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Evolvability analysis framework: Adding transition path and stakeholder diversity to infrastructure planning

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Abstract

This paper presents the Evolvability Analysis Framework (EAF), a new perspective on evaluating complex infrastructure systems. EAF enables decision makers to explore alternative transition paths, thus providing several multi-step options to achieve a desired end state. These multi-step transition paths can be particularly valuable when they mitigate the impact of system degradation during the deployment of new capabilities. Additionally, EAF is formulated in a manner that empowers decision makers to apply decision variables, such as a cost cap or an equity metric, which are increasingly relevant to modern decision-making. To demonstrate the method and its value, we apply the EAF to a case study inspired by Los Angeles' Vision 2028. We identify 26 transition paths across different performance dimensions. We model the cost and performance of each transition pathway and compare them using multiple measures, including traditional benefit-cost metrics and differential impacts on different stakeholder groups. Our results show that multi-step paths outperform single-step transitions to an end state ("big bang" approaches) in most scenarios. Multi-step paths also provide valuable alternatives when particular stakeholders value non-cost metrics.

KEYWORDS
complex systems, Evolvability, Infrastructure investment, technology transition, traffic simulation

1 | INTRODUCTION

Strategic planning is required to evolve and update complex systems. Even when stakeholders agree on the desired end state, there may be many ways to implement these transitions. For example, when implementing an electronically-monitored High Occupancy Vehicle (HOV) lane, that restricts access to vehicles with multiple passengers, would it be better to shut down a main road artery for a short period and reopen it once the project is complete, or would it be less disruptive to implement partial shutdown(s) for a longer period while maintaining some reduced service?

Most planners rely on discounting methods like net present value (NPV) analysis to evaluate the costs and benefits of alternative pathways, simplifying alternatives to a single figure of merit. However, this strategy can mask important differences among transition plans. For example, different transition strategies may have disproportionate in-process impacts on some stakeholders: shutting down a bus route for a week might result in vulnerable workers losing their jobs. Moreover, challenges experienced during intermediate states can create long lasting consequences, like public skepticism about adopting new technologies.

Decision makers need more insight into the tradeoffs involved in planning transitions of complex systems. This paper therefore develops the Evolvability Analysis Framework (EAF). The EAF offers important advantages over existing planning methods. First, it treats the "transition path" as a key decision variable, which helps to identify more valuable project alternatives. Second, formulating a system transition as a multi-step path enables relevant decision criteria—such as evaluating compliance with annual budget caps or minimizing in-process impacts—to be examined directly. To illustrate the value of an EAF approach, we present an application case study based on a stylized example of Los Angeles City's Vision 2028 plans, which lay out key goals for the transportation system performance in the greater Los Angeles region over the next decade.

2 | RELATED LITERATURE

This paper draws upon literature in infrastructure planning and changeable system design. We review both perspectives and describe how our project integrates and extends them.

2.1 | Valuing infrastructure investments: Benefit cost analysis can oversimplify complex projects

Government agencies play a critical role in selecting and funding infrastructure projects. Several methods have been utilized to directly compare alternative projects. Examples include variations of benefit cost analysis (BCA) and multi-criteria decision analysis. [1–3] When valuing infrastructure investments, government agencies primarily use BCA. [1] As of 2018, the US Department of Transportation (DOT) requires submission of a BCA with all surface transportation projects that are funded from discretionary grants. [4] Per the guidance, grantees should determine the costs and benefits of each alternative and compare them using NPV or cost-benefit ratio analyses. A well-produced BCA can provide an objective metric of each alternative's value that is simple for decision makers to understand.

BCA is not without limitations. These include underdeveloped methods to translate soft benefits into monetary value,[5] failure to consider equity,[6] and failure to consider uncertainty. [7] Perhaps the most compelling issue is that stakeholders often feel that BCA does not give a "complete picture" of the alternatives. [8] While BCA is a useful tool for standardizing comparisons, there are shortcomings to its simplicity, and some stakeholders feel that it does not capture all relevant information when selecting alternatives. One proposed alternative is Engineering Options Analysis (EOA), discussed more below.

2.2 | Designing for changing contexts: Sequential steps and path dependency

Complex long-lived systems must remain useful despite an uncertain future. Therefore, scholars of systems engineering have focused on the consequences of changing requirements, environments, and operating needs. [9] Change is expected; thus, these scholars have proposed strategies of design for changeability,[10] flexibility,[11,12] survivability,[13] and other "-ilities". [14] Two main design strategies dominate this literature: *robustness* (systems that are insensitive to changing contexts), and *flexibilty* (systems that are easily changed to accommodate new needs). For example, "enable and change" strategies[12]—such as building in margins and "hooks" to easily replace modules—can facilitate system flexibility.

One well-established approach to designing for flexibility is real options "in" systems. [11] Developed in the late 1970s in response to a realization that traditional valuation methods underestimated the impact of uncertainty in future operating environments, it adapts concepts from financial management to the problem of complex systems. It embodies both a design strategy and a valuation methodology. [15–17] In terms of design, the core idea is to delay investments until more information is available. The real option "in" involves designing an "option" to expand "in" the physical system, so that it can later be "called" if and only if needed in the future. [11,12] This has the advantage of minimizing downside risk without losing to opportunity for upside potential. In terms of valuation, typical analysis adopts a BCA framework but considers decision rules around calling options as part of a time series. [18] Real options (or more recently Engineering Options Analysis [EOA]) has been shown to increase project value significantly across multiple sectors. [20–23]

Even within the path dependent decision context of EOA, the formulation still assumes that designers are building a new system with no prior history. However, for most complex infrastructure systems, so-called "green field" design is a rare luxury. More often, legacy systems must adapt to unexpected changes. [25] In the context of systems engineering (as opposed to biology), evolvability describes the ability of designers to physically transform a system from an initial configuration to a more desirable configuration while still maintaining service. [26,27] When systems evolve, path dependence can be important. For example, in the context of upgrading military tactical networks, Szajnfarber et al. showed that quickly-deployed solutions with initially lower performance—followed by planned replacement—can lead to better final performance when compared to a "big bang" approach where a full capability was deployed at once. [25]

2.3 | Practical constraints facing transportation authorities

Municipal DOTs and similar authorities regularly face long lead times on capital expenditure, planning, and investment cycles. These investments typically span multiple budget cycles and administrations, with the intended or perceived benefits occurring decades after the initial planning. For example, a transit fleet must be planned to consider replacement cycles and funding constraints like the Federal Transit Administration's minimum vehicle lifetime and expectations on the minimum life of any capital expenditures (CapEx) that receives federal or state funds. [28–30] Investors must routinely plan for 20–50 years in the future. When doing so, they must make design decisions that can accommodate rapidly changing demand, technology, and operations. These requirements impose significant constraints. A transit agency may not be able to replace a 40-foot bus after just 3 years of use because of a change in demand or mobility preferences. A city may not be able to simply reconfigure a road for different forms of mobility if it was built 5 or 10 years earlier unless those changes were part of the original investment plan. [31–33] Subway rolling stock is expected to last (and is amortized) over several decades, and a city may not have the resources to update its transit operation center and embedded infrastructure every time a new technology is deployed to ensure compatibility, resilience of operation, and performance.

Cities also have legal and ethical obligations to their citizens. A transit line that is designed to promote equity in 5 years may fall very short of that goal if it disrupts citizens' commutes to work, school, or healthcare appointments while it is being constructed. [31] In general, cities are dynamic and constantly changing. Commute patterns and mobility needs evolve over time. This means planners' designs must allow for the flexibility to accommodate future unknowns within planning, budget, and other constraints.

