain	(SZ) Create additional wetlands/ expand extent of existing to reduce storm surge and wave action disruption impacts		(CP) Implement wetland expansion plan to mitigate necessary wetland disturbance at nearby agency construction project site

Table 1. (Continued.)

Condition for success	Vulnerability(V)/ opportunity (Op)	Certain/ uncertain	Actions taken at time = 0 (increase basic plan robustness)	Signpost monitoring (begins at time = 0) and trigger events	Actions taken at time > 0 (adaptive actions)
3. Adequate financial support	V a. Funding for management activities and/or monitoring program is cut at some future point during implementation	Uncertain	(H) Identify alternate sources for adaptation funding, (e.g. increased tolls) (H) Review current asset management program to identify overlapping monitoring efforts (H) Prepare tolling plans for future use in defensive actions (SH) Lobby for increased government adaptation funding	<i>Monitor</i> ongoing cost of management activities and implementation, and funding streams Trigger 1: if implementation costs exceed a primary threshold for a specified duration, take DA-actions Trigger 2: if implementation costs exceed a secondary threshold for a specified duration, take RE-action <i>Monitor</i> ongoing climate and performance monitoring costs Trigger 1: if monitoring costs exceed a specified threshold for a specified duration, take DA actions Trigger 2: if DA-actions are unsuccessful, take RE-action <i>Monitor</i> ongoing asset management activities via annual audit Trigger 1: if new retrofit synergies are identified (e.g., drainage improvement), take CP-action <i>Monitor</i> other agency projects and priorities Trigger 1: if facility replacement/ improvement synergies exist with other initiatives (e.g., updating toll plaza facilities), take CP-action <i>Monitor</i> stakeholder feedback on the plan Trigger: if approval drops below predetermined approval threshold, take CR action	(DA-1) Review asset management monitoring programs for subsequent cost overlaps (DA-2) Review environmental monitoring activities of nearby agencies for information sharing possibilities (DA-3) Implementing increased bridge tolls, or pursue alternate source of funding (RE) Reassess the plan
	Op b. Non-climate monitoring, maintenance and/or retrofit activities	Uncertain	(SZ) Review asset management program for maintenance, monitoring, and retrofit synergies (SZ) Conduct real-options analysis to investigate viability of non-climate improvements to structure	<i>Monitor</i> ongoing asset management activities via annual audit Trigger 1: if new retrofit synergies are identified (e.g., drainage improvement), take CP-action <i>Monitor</i> other agency projects and priorities Trigger 1: if facility replacement/ improvement synergies exist with other initiatives (e.g., updating toll plaza facilities), take CP-action <i>Monitor</i> stakeholder feedback on the plan Trigger: if approval drops below predetermined approval threshold, take CR action	(CP-1) Implement climate adaptation retrofitting as part of larger non-climate maintenance/retrofit project (CP-2) Investigate non-climate cost savings by integrating new agency initiatives into bridge approach retrofit or replacement (i.e., real options) (CR) Adjust basic plan in response to specific feedback (e.g. consider adjusting tolling if it is perceived as too high)
4. Sufficient support from political leaders and other stakeholders	V a. Acceptance from political leaders and other stakeholders	Uncertain	(SH) Implement public relations campaign to increase awareness of climate risks in real terms, (e.g. costs) (SH) Partner with state climatologist and research institutions develop ways to better communicate the risks associated with climate change	<i>Monitor</i> ongoing asset management activities via annual audit Trigger 1: if new retrofit synergies are identified (e.g., drainage improvement), take CP-action <i>Monitor</i> other agency projects and priorities Trigger 1: if facility replacement/ improvement synergies exist with other initiatives (e.g., updating toll plaza facilities), take CP-action <i>Monitor</i> stakeholder feedback on the plan Trigger: if approval drops below predetermined approval threshold, take CR action	(CP-1) Implement climate adaptation retrofitting as part of larger non-climate maintenance/retrofit project (CP-2) Investigate non-climate cost savings by integrating new agency initiatives into bridge approach retrofit or replacement (i.e., real options) (CR) Adjust basic plan in response to specific feedback (e.g. consider adjusting tolling if it is perceived as too high)

Table 1. (Continued.)

Condition for success	Vulnerability(V)/ opportunity (Op)	Certain/uncertain	Actions taken at time = 0 (increase basic plan robustness)	Signpost monitoring (begins at time = 0) and trigger events	Actions taken at time > 0 (adaptive actions)
5. Sufficient alternate facilities and/or modes exist	V				
	a. Insufficient number, delineation, or inventory of viable detours across SF Bay for cars	Certain	(M) Identify alternate/detour routes; Inventory detour routes for gaps in NBI/agency data (M) Install signage and develop detour plans (including traffic management options) for the event of disruptions (SH) Increase priority of projects that repair/construct/expand alternate routes	—	—
	b. Insufficient availability of alternate transport modes across SF Bay	Certain	(M) Install signs for transit, rail transport, or ferry transport that uses separate and/or dedicated infrastructure (e.g., BART, bus detour routes) (SH) Provide funding to support/grow transit service along alternate routes (e.g., increased frequency of BART and/or ferry service during disruptions) (SH) Negotiate contracts with private transport companies (e.g., private motor coach) to provide additional services on alternate routes during disruptions	—	—

Note: (CP) = capitalizing action; (CR) = corrective action; (DA) = defensive action; (H) = hedging action; (M) = mitigating action; (SH) = shaping action; (SZ) = seizing action; (RE) = reassessment.

well in advance of when they are actually needed (if, in fact, they are ever needed at all).

