Planning for Connected and Autonomous Vehicles –
How to Understand and Prepare for this Complex World

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Abstract

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In the future, it is expected that vehicles will be both connected and automated (CAV). This future CAV world will be complex and there will be a lot at stake. Public agencies need to be prepared with the right investments and policies; whether capacity and technology investments, policies concerning shared mobility, or changes in land use, to name a few. Legislatures and communities need to be concerned about the best regulatory framework and financial incentives to put into place. There are many questions to answer and there is a great deal of uncertainty, and communities across the country need help with their strategies, now.

The purpose of this investigation was to develop a powerful approach complete with analysis tools to support public planning agencies in this arena. Based on the results of our exploration, the preferred approach is a hybrid of two methods. First, System Dynamics is used to understand the “causality” of various driving forces such as technology, infrastructure capacity, public policies, investments made by public agencies and the private sector, and many other factors. When combined with the capabilities of Robust Decision Making, this customized approach will give policy makers and planners the tools necessary to craft the best strategies possible.

The urgency for planning organizations, governing bodies, and transportation agencies to understand and plan for CAV is high. In anticipation of these planning needs, the recommended approach has been defined in detail, piloted and is ready to be implemented across the country and around the world.
INTRODUCTION
Connected and Autonomous Vehicles (CAV) hold the promise of providing myriad benefits to a variety of stakeholders. These benefits may include reductions in congestion, emissions, crashes, and user costs. Benefits may also include increased mobility and a stimulus to the economies of metropolitan areas. Technology investments by private industry will be strong enablers in realizing these benefits.

Infrastructure investments by public agencies may also be enablers in bringing these benefits to fruition. These investments may involve the ability to which vehicles and the infrastructure communicate information. In addition, well-placed and well-designed capacity (lanes, parking areas, etc.) could also positively influence the adoption of CAVs and in turn provide desirable outcomes such as the benefits mentioned above. As CAV adoption rate increases, there will likely be continued investment by the private sector to reinforce these positive results.

CAVs could be growing in number and significance soon. However, there are lots of questions to be answered. A few of these include:

- Will traffic levels go up? Or down?
- Will there still be a place for transit in metropolitan areas?
- How will ride-sharing work with CAVs?

Certainly public agencies (DOTs, cities, counties, etc.) have a role in this due to their recognized charters in the transportation arena. So, more questions include a) How should the public sector make decisions on various infrastructure capacity or technology investments?, b) When should these investments be made?, and c) What about sharing some of these investment responsibilities with the private sector, given their potential upside in the CAV business? As a major stakeholder, expectations of private sector participation in infrastructure investments is a fair and important question, in addition to their own technology investments. Other public policy issues involve crafting financial incentives for the public, such as pricing for access to driving lanes, and incentives for shared mobility.

Critical Issues for Public Entities to Consider
Hence, with the need for planning support for CAVs, overall questions include:

1. What are the public sector’s critical roles in the deployment of CAVs?
2. What investments can the public sector make to maximize potential benefits, and minimize negative results?
3. Where will CAV adoption occur and what will be the driving factors behind the level of adoption? What public policies will induce the most benefit? The least?
4. What will be the impacts of CAV adoption? What factors will influence these impacts?
5. What will be the dominant ownership models for CAVs? Individual? Shared? A mix?
6. What impacts will anticipated changes in demographics impose on CAV adoption?
7. What will CAV mean to land use policies in the future, versus today?
In general, stakeholders include taxpayers, vehicle purchasers, pedestrians, technology companies, and the residents of metropolitan areas, to name a few. Therefore, public (or public/private) investments and policies related to CAV will receive a lot of scrutiny over the next few decades. And due to the long lead time for the benefits of major investments to “pay off”, the time to increase the understanding of these types of investments, and their potential impacts, is now.

SUMMARY OF THE PROBLEM
The main objective of the work described herein was to develop the best analysis methods for supporting public agency planning and decision making efforts for CAV. A clear and robust process needs to be put into place to enable agencies to consistently and effectively deal with issues they face. With the advent of CAVs, however, there is much to understand, and the complexity involved in projecting the future is significant. No doubt, a wide range of “futures” will need to be explored in order to make sure all relevant outcomes are considered, such as:

- What roadside infrastructure will be required to best support CAV operations?
- Could crash reductions dramatically reduce the need for safety infrastructure?
- What types of capacity will have the greatest significance? (lanes, parking, etc.)