2.4 | Gap: Evolving infrastructure systems

Although most infrastructure systems face the evolvability challenge described in Section 2.2, planning is typically done based only on a specified end state. For example, a city planning to build a new road may only examine the estimated NPV of alternative contractor bids for the proposed project. Even when a more sophisticated EOA framework is considered, the question is when and if to execute additional stages of development, not about the value of intermediate stages along a transition paths *per se*. We contend that considering the evolvability of the system when reaching a desired end state can generate substantially more insights into the true costs and benefits of alternative transition paths for a given system. Specifically, we add the transition "path" as a decision variable to open valuable alternatives that are not typically considered. This path-based formulation allows direct consideration of many of the factors lacking in prior analysis (e.g., equity). To that end, the next sections propose a new problem formulation that enables paths to be directly considered.

3 | EVOLVABILITY ANALYSIS FRAMEWORK

The Evolvability Analysis Framework (EAF) includes two main features: (1) A layered system representation that captures the temporal constraints on system change and makes explicit the avenues for influence and investment by different stakeholders; and (2) A process for analyzing system upgrades from an "evolvability" perspective. The analysis process leverages this layered representation to compare alternative transition pathways, which requires considering how a proposed operational change (e.g., introducing lane restrictions) implemented in the infrastructure and component layers (driving costs and delays) manifests in performance improvements over time. Depending on the selected transition paths, costs and benefits can occur at very different times. This can lead to non-linear benefits over time, even when the end-state is similar. This section presents the general form of the EAF. In the next section, we apply the EAF to study a stylized infrastructure upgrade example and illustrate its use and potential value.

3.1 | System representation in preparation for EAF analysis

The EAF operates on a four-layered representation of a system. Starting from the base, the layers are infrastructure, components, operations, and use (as shown in Figure 1). Layers and their interrelationships are described below. The value of formulating the system in this way is that it clarifies how much control decision-makers have over each system state, the temporal relationships between different system layers, and where/when the impacts of changes are experienced by users. Further, representing a system in this layered manner allows for identification of components within each layer that might be changed—simultaneously keeping the other layers constant—while transitioning the system from one state to another.

3.1.1 | Infrastructure

In the context of urban mobility, infrastructure refers to the road and rail network in a given geographic region. Substantive changes to infrastructure are extremely capital intensive and time consuming. While roads are serviced relatively frequently, putting a new road through an occupied area is generally infeasible. Nonetheless, many cities choose to make the investment in non-road infrastructure (e.g., building a new light rail line) because of the potential to substantially alleviate road congestion. Existing physical infrastructure constrains the options in other layers of the system. Less substantive changes, like designating a bus-only lane in the physical component layer (described below) can be much more feasible with only a temporary disruption. In general, when changing infrastructure, one must account for (1) the cost to buy and deploy the infrastructure, (2) potential delays before the new infrastructure is available (e.g., a new rail line might take years of development before it is available for use), and (3) degradation of system operations during deployment.

3.1.2 | Physical components

In urban mobility systems, physical components are less permanent and therefore easier to change than infrastructure components. Here, physical components include the stock of automobiles, buses, and trains that move through the system, as well as any easily changeable signage and road markers deployed to support mobility. In some cases, changing physical components is similar to changing infrastructure (though with fewer funds and less delay). In other cases, instituting the change may be fully outside the control of city planners. For example, a city can buy more buses and deploy items like traffic cameras with minimal disruption. In contrast, transponders installed in personal vehicles, while relatively inexpensive, must be purchased by individual drivers. As a result, achieving sufficient levels of adoption can take time. Assessing a component change requires consideration of the

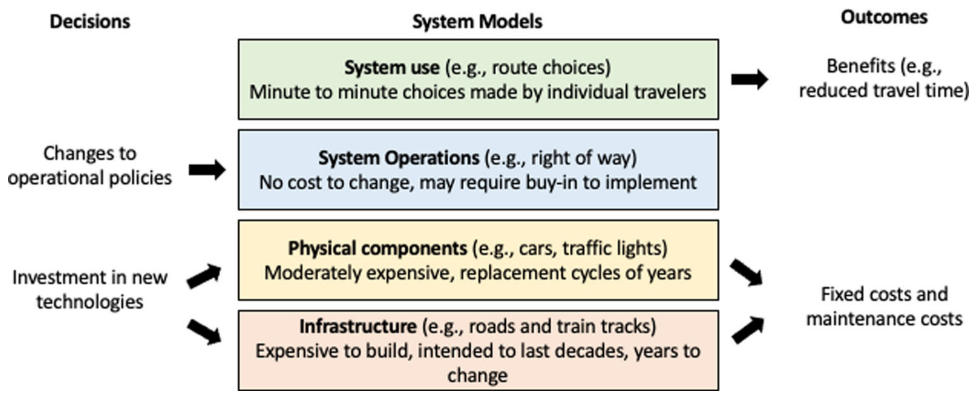

FIGURE 1 Evolvability framework overview

same attributes as infrastructure, with additional emphasis on multiple sources of delay.

3.1.3 | System operation

In the context of urban mobility, system operation includes the rules for how vehicles and pedestrians are allowed to move through the system (e.g., imposing lane restrictions during peak hours, or converting a car lane to a bus lane). Changing the system operating rules does not have an inherent cost per se, but in order for a new policy to be put in place at least two conditions must be met: first, most rule changes are subject to public comment and can involve a time-consuming political process. Second, the technology to implement the new capability must be deployed before the newly approved rule can take effect. For example, variable congestion pricing (without time-consuming toll booth transactions) is usually implemented using overhead transponders to communicate an instantaneous price to vehicle-based transponders that automatically debit users' accounts. Enforcement is typically based on images from license plate cameras linked to a registration database. This demonstrates how rule changes require alignment between a political process and technology implemented in the *components* layer.

3.1.4 | User behavior

Even when a new rule has been implemented, system users make their own choices about how to use a mobility system on a per-ride basis. For example, some users are extremely price sensitive to tolls and might choose to sit in traffic for an hour rather than pay a $5 toll. Depending on the preferences of different categories of users and the levels set for system attributes (like toll prices), users will respond in different ways to the same policy, which can have significant impacts on performance attributes like average travel times (and how travel times are distributed across stakeholders). To influence the behavior of system users, designers must understand users' preferences and how they translate to behaviors. For example, designers frequently use flow models or agent-based simulations to estimate system-level outcomes given stylized representations of users' preferences. [34]

3.2 | EAF analysis process: Modeling the cost and benefit profiles of transition pathways

Implementing an EAF analysis involves a five-step process shown in Figure 2. We briefly describe each step here and then elaborate through a case analysis in Section 4.0.

Step 1: Identify alternative transition paths from the initial state to the desired end state.

There are usually several ways that a system could be improved. For example, when upgrading from mixed traffic flow to variable congestion pricing, one may restrict lane access (e.g., through an HOV lane), collect a fee for priority (e.g., a toll road), or both. The goal of step one is to define multiple alternative paths, where each path corresponds to a sequence of operational states that must be useful stopping points. Continuing the above example, a planner might choose to introduce a fixed rate toll lane, operate in that state for several years and then later introduce variable toll rates based on vehicle type. Step 1 results in multiple alternative transition pathways that are compared against each other in the subsequent steps.

Step 2: Map capabilities needed to enable each intermediate operational state.

To implement a particular operational state, changes to the physical and infrastructure layers of the system are often required. For example, tolls cannot be collected unless a physical toll booth or electronic tracking and payment system is installed on the road. In Step 2, a mapping must be created between each intermediate operational state and the technologies and/or infrastructure needed to enable it. This connection between technology and operations must be made explicit because doing so can reveal extended lags in system performance. As noted in Section 3.1, even if designating a new toll road can be approved with a vote, it cannot be implemented until the relevant technology enablers are in place. For example, if this requires individual travelers to purchase and register transponders, and the city to install overhead monitoring, the delay might be significant.

