Atlas Initiative for Critical Infrastructure

Strategy Essentials

Systems Engineering and Systems Integration Applied to Infrastructure

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October 13, 2025

Engineers are confronting a variety of environmental challenges, demographic shifts and sociological, economic, and technological changes that will require a drastic rethinking of how we build, operate, and maintain our infrastructure systems. There is a need for a new approach.

Holistic Systems Thinking Required. We must consider holistic city, community and neighborhood systems, including the cultural, social, economic, political, ethical, medical and environmental aspects at different scales to better prepare engineers for possible future needs and challenges.

The 4th industrial revolution is already well underway, and it presents a picture of a complex world where many aspects overlap, and the vectors of change are also causing impact across systems. Unfortunately, we usually constrain our thinking to very narrow pathways.

Engineers must start the process by asking the right questions about the future built environment that doesn't exist yet, contemplate solutions, and postulate the resulting benefit – before we begin the process of designing or building. And we must do that while embracing our need to navigate "value tensions." That is the starting point on the path toward technology stewardship.

Why is this important? Climate, healthcare, food and water supply, transportation, soil contamination, biodiversity, city economies and healthy communities are more complex systems than a building, road, or engine. Yet engineering principles must still apply. Engineers need to better understand this new paradigm and partner with planners, community leaders, risk managers, and all those who strive to deliver sustainable and resilient development for the future.

For example, a large portion of the population is fully connected, and digital infrastructure systems are used extensively. Designing these physical and digital networks will require a full-systems integration approach, that spans traditional and non-traditional engineering disciplines, but also partners with scientists, educators, governments, and the wide range of other players/occupations that enable us to address quality of life issues.

Also, power generation and distribution, transportation modes, water and wastewater systems, will all have to be smart, and be smart in a holistic way. A systems-of-systems approach will be essential. Otherwise, solutions in one system simply cascade into unintended consequences in a different system.

Example 1. A practical example presented itself in November 2020. The state of Maine enacted efforts to address global warming by giving financial incentives to owners of solar installations, particularly for new solar installations. The incentives included financial credits for sending excess energy back to the transmission grid. Some landowners took advantage of this offer. However, the larger number of solar installations occurred in land that was sold to new landowners in the year the incentives started.

There was a land rush for south-facing properties which made the original landowners happy, but it boosted the real estate market values to a point where most Mainers were priced out of the market. The new owners were mostly speculators or financial fund managers, not native Mainers.

It seemed like it was working at first. 850 megawatts of excess power per year was generated within the first three years – enough to power more than 800,000 homes. Success was declared.

But because of the financial debits associated with the excess energy rebates, the state's utilities lost $160 million annually and couldn't maintain the power infrastructure (e.g., poles, wires). An electricity rate hike was the only solution. The average residential customer's annual cost increased by $139. The average industrial customer's annual cost increased by $128,000. Those who reaped the reward were only the speculators and financial funds, not primarily the Maine residents.

The financial pain became evident to everyone and the local paper, the Bangor Daily News, ran an article in 2023 that was entitled, "A solar power boom that may be a classic climate mistake." Worse yet, after the rate hike, some homeowners started switching back to oil and natural gas – the very thing that the state leaders were trying to avoid.

If the ecosystem effects are not planned and accounted for, the outcomes rarely meet the intent. This is not an indictment of our good intentions. It is an indication of our lack of holistic thinking.

Example 2. Another practical example in electric vehicles (albeit a limited one) emerged in May 2024. I was able to track and measure the journey of two friends making their way across the state of Pennsylvania from Philadelphia to Pittsburgh on the Pennsylvania Turnpike. They were

delivering an EV van from the manufacturer in Philadelphia to the buyer in Pittsburgh. One drove the EV van being delivered, and the other drove an Internal Combustion Engine (ICE) van (same model), so they could return to Philadelphia. The return trip started at approximately the same time of day as the outbound trip and was under the same weather conditions.

The journey was 330 miles long over what is low grade/semi-flat terrain for about half the distance and often hilly/mountainous terrain for the other half. This is a geography that is more difficult than a flat route through Kansas or city driving in Los Angeles but does represent a great deal of our country. Both the balance of gas and electric charge at the end of the trip were deducted from the calculation so that the comparison is accurate for just the driven miles.

I measured three things – travel time, cost and greenhouse gas emissions, as follows:

- Travel time ICE vehicle: 6.2 hours EV: 18.0 hours
    - The ICE trip included one gas stop, with multiple gas pumps available at each stop with relatively short waiting times per pump.
    - The EV trip included five charging stops (each stop on the PA turnpike had four charging stations usually with about 3 to 4 cars lined up at each station).

- Cost ICE vehicle: $35 EV: $70
    - The ICE cost was $50, but only $35 once the PA highway tax is removed for proper comparison to electric charging costs which had no highway tax assigned at that time.
    - The EV cost included five charging stops at $14 per charge).

- Greenhouse Gas (GHG) emissions ICE vehicle: 135 kg EV: 220 kg
    - The GHG emissions per mile for a 6-cylinder ICE van is well documented by the U.S. Federal Highway Administration and was used for this calculation.
    - The total Kilowatt-hours (KWHs) for the EV for the five charges were multiplied by the GHGs emitted per KWH recorded as the average for Pennsylvania – based on the combination of power sources (coal, oil, nuclear, wind, solar and water) documented by the Dept of Energy for each state.

The electric van took three times as long, cost twice as much, and produced 1½ times the greenhouse gas emissions as the internal combustion engine van. This was recorded in 2024, so the difference in GHG emissions should become less in the future assuming the state begins to produce more electricity by renewable sources – possibly reaching parity. The severe time difference will reduce as the charging stations continue to build out, but that is also a cost that everyone bears, both EV and ICE drivers.

This example is not perfect. It is just one moment in time, one geography, and it doesn't include other factors that should also be included. The entire ecosystem for consideration should include lithium battery sourcing/mining/labor abuses, lithium battery disposal/landfill/reuse, life of

transportation structures (e.g., bridges) with increased EV weights, life of pavements with increased EV torque/friction, cost of national charging infrastructure, economic transition costs to oil and natural gas business and employment, and so forth. But it is an example of at least three factors that should be part of the basic financial and environmental considerations to determine the benefits of a national movement to electrify transportation.

Engineering Profession's Responsibility. Engineers need the confidence to boldly anticipate society's infrastructure needs and the humility to know that we will only succeed in a partnership with all vested actors. And they need to expand their capacity to identify, understand, and manage risk and uncertainty. There are characteristics of the engineering profession that make us unique to accomplish this. We have the expertise to design, construct, maintain, and modernize infrastructure. We can be taught to consider, at a very early stage, the implications of change to ensure the combined safety, health, welfare and ethics of society are optimally served. We are respected, so we will have a platform from which we can translate these changes into public leadership, communication and education efforts. With the right tools, engineers can prepare for near-term change and spend some time thinking even longer term.