With a new set of transportation technologies, and many changes expected in the near future, there is a long list of things that will be affected. For example, USDOT did a study regarding the impacts of CAV on typical planning processes and the need for enhancements to transportation planning workforce development. Some of the affected items are listed here:

- Long-Range Visioning
- Statewide Long-Range Transportation Plan
- Regional Long-Range Transportation Plan
- Transportation Improvement Program
- Short-Range Transportation Plan
- Congestion Management Plan
- Asset Management Plan
- ITS and Operations Plan
- ITS Architecture
- Strategic Highway Safety Plan
- State Implementation Plan
- Transit Development Plan
- Transportation Demand Management Plan
- Non-motorized (bicycle and pedestrian) Plan
- Corridor Studies (Modal or Multimodal)
- Public Involvement Plan
- Freight Plans
- Financing Plans
- Highway Safety Improvement Program

In order to enable public agencies to understand which investments are most important for them to make, and which policies to implement, powerful analysis and planning methods are
required. Due to the rapid events associated with CAV currently occurring, it appears that solid analysis and decision making tools to support these planning efforts are needed soon.

**Requirements for a Solution**

In general there is a need for more robust forecasting capabilities to support scenario analysis and planning processes regarding the advent of CAV. In order to get a better idea of what this means, a set of relevant requirements were identified. These requirements for developing the best approach for CAV scenario and planning analysis include the following:

a) The impacts of many different influences are necessary to understand
b) There will likely be non-intuitive outcomes in some investment or policy scenarios
c) There will also likely be unintended consequences involved in many investment or policy scenarios
d) The progression of the future of CAV will be a “path function”. In other words, the order and timing of actions or interventions in the system, such as making capacity investments, will affect the outcomes differently, depending upon how or when those investments are made, or how or when policies are implemented
e) There will certainly be “feedback” in the CAV system, such as technology investments that create a better user experience, and hence this may encourage adoption of CAV, and lead to more investment in technologies, and so on – this is referred to as a “growth loop”
f) There may also be the reverse of growth loops present in the system; these are known as “death spirals”, and this would be a phenomenon which most would prefer to avoid
g) An approach needs to include (and support) Robust Decision Making, including:
   a. Effective strategies that succeed across all anticipated futures
   b. Adaptive responses, depending upon how the future unfolds
   c. Hedging strategies that thwart undesired outcomes
   d. Shaping strategies that tend to promote desired futures
h) An approach must be able to consider a wide range of plausible futures
i) Ability to perform “what if” analysis, and perhaps quantitatively simulate these cases
j) Ability to vary controllable and uncontrollable (uncertainty) variables, to observe results
   a. Apply risk analysis techniques to analyzing potential scenarios
k) Ability to use Monte Carlo methods in scenario analyses and related simulations
l) Ease of implementation for the approach, ability to update results, on-going usage

**CHOSEN APPROACH**

It is important to have an approach that will allow planners from transportation agencies to make the best infrastructure investments, and create the best policies possible. An approach that meets the criteria listed above was chosen which uses proven methods that have been used across industries successfully in the past. This approach has also been defined in detail.

These methods have existed for decades, and are widely applicable across industry as well as the public sector, for understanding the behavior of a variety of “systems” including:
Some History on System Dynamics

Pioneers in the development and application of System Dynamics include Peter Senge with “The Fifth Discipline” (1), and Jay Forrester with books that include “Industrial Dynamics” (2) and “Urban Dynamics” (3). The use of causal diagramming and system simulation enables complex systems to be depicted and understood, where other tools and methods fall far short. These capabilities include the ability to develop a “point of view” on the future, and enable scenario analysis that provides the utmost confidence in solutions and plans. When combined with “Robust Decision Making”, strategies can be formulated based on the best information and insight possible, and include the consideration of plausible futures that traditional brainstorming and scenario analysis techniques often miss.