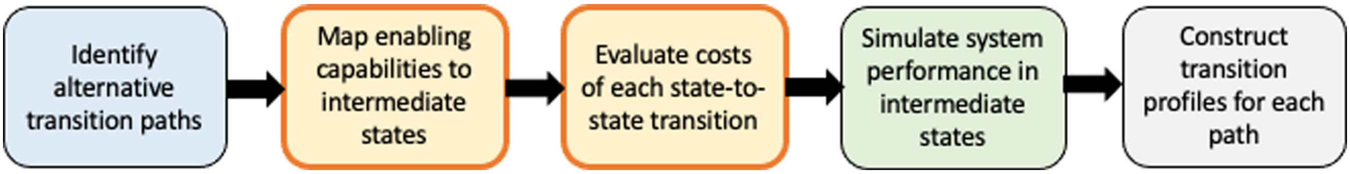

FIGURE 2 Evolvability analysis framework (EAF) process

Step 3: Evaluate costs of each state-to-state transition.

Step 3 involves (a) a cost accounting of each of the component technologies that are needed to transition from one state to the next, and (b) a designation of when those costs occur. This is not the same as recording the costs of each of the technologies mapped in Step 2. Rather, the focus is on the incremental costs of each possible transition through the system. For example, the transition from a bus lane to an HOV lane requires a different set of investments than a transition from a toll lane to an HOV toll lane.

Step 4: Simulate system performance in each intermediate state.

Each intermediate state is an improvement over the baseline; however, it is not straightforward to evaluate how much improvement will accrue in each intermediate state. To evaluate these improvements, a simulation may be used to estimate the benefit in the use layer. Although transients are generally important to consider, in the EAF we focus on the equilibrium performance of each intermediate state for the baseline analysis.

Step 5: Construct transition profiles for each path.

The main result of an EAF analysis is a set of cost and benefit profiles for each alternative path. These profiles are constructed by linking transition costs and timings to the progression of benefits as upgrades are performed. These pathways form the basis for many potential follow-on analyses. They can be synthesized in traditional NPV or CBA formats, but they can also provide insights into path-based metrics, for example, an annual cost cap.

4 | EAF CASE STUDY: UPGRADING LOS ANGELES'S TRANSPORTATION SYSTEM

To demonstrate how the EAF is implemented and to illustrate the insights it can provide to a decision-maker, we apply it to study a stylized example from the City of Los Angeles. In preparation for the 2028 Olympics, LA has announced its intent to drastically modernize its mobility system. The stated goals include "providing high-quality mobility options that enable people to spend less time traveling" and "enhancing communities and lives through mobility and access to opportunity".[35] The city has committed $400B in investment to this project. Currently, LA only has a limited light rail system, and given practical constraints regarding limiting the displacement of residents and complex municipal boundaries, major infrastructure changes are not being considered. Instead, planners will focus on improving the utilization of existing infrastructure by, for example, changing parking rules to increase available lanes during rush hour and making better use of "rolling" on sidewalks (e.g. bikes and scooters). Lane restrictions and increased bus service are also being considered.

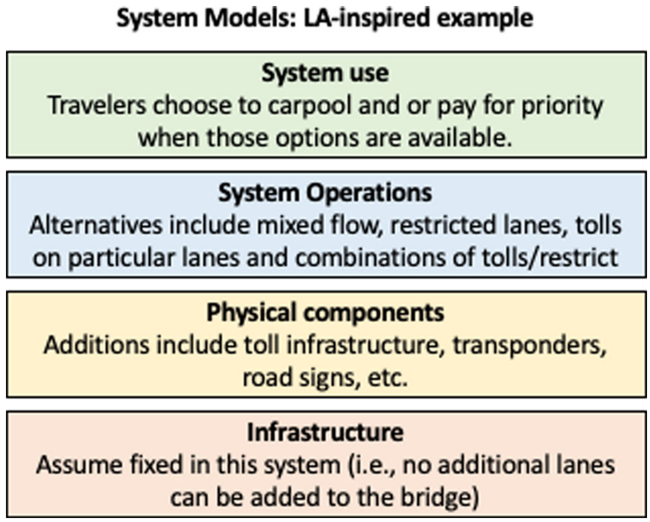

FIGURE 3 System models within the case study context

4.1 | System representation: A highly stylized urban mobility system

Figure 3 illustrates the simplified system upon which subsequent analyses will be performed. Our analysis will focus on a transition from the current state of largely "mixed" traffic to "vehicle-targeted congestion pricing" restrictions that are variable based on vehicle type and levels of congestion. Specifically, we will perform our illustrative analysis on a long, three-lane bridge that connects a key suburb to an urban core. Although this scenario was inspired by LA's planned upgrades, the specific model is also representative of traffic flows in many urban areas including for example, the San Francisco By Bridge or the George Washington Bridge connecting New York and New Jersey. In our analysis, we will assume it is the only viable path for travelers to enter the city, and that environmental restrictions limit physical expansion of the bridge. Therefore, all interventions will involve changes to right-of-way (e.g., whether a particular lane is restricted to city busses). In our simplified analysis, we will only record improvements on traffic flow of the modeled bridge, which underestimates the impact these changes would have on surrounding commuters. Figure 3 shows the mapping of our example system to the four-layer representation specified in Section 3.1.

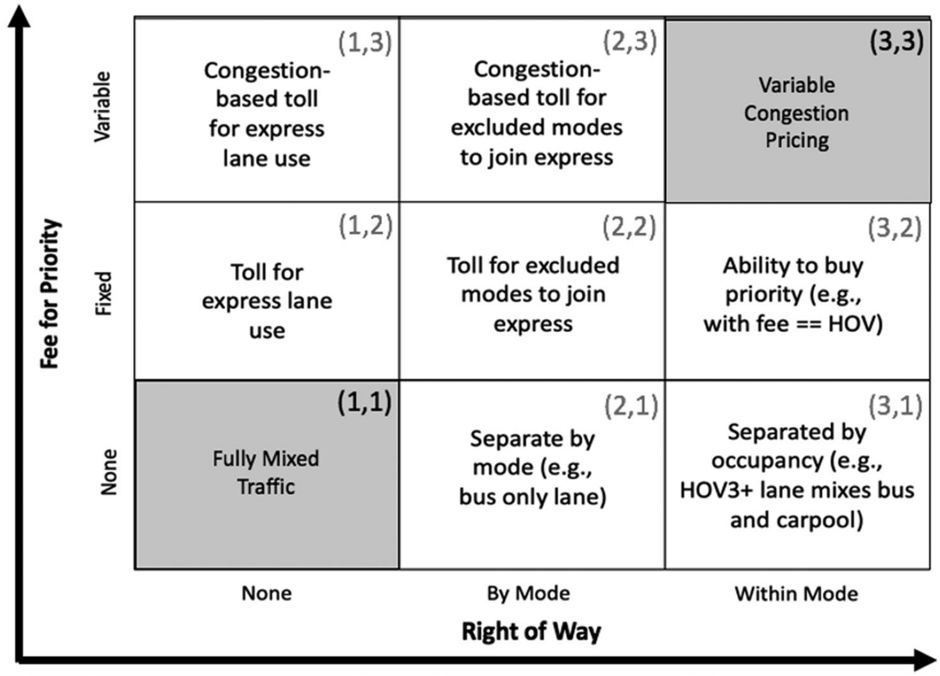

FIGURE 4 Case study operational states

4.2 | EAF analysis process

In the sections that follow, we demonstrate how the EAF would be implemented in this context and then compare its results to a standard NPV analysis with the same assumptions to illustrate the insights that can be gained from EAF.

Step 1: Identifying alternative paths

The current system state (S1) is one of fully mixed traffic. That means any vehicle can use any lane. By definition, all traffic flows at the same average speed. In this scenario, all stakeholders have agreed that within 15 years the system will have transitioned to the desired end state (SN). SN is an extreme version of congestion pricing with variable access whereby each vehicle that uses an express lane is assigned an individual price depending on class, occupancy, and system congestion levels. This enables the city to (potentially) control flow through the system using targeted pricing and significantly improve travel experiences for all. What remains to be decided is how best to implement the transition between states S1 and SN.