The dynamic adaptive plan remains in place as long as (1) the goals and objectives identified during its development remain valid, and (2) the plan is meeting those goals. If goals and objectives shift away from those originally identified, or unforeseen events occur that invalidate them, then the plan is suspended and reassessed. Similarly, the plan is reassessed if the definitions and conditions for success or vulnerabilities change. This can be a function of trigger events that indicate the need for bridge approach retrofitting, replacement, relocation, or regional adaptation [i.e., Options 4 (a–d)]; or events that directly require reassessment (e.g., significant drop in actual and projected travel demand, or unmanageable costs of continuing with the plan).

Conclusions and Suggestions for Future Research

Within the transportation community, the growing evidence that the global climate is changing is leading to a shift in focus toward the deep uncertainties associated with its magnitude and rate of change, its impacts on society, and the external factors contributing to these changes and impacts. These global uncertainties then lead to uncertainties about how large-scale changes in climate can be translated into local impacts that could adversely affect civil infrastructure. All of these deep uncertainties pose difficult challenges to engineers, planners, and policymakers who are involved in the management of existing transportation infrastructure systems.

In our opinion, the traditional methods for handling uncertainty in transportation planning are inadequate to address the deep uncertainty associated with climate change. Methods such as sensitivity analysis, probabilities, Monte Carlo simulation, and scenario planning are ill-equipped to deal with deep uncertainty (Level 4). They are designed to deal with a predicted future condition, or else are used to identify a robust static plan that can deal with a range of plausible conditions, but cannot adapt should conditions change beyond the predictable or plausible. We propose that methods that seek flexible solutions—ones that increase both the static and adaptive robustness of response plans to myriad plausible futures and conditions—are better suited to infrastructure adaptation planning. Dynamic Adaptive Planning (DAP), a generalized planning approach that builds robustness into adaptive plans, is one approach that is suited to address deep climate uncertainties in adaptation planning. DAP recognizes and accepts that deep uncertainty is inherent in developing response plans, and utilizes flexibility, adaptability, and learning through ongoing monitoring to address deep uncertainty.

In this paper we have shown how DAP can be applied to transportation infrastructure planning under uncertain climate change, land use, travel demand, and societal and institutional conditions, with an illustrative case study of the Oakland Approach to the San Francisco-Oakland Bay Bridge that is susceptible to physical climate impacts (e.g., sea level rise and storm surge), changes in travel demand and land use, and uncertain financial and stakeholder support. Our treatment of uncertainty in the example is not exhaustive, but does illustrate how DAP is capable of handling deep uncertainty, enabling a transportation system to meet its objectives through the use of flexibility, adaptability, and learning mechanisms.

One significant barrier to applying DAP is likely to be institutional. Resistance to making up-front investments can be expected from managing agencies when risks are perceived to be low and long-term benefits are unclear; decision makers might hesitate to

specify changes to the system far into the future. It is important that future research in this area attempt to understand how agencies perceive climate change risks, including in contexts different from that of the case study, and quantify the tradeoffs in long-term and short-term benefits versus up-front costs. Similarly, future research should investigate the distribution of costs and benefits across time as well as across various actors, stakeholders, and sectors—again, in a variety of contexts. Others have raised the issue of costs versus benefits in adaptive policies (e.g., Boyd and Folke 2012; Brunner et al. 2005), but the clearly specified and structured DAP approach enables the quantitative assessment of the (uncertain) costs and benefits (Yzer et al. 2014). Others have also stressed the importance of involving stakeholders in the development of adaptive policies (e.g., Pahl-Wostl et al. 2007; National Research Council 2004). Again, the structured DAP approach facilitates the involvement of stakeholders in every step of the policymaking process (Marchau 2013).

One way to reduce costs and address institutional resistance is to mainstream DAP with existing programs and decision-making processes (Huq and Reid 2004). Agencies with existing asset-management programs are likely to have monitoring programs in place that would overlap with DAP monitoring programs. Therefore, future research should also investigate ways in which DAP could be combined or configured to operate in parallel with asset management programs. Doing so would mitigate up-front resource investment costs and take advantage of synergistic activities. It is also important to involve community stakeholders and other actors in addition to managing agencies. Doing this is critical in identifying the full range of vulnerabilities and opportunities, and in ensuring public and political acceptance of plans developed using DAP. Similarly, it is important to understand how the plans might be affected by different actors and stakeholders over time, as well as by goals that may shift over time.

Perhaps the biggest barrier to the use of dynamic adaptive plans is the current dominant paradigm in planning that even deep uncertainties can be captured statistically and probabilistically based on past data (i.e., that Level 4 uncertainties can be treated as if they were Level 1 or Level 2 uncertainties). What is required is a shift to a paradigm that accepts the fact that some aspects of the future cannot be predicted in this way, and that plans should take into account the possibility of very low probability, high impact events (black swans).

In our illustrative example we applied DAP to the San Francisco-Oakland Bay Bridge, focusing primarily on climate change impacts and vehicular access to the existing bridge spans. However, the DAP approach could be expanded to include other transportation modes (e.g., rail, air, bike/pedestrian) and other interconnected infrastructure affecting the plan's primary goal of ensuring an adequate cross-bay link. Doing so would better acknowledge potential climate impacts on broader mobility concerns.

Given DAP's high-level approach to uncertainty planning, it could also be applied as a means to integrate many interconnected or interdependent long-term regional strategic planning and infrastructure management issues. Although the illustrative example addresses climate change adaptation for a single infrastructure asset (almost) in isolation, DAP's scope could be expanded to integrate and consider the uncertainties of long-term transportation network planning issues that affect broader decision-making (e.g., changing regional economics and funding streams, land use, travel demand, infrastructure preservation, next to climate change) in a more comprehensive systems approach that better acknowledges competing uncertainties. Doing so would enable agencies to examine and weigh the competing uncertainties that affect their overall planning and management practices, resulting in a more unified approach to

dealing with uncertainty in long-term strategic planning in the transportation sector.

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