Examples of successful application of System Dynamics to transportation-related “systems” are listed here. These examples are from work performed at the Wyoming Department of Transportation:

a) Project Pipeline Study -- Managing Risks in the Project Pipeline, Final Report (4)
b) TRB Journal Paper, Minimizing the Impacts of Cost and Revenue Uncertainties on Transportation Project Delivery (5)
c) I-80 Study, Intermodal Options, Feasibility of a Next-generation, Intermodal Rail-truck Transport System for the Western I-80 Corridor, Final Report (6)

Our approach is capable of facilitating an analysis of complex systems such as CAV, as well as the myriad influences that might affect that system. This analysis approach includes the ability to diagnose system behaviors, depending upon the driving influences, and make an assessment of the resulting outcomes. To begin an approach of this type, the initial set up for the analysis of CAV futures is important in framing up a comprehensive and successful study.

Identifying Dynamic Drivers or “Influencing Factors”

This step is important in framing up an analysis, since it requires the analyst to identify the causal factors that may impact the situation. For example, the external influences on a given situation may include the following types of factors -- environmental, political, demographic, financial, economic, and others. These examples are shown in Figure 1 below. Depending upon
the situation, factors such as these should be considered in terms of “how” they might impact the Situation, or “System”, and to what extent.

Figure 1 also shows the overall “system” framework diagram which lists the System Drivers, System Entities, and Key Performance Indicators (KPIs) which are representative of the CAV “system”. The system drivers include forces that are controllable, such as strategies that might be employed. System drivers also include influences that cannot be controlled, and hence provide uncertainty and risk in the future.

Summarizing the importance of the framework – Depending upon how the system entities respond to the driving influences will determine what the resulting outcomes are. These outcomes are measured in terms of Key Performance Indicators, or “KPIs”.

**FIGURE 1 System Analysis Framework for CAV**

Given this framework of various influences, and highly unpredictable responses, the chosen approach to this effort is expected to bring the best modeling and analysis methods to bear. The exact future of CAV is certainly unknown at the moment, and the number of influencing factors is large. These factors include those that can be controlled, such as policies and investments, as well as a large number of uncontrollable factors. This reality implies great complexity and uncertainty in terms of being able to predict the potential range of outcomes, and which strategies may be the best for public agencies to implement.

Hence the recommended approach is to utilize the discipline of System Dynamics as the core analysis method, and when combined with the use of Robust Decision Making (RDM), it is anticipated that the best possible investment strategies can be arrived at. This approach is described and illustrated in the following pages.
The case for System Dynamics (SD) and RDM for the Analysis of CAV

Causal Analysis – Once the above items in Figure 1 are documented, a causal analysis can begin. In short, this involves considering the various elements of the “Situation” (system), and the effects of the Dynamic Drivers (External Influences) on the various elements of the system. This process is tedious, but it assures that the analyst clearly defines the mechanisms present in the system, based on cause and effect. Whether the eventual scenario analysis tool is a simple spreadsheet, or more sophisticated such as a full dynamic simulation of the situation, causal analysis is crucial in the overall approach.

Consider a basic framework, such as that shown in Figure 2, for modeling the advent and potential growth of CAV. Let’s assume that investment, public or private, results in improvements in vehicle and system capabilities, in terms of “Benefits per Car”. This will presumably lead to increased adoption of CAV, both by the public at large and by commercial entities. “Total Benefits” to society may include improvements in congestion, safety, personal costs of transportation, and so on. Thus, higher rates of adoption will boost Total Benefits and, in turn, lead to more investment, and hence the cycle gets stronger and stronger. This is known as a “growth loop” which, when left alone, will grow exponentially.

FIGURE 2 CAV Adoption “Growth Loop”

With no other influences, this self-reinforcing loop (“R”) will grow to infinity. Of course, that will not realistically happen. In the case of CAV, as with any other system, there will be natural limits, like the number of people in a given metropolitan area which is a finite number. Hence, the exponential growth will, at best, eventually level off as shown by the “Limits to Growth” scenario shown in Figure 3, where multiple scenarios are shown versus overall benefits of CAV in terms of Key Performance Indicators or “KPIs”. Advocates of CAV would be happy to see this scenario play out over time, and thus should be very interested in the conditions and influences that would cause (or allow) this future to happen.
Another scenario would be if the CAV community “did everything wrong”, and the initial growth from investment, vehicle improvements, and CAV adoption does not lead to strong, sustained growth of CAV over time. Some factors that might lead to this would be bad public policies, or misguided capacity use incentives, for example. Other factors might be an excessive number of crashes or fatalities attributed to the use of CAV in its early years. This type of scenario might look like the bottom curve in Figure 3, where there is initial growth, but then negative influences turn the early growth around into a “death spiral” where adverse influences drive adoption and usage downward. This is illustrated by the “Nice Try” curve.