The first step in an EAF analysis involves assessing the extent to which there are viable intermediate system states. A transition from S1 to SN requires a relatively substantial transition in each of the infrastructure, component, operations, and behavioral layers. As a result, there may be advantages to implementing this transition through a series of intermediate states to make the transition period more palatable to end users. For example, rather than enduring 5 years of continuous construction, the city might plan a single year of construction that partially improves the operating environment; after adjusting to this new norm, another transition could be initiated. This approach can have budgetary advantages as well since it can spread costs (and ensure benefits are received) closer to when costs are incurred. Of course, this approach could create its own fatigue (e.g., if users feel like the rules are constantly changing). The point is not that incremental transitions are *necessarily* better; rather, the goal is to enable decision-makers to explore and understand in which cases incremental transitions are more or less valuable.

In our scenario, the transition from S1 to SN involves two main dimensions of change: (1) *right of way*, in terms of mode-based lane restrictions, and (2) *fee for priority*, in terms of congestion-based access pricing. In S1, all vehicles receive the same access to lanes and the same price (free) to use them. In SN, each individual vehicle type experiences a different price for a given lane and can choose to pay for a priority lane. For example, a single occupancy vehicle may choose to pay to use an express lane and receive a proportionally higher offer price because it is neither a bus nor an HOV. Each of these dimensions has multiple potential intermediate states; for example, in the lane restrictions dimension, many cities implement a bus-only lane while others limit by occupancy and time of day. In the fee for priority dimension, some roads use fixed price tolls while others dynamically set the price based on current congestion levels.

For the purposes of this analysis, we introduce one intermediate level in each dimension for a total of nine operational states (see Figure 4). We adopt a naming convention using the x and y "coordinates" of each state, so S1 would be S(1,1). Moving along the *right of way* (x-axis) from the S(1,1) state, S(2,1) adds a restricted lane that is only available to busses, and S(3,1) permits HOVs to also use the restricted lane. Moving along the *fee for priority* (y-axis) from the S(1,1) state, S(1,2) adds a fixed toll that is the same for all vehicles to use an express lane, and in S(1,3) the level of that toll varies based on real-time congestion. S(2,2) combines S(1,2) with S(2,1) so that the restricted lane is free to busses, but other vehicles can pay the fixed toll to use it. S(3,2) extends

S(2,2) such that HOVs also have free access to the restricted lane. In S(2,3), the express lane is free to busses and everyone else is offered the congestion-based price. Finally, in S(3,3) each vehicle type pays a different price for each lane and can choose to pay more for a priority lane.

Each of the seven states other than S(1,1) and S(3,3) represent intermediate states for an infrastructure update. For example, a city might choose to get commuters accustomed to tolls first by deploying toll booths to restrict a few key express lanes before making the more substantive change to S(3,3). This would result in a path of S(1,1) = > S(1,2) = > S(3,3). If we impose the restriction of monotonic increase in capability, there are 26 unique paths from S(1,1) to S(3,3).

Step 2: Map enabling capabilities to intermediate states

Before any of the operational states defined above can be implemented, the technologies that enable each of them must first be purchased and deployed. This requires a mapping between the operational states and the set of technologies that enable them (see Table 1). In this example, there is significant overlap among the technologies needed across the states, though in some cases a technology needed to support an intermediate state might not be needed again. We track the re-use and obsolescence of technologies across each state since it can be politically untenable to encourage adoption of, say, a basic in-car transponder 1 year and then require that everyone adopt a new two-way communication system the next year. We also separately track technology investments that can be made centrally versus those that require transactions by individual stakeholders.

Step 3: Evaluating costs of each state-to-state transition

For each unique technology, we estimate implementation and annual maintenance costs. Implementation costs are incurred during the first year of each state, and annual maintenance costs are incurred every year after a technology is deployed. For example, if you plan to deploy installing them requires temporarily shutting down an intersection for a period of time, the analysis must account for performance degradation during that 10-day period. For the purposes of this illustrative analysis, technology level costs are estimated by aggregating information from the USDOT Costs Database, FHWA Cost Estimator Tool, CalTrans Contract Cost Database, and FHWA Priced Managed Lane Guide. Performance degradation estimates are derived from the performance model described in Section 4.3.

Although costs and delays are estimated at the technology level, the EAF unit of analysis is the *transition path*. Therefore, we need a measure of cost, delay, and performance penalty applied to each path. The cost to transition is a simple sum of the contributing costs,

$$Transition\ Cost\ =\ \sum_{t=1}^{y}\sum_{k=1}^{m} technology\ cost(t)_k \tag{1}$$

where m is all technologies in the deploying state that are not in the current state,

y is the maximum deployment time of technologies in m, and

TABLE 1 Map of states (n) to technologies (m)

			In Vehicle		On Road			Cyber		
S(I,j)		Shorthand	RFID device	Mode adjust. RFID device	Static sign	Digital sign	…	Traffic MGMT center	Var. toll pricing software	…
1	1	Fully mixed traffic					…			…
1	2	Toll for express lane use	1		1		…	1		…
1	3	Congestion-based toll for express lane use	1			1	…	1	1	…
2	1	Separate by mode (e.g., bus only lane)			1		…			…
2	2	Toll for excluded modes to join express	1		1		…	1		…
2	3	Congestion-based toll for excluded modes to join express	1			1	…	1	1	…
3	1	Separated by occupancy (e.g., HOV3+ lane mixes bus and carpool)			1		…	1		…
3	2	Ability to buy priority (e.g., with fee = = HOV)		1	1		…	1		…
3	3	Variable congestion pricing		1		1	…	1	1	…

TABLE 2 Features (p) for each technology (m)

Type	Technology	Implementation cost ($K)	Annual maintenance cost ($K)	Deployment time (years)	Technology penalty (% worse)
In vehicle	RFID Device	$70.00	$0.00	1	0%
In vehicle	Mode Adjust. RFID Device	$80.00	$0.00	1	0%
On road	Static Sign	$6,500.00	$20.00	1	50%
On road	Digital Sign	$12,000.00	$350.00	1	50%
…	…	…	…	…	…
Cyber	Traffic MGMT Center	$5,000.00	$250.00	5	0%
Cyber	Var. Toll Pricing Software	$55.00	$3.00	2	0%
…	…	…	…	…	…

