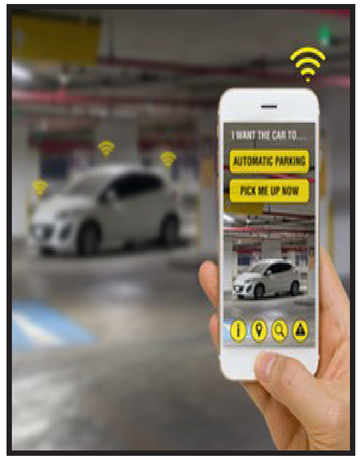
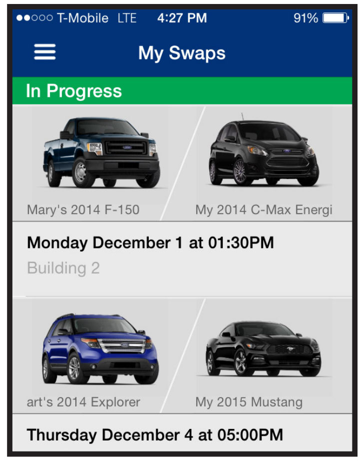
AN AUTOMOTIVE WORLD IN MOTION

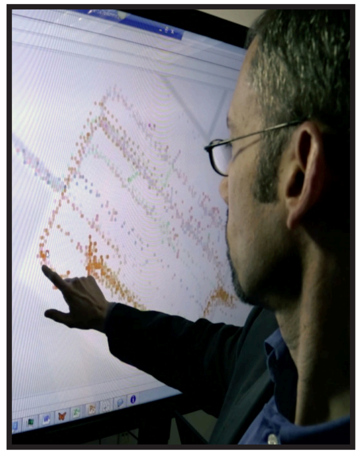
Systems Engineering Vision • 2025

The purpose of the Automotive Systems Engineering Vision 2025 is to *inspire and guide* the direction of systems engineering across diverse stakeholder communities, which include:

- Engineering Executives
- Policy Makers
- Academics & Researchers
- Practitioners
- Tool Vendors