A third scenario could plausibly be a case where there is initial growth, and there appears to be reasonable on-going growth tendencies in the adoption rate. But over time, as usage continues to grow, the conditions are such that growth is not allowed to reach its “natural limits” (e.g. physical, economic, demographic, etc.). Instead, due to uncertain policies or infrastructure capacities which do not “keep up” with the changing landscape, the growth stalls out, and may waver over time unless the right conditions and influences can restore and/or sustain continued growth. This is shown as the middle curve in the scenario diagram, entitled “Drifting Goals”.

Thus, a range of scenarios is possible given the initial “growth loop” shown in Figure 2. Three possible scenarios, from Figure 3, are summarized here:

- **“Limits to Growth”** – successful deployment of AVs overall, with a natural limit(s); e.g. highway or parking capacities, metro population, local economy, etc.
- **“Drifting Goals”** – could be a result of policy failure(s) or uncertainties re: which policies are effective/not; or other influences such as variable demographics, public trends, or economic cycles.
- **“Nice Try”** – in spite of initial growth trends, the situation/location does not support sustainable AV usage and growth; e.g. due to low population or urban density, or other factors. Or perhaps AV usage fails in general.
Let’s examine how these scenarios might be modeled, starting with the original “growth loop” from Figure 2. The purpose here is to illustrate how "controllable" influences can be depicted, and then how these influences can be factored into an assessment of their effects on the "system". This is done either through the creation and subsequent distillation and analysis of a causal diagram, or by developing and using a full-blown dynamic simulation of the system influences. It is also important to illustrate how "uncontrollable" influences can affect things, and distinguish these influences from the "controllable" ones, i.e. ones that make up the strategies that are being considered or formulated.

Figure 4 shows the original growth loop, plus a few representative factors that might come into play in the growth of CAV over time. Therefore, depending upon the strengths of each of these individual influences, the overall outcomes may vary considerably. Hence it is important to lay out all the relevant causality regarding CAV, and to examine it in a systematic manner.

**FIGURE 4 Example Influences on the Core CAV Growth Loop**

This diagram (Figure 4) is only an initial baseline showing example causal influences on the system. The diagram needs to be expanded, in order to capture the major dynamics which we believe will exist in the CAV System, such as feedback. To reiterate, Figure 4 illustrates a “growth” system, along with several categories of influences that might affect that growth, either positively or not. In fact, the actual CAV System could involve the reverse of “growth” at some point in the future, if the growth is not sustained and/or the outcomes of the system are not well received by the public.
An example of some more detailed causal influences is shown in Figure 5. Note that the influences shown in the figure each drive the core growth loop. The core loop already was a strong source of feedback on its own. Adding these external influences can create additional feedback, such as the link from “Benefits” to “Media Focus on CAV”. This feedback strongly increases the amount of growth stimulus, including the strength of the original core growth loop. Please be aware that other influences can have a negative effect on the growth of CAV adoption, and may result in negative feedback forces as well. Hence, it is important to depict and analyze these influences and how their cause-and-effect may determine future outcomes.

FIGURE 5  Representative Causal Influences and Feedback

To be sure, the value and importance of causal diagramming is compelling:

- To understand leverage points where optimum influences can be applied in order to affect system behavior positively; for example:
  - Some influences have multiple effects, and may or may not be significant
  - Also, influences that act upon reinforcing loops, or create reinforcing loops, are particularly important in determining system behavior
- The discipline of causal diagramming leads to the ability to analyze system behavior, and simulate system outcomes and “futures”, thus enabling comprehensive scenario analysis
- This type of analysis enables the analyst to understand the non-intuitive nature of complex systems, and to anticipate “unintended consequences” long before they actually happen
The influences shown in Figure 5 can positively affect the “growth wheel”, so that it “spins” more strongly in the clockwise direction. These influences can be quantitatively modeled by using influence coefficients to simulate the strengths of cause-and-effect between system entities. For instance, in examining Figure 5, setting federal safety standards can result in consistency of regulations, more industry confidence in the federal role in CAV, and ultimately more investment from industry. Early estimates of these influence coefficients can be made for the purposes of beginning the system simulation process, and then can be adjusted frequently in order to match the overall behavior of the system in reality. In this manner, the models can be “tuned” in order to improve the accuracy of the simulations in projecting future outcomes.