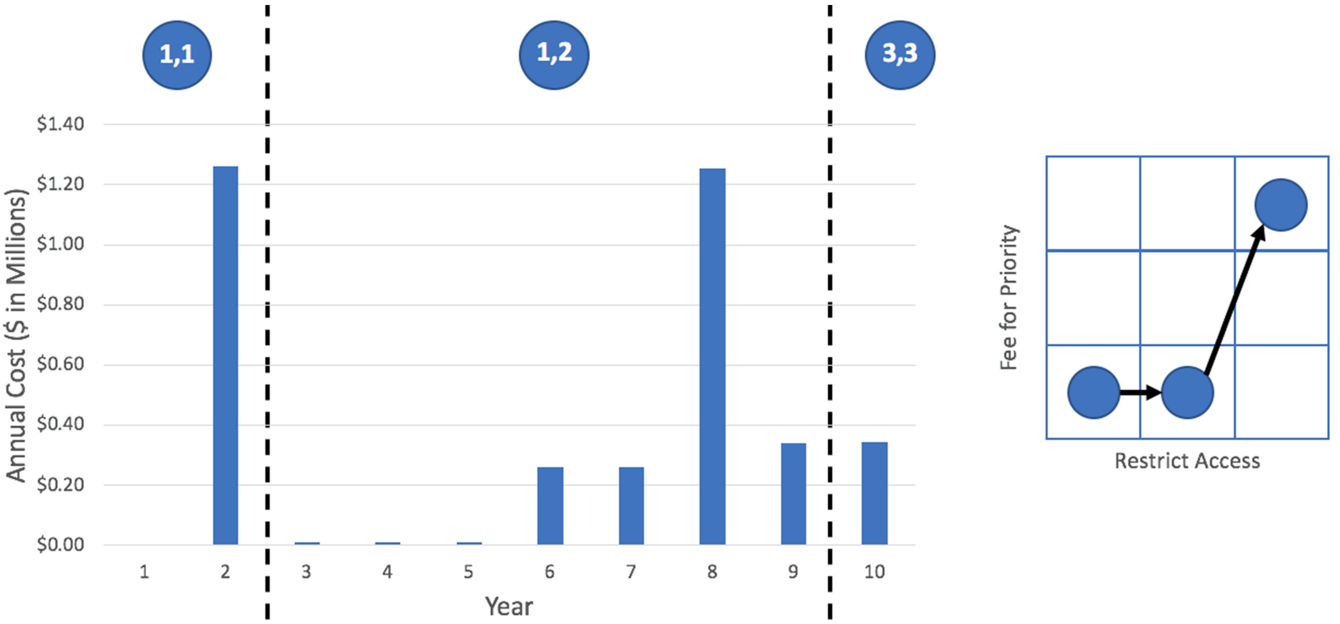

FIGURE 5 Sample cost profile for a S(1,1) to S(1,2) to S(3,3) transition path, assuming 2 years between transitions

$$technology\ cost\ (t)_k = \begin{cases} implementation\ cost_k, & |if\ t = 1\ (i.e.,\ first\ year\ of\ state\ deployment) \\ 0, & |if\ t > 1\ and\ technology\ k\ is\ not\ fully\ deployed \\ annual\ maintenece\ cost_k, & |if\ t > 1\ and\ technology\ k\ is\ deployed \end{cases} \quad (2)$$

For delays, we assume that the next state is operational once the last technology is deployed, so

$$Benefit\ Realization\ Delay = MAX_{k=1}^{m}\ technology\ deployment\ time_k \quad (3)$$

where m is all technologies in the deploying state that are not in the current state.

Finally, for the penalty, we add the temporal profiles of the delays, so

$$Penalty\ S\ (t) = SUM_{k=1}^{m}\ technology\ penalty\ (t)_k \quad (4)$$

where m is all technologies in the deploying state that are not in the current state,

t is the current deployment year, and

$$technology\ penalty\ (t)_k = \begin{cases} performance\ penalty\ (k), & if\ technology\ not\ deployed\ by\ year\ t \\ 0, & if\ technology\ is\ deployed\ by\ year\ t \end{cases} \quad (5)$$

This process results in the matrices and cost profiles illustrated in Table 2, which encodes the features, p, of each technology, m. Figure 5 shows the generated path cost profile. Only technologies shown are included in the analysis.

Step 4: Simulating performance in intermediate states

Each transition is implemented because the new operating states are expected to improve system performance. For example, creating a dedicated bus lane is thought to make public transit more efficient

TABLE 3 Network setup and mode usage assumption

Network attributes		Mode usage		
Road length	**7 km**		**Heavy use**	**Light use**
Number of lanes	3	Total number of travelers	7000	4000
Total simulation time (seconds)	5000	Bus occupancy if bus lane was not available	50%	30%
Total number of buses	100	Bus occupancy if bus lane was available	100%	50%
Bus capacity	20 travelers/ bus	Maximum fraction of solo drivers will use HOV if express lane opens to HOV	50%	10%

because it nominally encourages more people to leave their cars at home. As a result, even though the creation of a bus lane limits the available real estate for cars to use, the non-restricted lanes should move more freely with fewer cars on the road. Since there are many complex interacting factors that determine actual performance improvements due to a new operating mode, this type of assessment is typically conducted via simulation, preferably incorporating rider-level decision-making.

For the present example, a baseline model was created matching the bus lane scenario previously described. All simulations were conducted using the Simulation of Urban Mobility (SUMO) modeling environment—an open-source, microscopic and multi-modal traffic simulation package designed for large scale transportation networks. [34] We represented a traffic simulation on a 3-lane bridge with two demand levels operationalized by the total number of travelers on the road. We adjust the fraction of people using each vehicle mode in each state such that travelers adopt new infrastructures when available; for instance, we assume more people will use buses if a bus-only lane becomes available. Table 3 lists the simulation attributes.

We generated 10 simplified scenarios corresponding to the nine capability states and a tenth to represent the performance degradation associated with a single lane closure. Table 4 summarizes the attributes of each scenario. Note that there was no individual traveler decision model implemented in this illustration; instead, we assumed the fraction of travelers who would convert to public transit if a dedicated bus lane were available and similarly how many drivers would find companions to gain access to the HOV lane when those states became available. Further, to distinguish the benefits of time-of-day pricing, we implemented two demand levels: light use and heavy use.

Figure 6 shows the distribution of results for each scenario. In each cell of the 3 × 3 transition grid (introduced as Figure 4), we show a boxplot representing the full population (grey), the bottom 5% travelers (green) and the top 5% travelers (red). All values show the percent decrease in travel time relative to the initial state, S(1,1) for that demographic. The extra “transitional” state is used to calibrate degradation of performance due to lane closers, for example, if a lane needs to be shut down to install new signage.

Overall, mean performance improves as capability states move up and to the right, however the improvement is nonlinear and unequally distributed across stakeholders. For example, moving up the y-axis from a mixed traffic state, S(1,1), to a toll lane state, S(2,1), has a strong positive impact on the top 5% but degrades performance for the slowest 5%. S(3,3) has the best mean performance for the population and the bottom 5%, but it is slightly worse than S(3,2) for the top 5%, though it is still much better than their initial performance in S(1,1). The specific results will be examined further below.

TABLE 4 Summary of SUMO scenarios

State	Description of SUMO implementation
S(1,1)	All modes share the road
S(2,1)	Add a restricted lane that is only available to busses
S(3,1)	Permit HOVs to use the restricted lane as well
S(1,2)	Add a toll for an express lane; anyone can use the restricted lane as long as they pay the toll
S(2,2)	Restricted lane is free to busses; other can join if they pay the fixed toll
S(3,2)	Add HOVs to those who gain free access to the restricted lane
S(1,3)	The fee to enter the express lane is constant for everyone but that level varies by the real-time congestion
S(2,3)	The express lane is free to busses and everyone else is offered the congestion-based price
S(3,3)	Include HOVs in those who gain free access to the restricted lane and everyone else is offered the congestion-based price
Transitional	Single lane shut down for construction using S(1,1) scenario

We translate the percent decrease in travel time to dollar values to facilitate NPV comparisons of each path. Previous literature has estimated that commuters are willing to pay approximately $20/h to reduce their commute travel time,[36] which we use to make the conversion. For example, if a given driver reaches their destination 15 min sooner, we can calculate the monetary benefit as $20/h * (15 min/60 min), or $5. If we assume that commuters take two trips per day, then the total daily benefit per driver would be $10. This logic is applied to all of the travelers in the model:

$$\textit{Daily Benefit} = \$20 * \textit{Daily Time Saved}\ (\textit{in hours}) \tag{6}$$

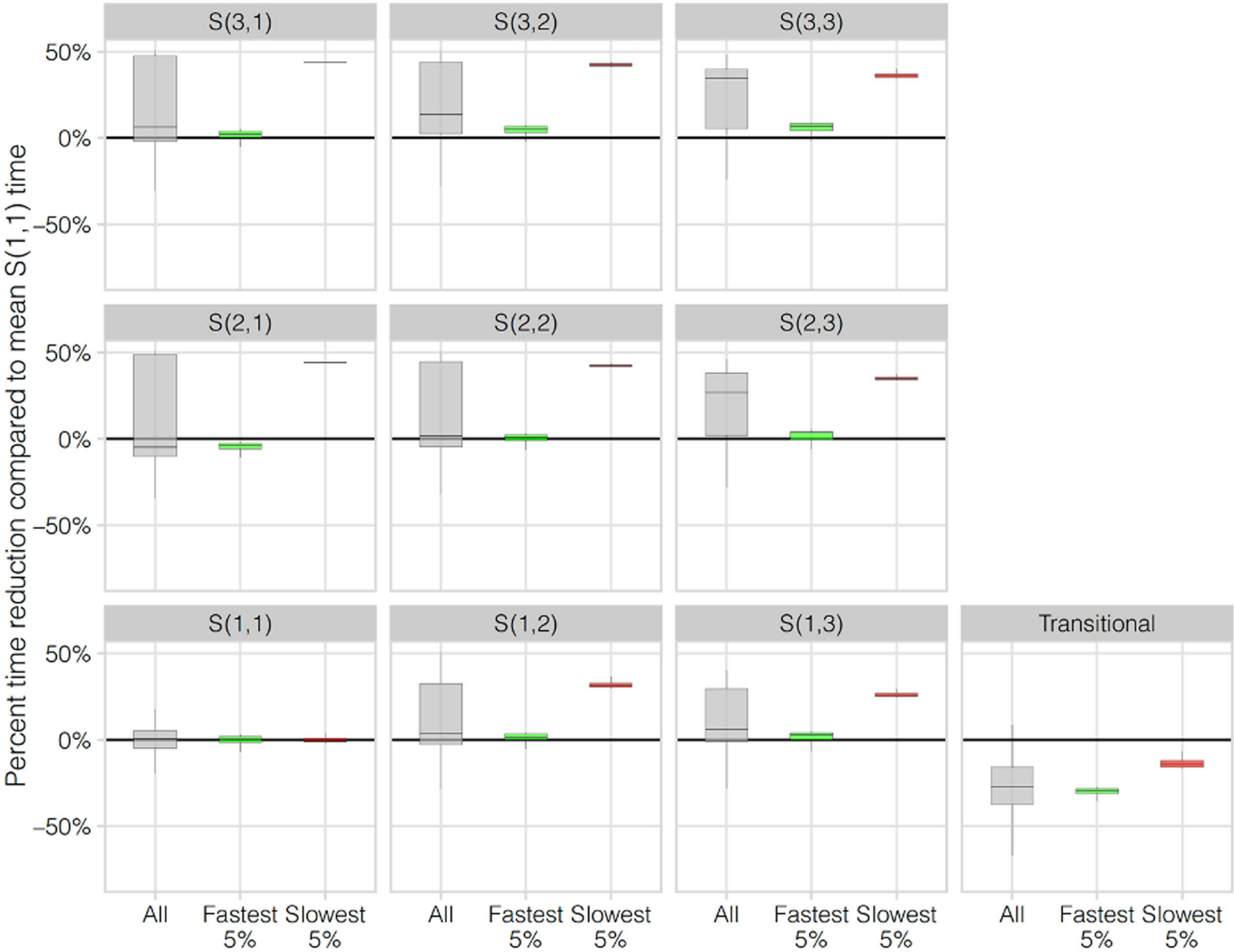

FIGURE 6 SUMO simulation results: capability states performance relative to the fully mixed state (s(1,1)); transitional shows degradation during a state-transition

where…

$$\textit{Annual Benefit} = \textit{Num Daily Commuters} * \textit{Annual Work Days} * \textit{Daily Benefit} \tag{7}$$

NPV can then be calculated by summing the discounted benefit from reduced travel time minus the cost in each year. This was computed for each of the transition paths described below.

Step 5: Constructing transition profiles

Now that we have defined the (1) technology-level costs and delays, for each of the technologies needed to enable each state, (2) mapped them to each transition, and (3) defined an equilibrium performance for each state and a performance penalty during each transition, we can now construct the cost and benefit profiles for each of the 26 transition paths. For consistency, we assume that all paths start in S(1,1) at $t = 1$, and that each transition for each path, n, begins 1 year after the previous transition is complete at t_n. For example, if a transition (t_2) from S(1,1) to S(2,1) is complete at the beginning of year 5, then the transition from S(2,1) to the next state begins at year 6. All state implementation costs, which are composed of the technology costs to enable a particular state, are incurred at t_n, with annual maintenance costs recorded every year an individual technology is deployed until the technology is no longer needed to enable the current state. Each of the m technologies needed to enable a new state has a technology deployment time, or the time in years it takes to bring the technology to operational status. For example, suppose a path is composed of the transitions S(1,1) = > S(1,2) = > S(3,3); states S(1,2) and S(3,3) require a traffic management center, and a traffic management center takes 3 years to deploy. The implementation cost of the traffic management center is only recorded during year 1 of S(1,2)'s deployment. Years 2 and 3 incur no costs as the traffic management center has not finished deploying. Once deployment is complete at the start of year 4, annual maintenance costs are recorded every year for the remainder of the analysis. An additional implementation cost is *not* recorded when transition to state S(3,3) begins because the technology was previously deployed in state S(1,2).

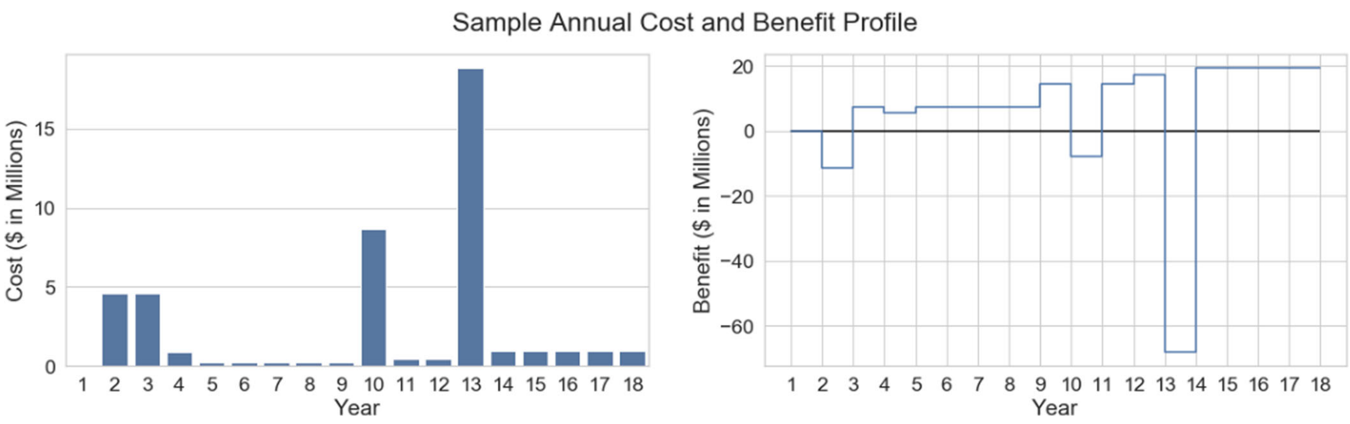

FIGURE 7 Sample cost profile and benefit distribution

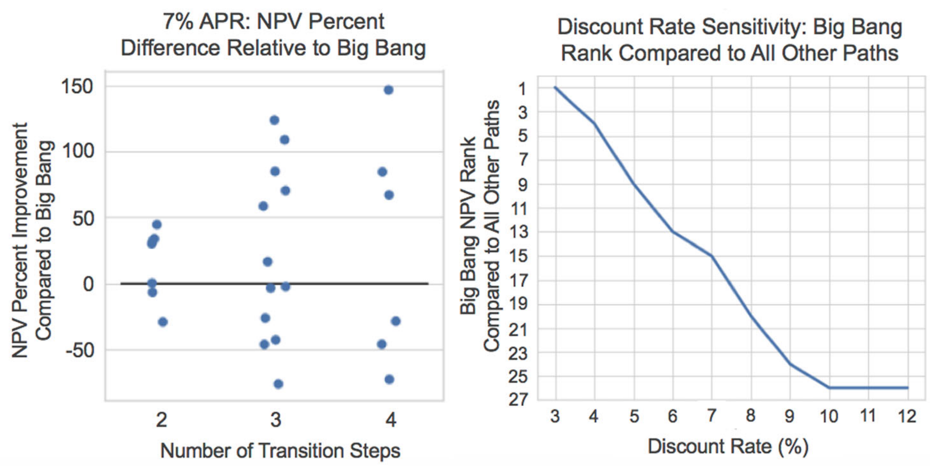

FIGURE 8 (A) Relationship between Path NPV and path length; (B) sensitivity analysis on impact of discount rate on Big Bang performance