So, after creating a full causal map, the next two steps are – 1) distilling and analyzing the causal diagram, and 2) gathering data to validate the diagram and/or modify it, and to prepare for eventual simulation of the system if desired or warranted.

Analysis of the Causal Diagram
This step is where significant insight can be developed early on, before investing time in simulating the system. In other words, in performing this analysis thoroughly, the analyst should be striving to “discover” things that, if acted upon, could create greater benefits, save the most money, and so on. It is in this step that a comprehensive view of the situation (i.e. a diagnosis of system behavior) can be defined in order to identify possible improvements in the situation, formulate candidate strategies, and estimate the value of these strategies.

By distilling a complex causal map, it is possible to discover the key dynamics that may be present in the system, and core to defining system behavior. Distillation is accomplished by looking for all sources of feedback (e.g. “growth spirals”), and determining how strongly future growth is driven by these reinforcing influences. Also, any negative influences of feedback are identified, and the strengths of these influences are also assessed (“death spirals”). This qualitative analysis is usually very effective in identifying solid strategy opportunities, but obviously is not as powerful as a full quantitative simulation.

Next in the process is the search for data to validate the causal map, and make any relevant updates. Good data will help support or perhaps challenge the rationale for the premises that are built into the causal map, regarding the individual linkages of cause and effect. The search for data can also support the creation of a quantitative simulation of the situation that may significantly increase the understanding of system behavior, and enable thorough scenario analysis and the testing of a range of strategies, as well as exploring uncertainty variables that might affect future outcomes. It is essential to identify data that correspond to key causal relationships in the diagram, as well as verifying presumed trends regarding system behavior over time, given various conditions.

System Simulation
Following the step of gathering relevant data on the system comes the step of simulation. The purpose of simulating the system is to better understand system behavior, and to explore and test
potential strategies. This consists of constructing a quantitative model of the causal relationships present in the system. This simulation model can be utilized to test various scenarios that are important to explore over a relevant time horizon. Once the system is “wired together”, the analyst can begin simulating plausible futures using a range of necessary input data, as well as candidate investment and policy strategies. Then the analyst can examine the simulation results throughout the timeline of the scenario – such as a 30 year period.

**Baseline Simulation**

Shown here in Figure 6 is an actual baseline simulation model for CAV, which will be expanded and updated over the next few months. As a variety of future scenarios are posed, the quantitative simulation will be adapted in order to accommodate these cases, and the knowledge of system behavior will be enhanced accordingly.

![Diagram of Baseline Simulation](image)

**FIGURE 6 Example Simulation of CAV Growth**

Initial results from running this simulation model are shown below in Figure 7. As you can see, in this example the results depict the “Limits to Growth” scenario, illustrated in Figure 3. By looking at the “Adoption” curves and the “Total Benefits per Year” curve, one can see that healthy growth occurs for several years, and then begins to level out as the available riders in the region have been largely shifted over to utilizing CAVs.
FIGURE 7  Example CAV Growth – Pilot Simulation Results

With this simulation capability, the analyst can now pose and test various strategies. The analyst can also test combinations of uncontrollable variables; or those factors that pose uncertainty or risk to the future of CAV.
Scenario Analysis and Robust Decision Making (RDM)

The typical approach to scenario analysis is to define a “trade space” of consideration that defines the dimensions of exploration for both controllable and uncontrollable variables. This generally consists of identifying parameters that could vary over a certain range of values, in order to set up the analysis runs. This will enable a range of “what if” scenarios to be examined.

Shown in Figure 8 is a framework for setting up a scenario analysis. This framework includes potential causal influences or “drivers” (as illustrated in Figure 1), and the KPIs (outcomes) that will need to be examined in the outputs of the simulations.