The new and improved performance level is not realized until the deployment of all technologies in a state is complete at delay $d_n = MAX_{k=1}^{m}$ *technology deployment time*$_k$. Some technology deployments, like road painting or overhead sign installation, degrade system performance during deployment as they require temporary lane closures to deploy. During each year between t_n and $t_n + d_n$, a degraded system performance may occur while technologies are being deployed. The degradations are incorporated into the benefit profile of the path. Figure 7 shows a sample transition paths in terms of its cost and benefit profiles. The dips in the benefit profile represent a degradation during deployment while the peaks represent a state that is fully deployed and operational. Individual paths matter because the variation in utilized technologies results in different benefit and cost profiles, which can have significant implications for a decision maker. The next section will discuss examples of how decision makers can benefit from this type of analysis and tailor the EAF to their priorities.

5 | RESULTS AND DISCUSSION

In a traditional NPV benefit-cost analysis, a decision-maker would compare the discounted benefit and costs from implementing the new state. The EAF still enables a typical NPV analysis based on the cost and benefit curves defined above, but it also provides a much richer perspective on the alternatives faced by decision-makers. In this section we focus our discussion on the benefits of an EAF analysis and illustrate them using results from the LA-inspired case study.

5.1 | EAF creates an additional—and valuable—decision dimension

Figure 8A shows the NPV for each of the 26 paths. Each point on the graph corresponds to a potential transition path from S(1,1) to S(3,3) and has its own cost and benefit accumulation profile. Any point above the reference line indicates an improved NPV outcome compared to the "Big Bang"—the one-step path transition from a fully mixed to variable congestion pricing state. The results reinforce the value of including alternative paths in the analysis. About half of the paths have an NPV improvement compared to the Big Bang. If the decision-maker had only considered 1-step approaches, these valuable alternatives would have been missed.

Since the value of delaying investments can be strongly dependent on individual modeling parameters like the discount rate, likelihood of cost overruns, and performance degradation during transition, we conducted a sensitivity analysis. The full results are reported in Appendix 1. The only parameter that impacted the main result—that introducing multi-step paths to enable a final capability creates valuable options for decision makers—was the discount rate. Figure 8B shows how the ranking of the Big Bang option changes over a range of discount rates. All baseline results were calculated with a rate of 7%, which follow guidance the US Department of Transportation and Office of Management and Budget for BCA. This results in 13/26 paths offering NPV improvements over the Big Bang. While discount rate has a strong effect on that fraction, across the range of APRs recommended in the literature (3%–12%), only an APR of 3% enables the Big Bang to dominate; otherwise, there are multi-step paths that improve value.

While the evolvability framework developed here is useful for studying multi-step paths, it is a very simple model that is not intended to support complex infrastructure decisions. Degradation levels utilized in the model are based on the SUMO simulations. Changes to these degradation levels can have a significant impact on path NPV. Decision makers who utilize this framework should pay careful attention to degradation levels and ensure they are reflective of their context to ensure they have full information before deciding how to proceed.

5.2 | EAF lets you explore more realistic decision-criteria

The EAF enables decision-makers to introduce important policy considerations that are not supported by traditional NPV analysis. We describe two illustrative examples.

First, consider a typical municipality with a capped operating budget. Due to other fiscal demands and the nature of public spending, the municipality may only be able to spend a certain amount of money per year on a planned infrastructure improvement. By encoding the transition path from year-to-year, the EAF allows this type of constraint to be incorporated explicitly. Here, we would simply filter for paths that meet the yearly cost cap condition and present the remaining alternatives to decision-makers. This option is uniquely enabled by the EAF's combination of path-oriented alternatives and the way the analysis is constructed. While a traditional NPV analysis can study costs and benefits per year, a more sophisticated analysis is needed to understand the implications of delaying expenses in a given path. Rather than giving decision makers a single number to synthesize each alternative, the EAF naturally enables this type of real-time option filtering.

Second, in many public contexts a simple financial analysis does not capture all relevant constraints and/or priorities. Commuters may not tolerate substantial delays for an extended period of time, which could create path dependencies in later technology adoption. This can also introduce important equity concerns if transportation disruptions disproportionally affect a particular segment of the population. To analyze paths with this type of concern in mind, we can again filter the results to include only the paths which achieve certain criteria. There is no equivalent analysis that can be done in a typical NPV since it neither

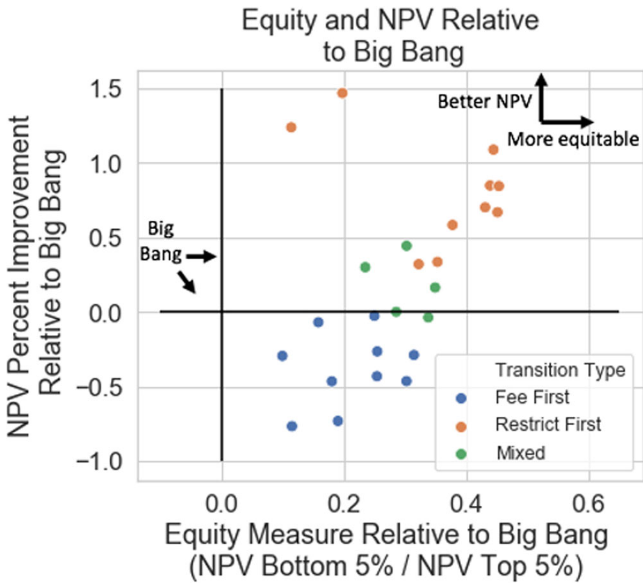

FIGURE 9 Average path NPV versus equity measure

records the distribution of benefits nor the "physics" of the transitions, including delays in achieving benefits.

To illustrate how these types of considerations can be implemented and affect the decision, we consider a decision maker who strongly values maintaining service to demographics with the least access to transportation. For each path, we calculate an equity ratio of the NPV for the bottom 5% of the population (those using mostly multi-step bus routes), divided by the NPV for the top 5% of the population (those in cars who have the resources to pay for priority). Again, we compare all paths to the "Big Bang" baseline. As shown in Figure 9, the "Big Bang" is the least equitable path and would likely not be considered by this decision maker. We categorize the remaining paths by whether the first transition begins with a purely fee first, restrict first, or mixed state. Most of the options follow a linear trend line, where "restrict first" options have the highest NPVs and are the most equitable while the "fee first" options have the lowest NPVs and are the least equitable. For the case described above, the analysis finds multiple "restrict first" options that have both high equity and NPV compared to the Big Bang. For decision makers who care about equity, EAF provides a significant advantage over traditional cost–benefit analysis.

6 | CONCLUSION

This paper presented the Evolvability Analysis Framework (EAF) as a new perspective on evaluating complex transportation system upgrades. By focusing on *transition paths*, EAF gives decision makers additional information about multi-step options to achieve a desired end state. These alternatives almost always offer options that perform better than jumping directly to the desired system end state through a Big Bang approach. Additionally, EAF's formulation gives decision makers the ability to incorporate additional critical decision variables that traditional benefit-cost analyses omit, like budget caps or measures of equity. With these additional considerations, decision makers will be better equipped to tailor system improvement investments for the specific needs of the community they serve.

In this paper we focused on demonstrating the viability and potential value of this approach with a simplified model of improving a transportation system. A more detailed, context-specific analysis requires several additional modeling innovations that are the focus of ongoing work.

First, in this initial analysis we used a traditional NVP valuation framework. Since Engineering Options Analysis (EOA) techniques are designed to address path-dependent decision-making, a future, more sophisticated analysis could take advantage of the associated analysis approach. EOA emphasizes mitigating future uncertainty. EAF focuses on the need to maintain system performance during upgrades. Merging those techniques with our focus on multiple transition paths, with useful planned intermediate states could improve both approaches.

Second, implementing the EAF requires a simulation tool with an individual rider decision-model that accurately models how riders will respond to system changes, such as being able to join a carpool or pay a toll for access to a restricted vehicle lane. We are currently developing a way to link the outputs of a mode-choice conjoint survey into an endogenous decision model within SUMO. At the scale of example model used in this study, we would not expect results to change significantly if a decision model were incorporated into our simulations.

Third, we did not take advantage of the distributional characteristics of our results. Nonetheless, they provide a preliminary view of the importance of considering the variation in how infrastructure updates impact users in specific demographics. In our simplified model, performance is measured at the *vehicle* level, but to fully develop equity measures, the results need to be captured at the *rider* level, which is another modeling tool under development.

Finally, while this paper focuses on an instance of the development of transportation-related infrastructure, the notion of evolvability as a design principle applies to many complex systems, from military fleet deployment to other forms of infrastructure like the power grid. As modern systems become increasingly path dependent and interconnected, evolvability will become increasingly important.

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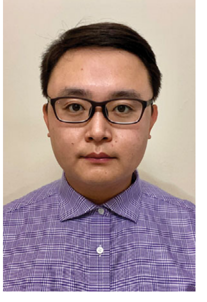

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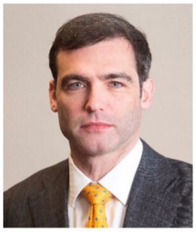

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APPENDIX 1

SENSITIVITY STUDY

In all of the previous analysis, we showed a number of advantages to path-centric thinking for transportation investment. While these results are promising, it is important to understand their limitations. This objective of this section is to assess how changes to the input data affect the number of valuable multi-step paths available to the decision maker. Four input variables will be studied: the discount rate, technology costs, technology deployment time, and for a path, the time between when one state is finished deploying and the next state begins deploying. Benefit levels will be discussed in a future paper.

We determined a reasonable range for each of the input data, shown in Table A1. A one-way sensitivity analysis was conducted, whereby the model was re-run with one input variable changed along its range while holding the other variables constant. The NPV rank of the Big Bang option for each run, relative to other paths, was utilized to determine how many valuable multi-step paths the decision maker can choose from. For example, if the Big Bang option has a higher NPV than all other paths, its rank would be 1.

The results of the technology costs, deployment time, and time between state deployment sensitivity study are shown in Figure A1. Technology costs, whether annual or one time, have no impact on Big Bang rank due to their low combined effect on the NPV. Deployment delays increase the number of valuable options for decision makers, which is important to consider as often times infrastructure upgrades can have schedule delays. Additionally, time between deployments has little impact on the number of multi-step options available to decision makers.

Finally, the results of the APR study are shown in Figure A2. At a 3% discount rate, the Big Bang ranks first compared to other paths. This is likely because the discounted costs for multi-step paths are closer to the Big Bang costs at a lower discount rate, while the Big Bang achieves the maximum benefit the fastest. The results of the paper hold for all other discount rates, however, it is important to note that at very low discount rates the Big Bang will dominate all other options.

TABLE A1 Sensitivity study variable ranges

Variable	Type	Baseline	Lower bound	Upper bound
Discount rate	%	7%	3%	12%
Technology costs	% Over original baseline	0%	0%	200%
Technology deployment time	% Longer than baseline	0%	0%	200%
Time between deployment	Time in years	1	0	4

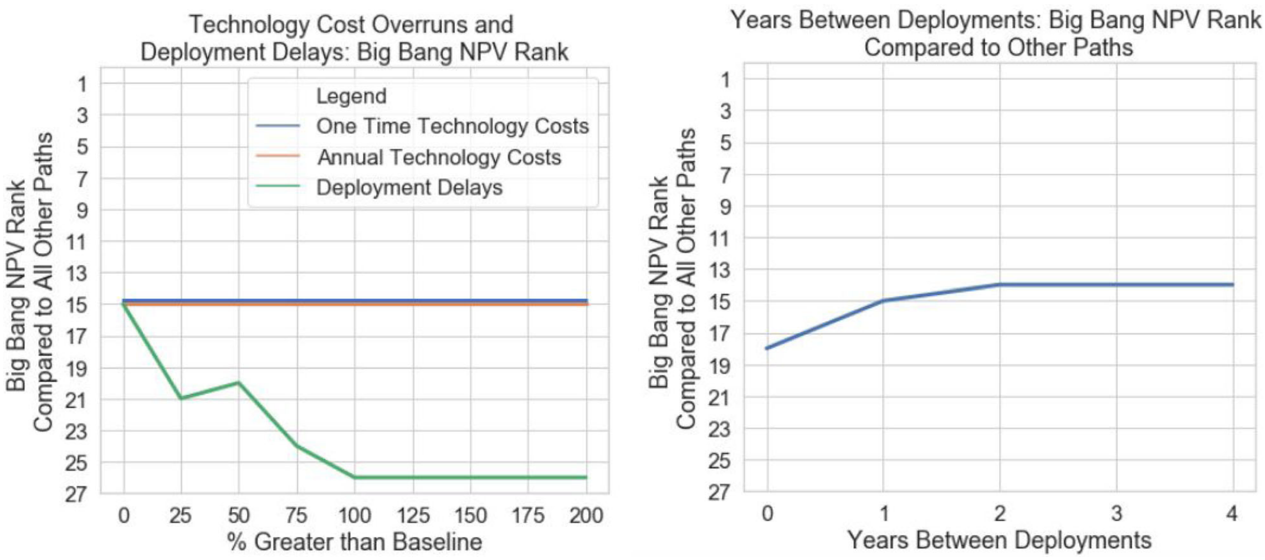

FIGURE A1 (A) Technology cost overruns and deployment delays sensivity results and (B) years between state deployments sensivity results

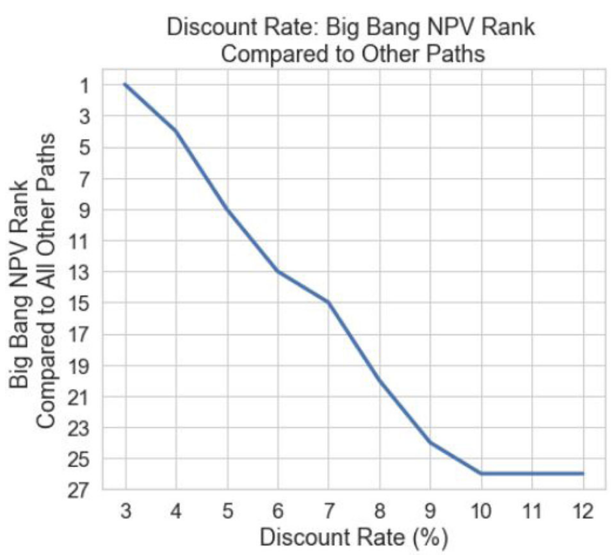

FIGURE A2 Discount rate sensitivity results