**FIGURE 8 Framework for Scenario Analysis**

The process here will be to posit values for variables that cannot be controlled, such as CAV adoption rates as a function of user benefits or benefits to society overall. The analyst can also consider candidate investment *and policy* strategies to test amidst system influences. The crux of sound scenario analysis is to define only coherent combinations of controllable variables and uncontrollable variables, as well as their quantitative values. In other words, some variable values cannot generally exist simultaneously such as a decreasing population but yet a need for new lane or parking capacities. Hence, the number of scenarios to be considered can be limited by using these methods.

**Strategy Development**

In exploring a range of scenarios, it will be possible to create a set of robust strategies, with the objectives of minimizing risks, maximizing outcomes, etc. Below are some examples of strategies from the RDM method that may support these objectives:
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Where to go next – Following a comprehensive analysis, and the creation of a vetted set of strategies, it is time to implement and manage these strategies.

Management of CAV Strategies
The mantra of “Model, Measure, Manage” is a key theme of the process recommended here, regarding the on-going management of strategies that have been put into place. The “Model” is in place, and now “Measures” need to be implemented, for monitoring and updating the adaptive strategies. This approach supports the recommended strategies from Robust Decision Making, in terms of utilizing a process that is essentially the same as the familiar “Plan, Do, Check, Act”.

Thus, as a result of the modeling exercise, and the strategies that have been defined and implemented, it will be important to begin “measuring” how the actual future is unfolding. For example, when an investment in new capacity is made, based on a premise related to the anticipated effects of that investment, those effects (actual outcomes) will need to be measured and compared against the anticipated (projected) results. In this manner, strategies can be monitored and adjusted, and the overall strategy can be adapted accordingly. Two types of indicators typically apply:

Leading Indicators – Noting the actions that were performed versus the actions planned
Lagging indicators – Noting the projections of outcomes for the set of actions executed versus the actual outcomes that occurred

In summary, the following attributes of this recommended approach are critical to having good long term strategies:

Mapping system causality provides the necessary information for understanding a complex system such as CAV
Collecting good data will help validate the assertions re: cause-and-effect relationships in the system diagram, and enable eventual simulation of the system.

Distillation of the CAV causal diagram will provide insight into how the future will “play out”, the nature of overall system behavior, and early results in terms of understanding.

Simulation can provide tremendous insight into system behavior and support scenario analysis significantly, including the ability to run “what if” cases, and consider risks.

RDM is a comprehensive method for creating strategies that will minimize the risks related to unknown futures, and maximize desired outcomes.

CONCLUSIONS AND RECOMMENDATIONS

Powerful methods for scenario analysis are needed for understanding and planning for the advent and future of CAV. Several methods are currently in use, such as a fairly standard form of scenario analysis where plausible, coherent scenarios are listed, and analysts formulate a range of strategies accordingly. The complexity of some arenas, however, such as the potential futures for CAV, demand more rigor than traditional methods. A suitable approach must be able to uncover the nuances of possible CAV futures, and successfully explore strategies that consider myriad causal influences on how these futures may play out. In addition, the approach must deal with non-intuitive outcomes and unintended consequences of policy and investment decisions.

Based on the results of our investigations, the preferred approach is a hybrid of two methods. First, System Dynamics is used to understand the “causality” of various driving forces such as technology, infrastructure capacity, public policies, investments made by public agencies and the private sector, and many other factors. When combined with the capabilities of Robust Decision Making, this tailored approach will give policy makers and planners the tools necessary to craft the best strategies possible.

To augment these capabilities, a prototype simulation has been constructed, and appears to be a useful model and test bed for CAV analysis efforts. This modeling capability will add great understanding regarding CAV “system” complexity, and to the ability to explore various potential future scenarios, versus simply brainstorming a range of plausible outcomes. This prototype is ready for full-scale usage in participating agencies.

Finally, a solution that can be proliferated across agencies and geographies is sorely needed, in order to provide consistency in an approach. Additionally, the urgency for planning organizations, governing bodies, and transportation agencies to understand and plan for CAV is high. In anticipation of these planning needs, the recommended approach has been defined in detail, has been piloted, and is ready to be implemented across the country and around the world.
REFERENCES