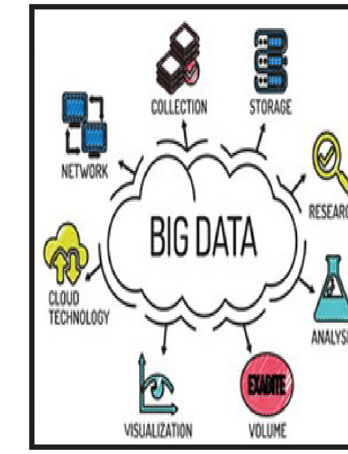






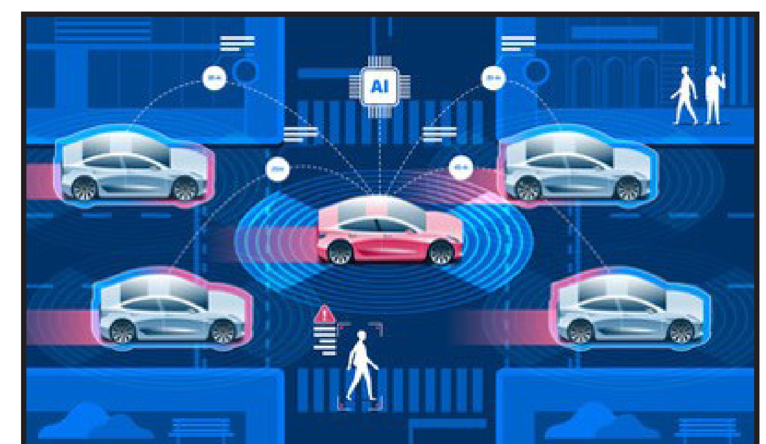
ALIGN AUTOMOTIVE SYSTEMS ENGINEERING INITIATIVES

PROMOTE AUTOMOTIVE SYSTEMS ENGINEERING RESEARCH



ADDRESS FUTURE AUTOMOTIVE SYSTEMS ENGINEERING CHALLENGES

BROADEN THE BASE OF SYSTEMS ENGINEERING



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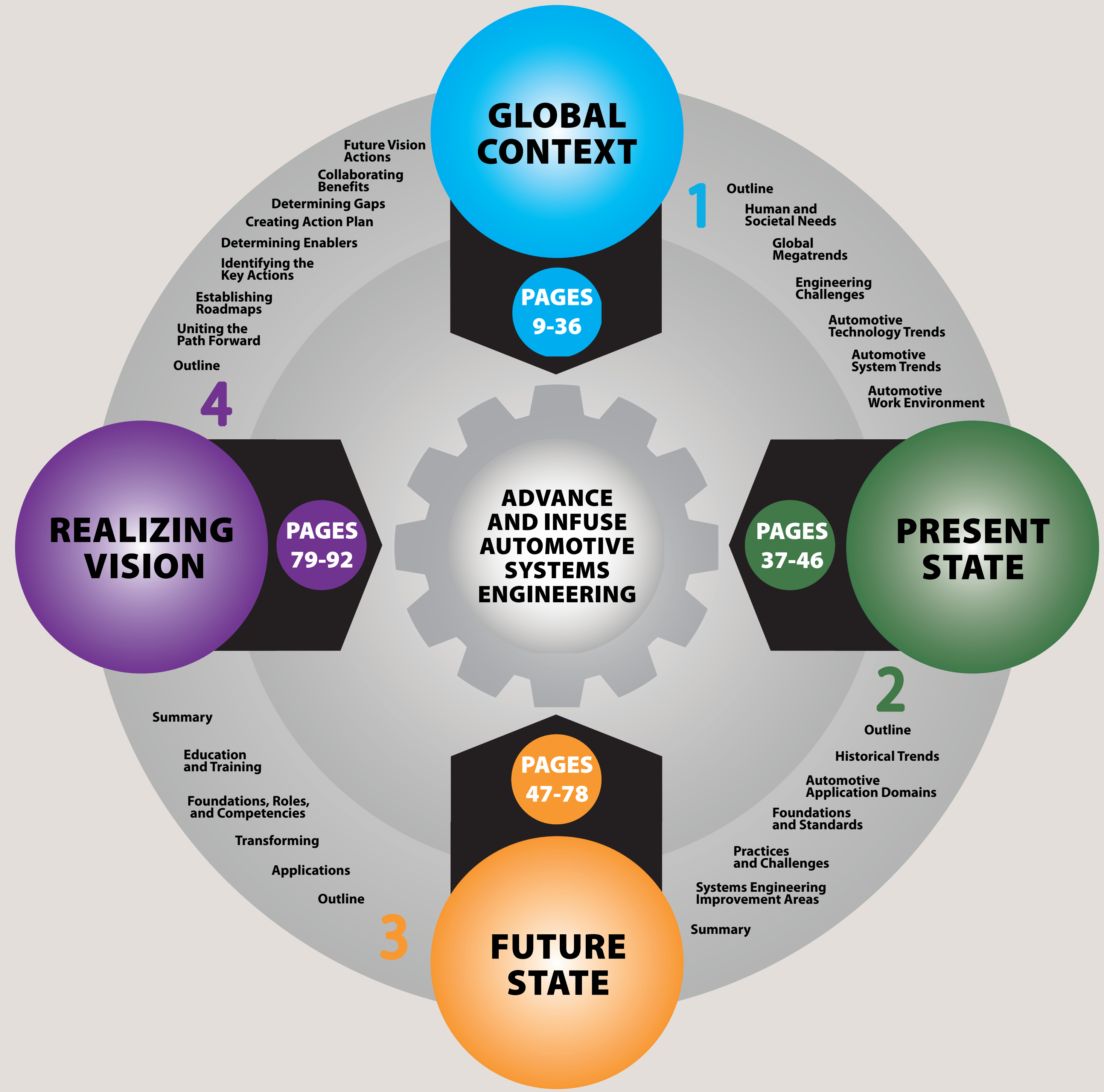
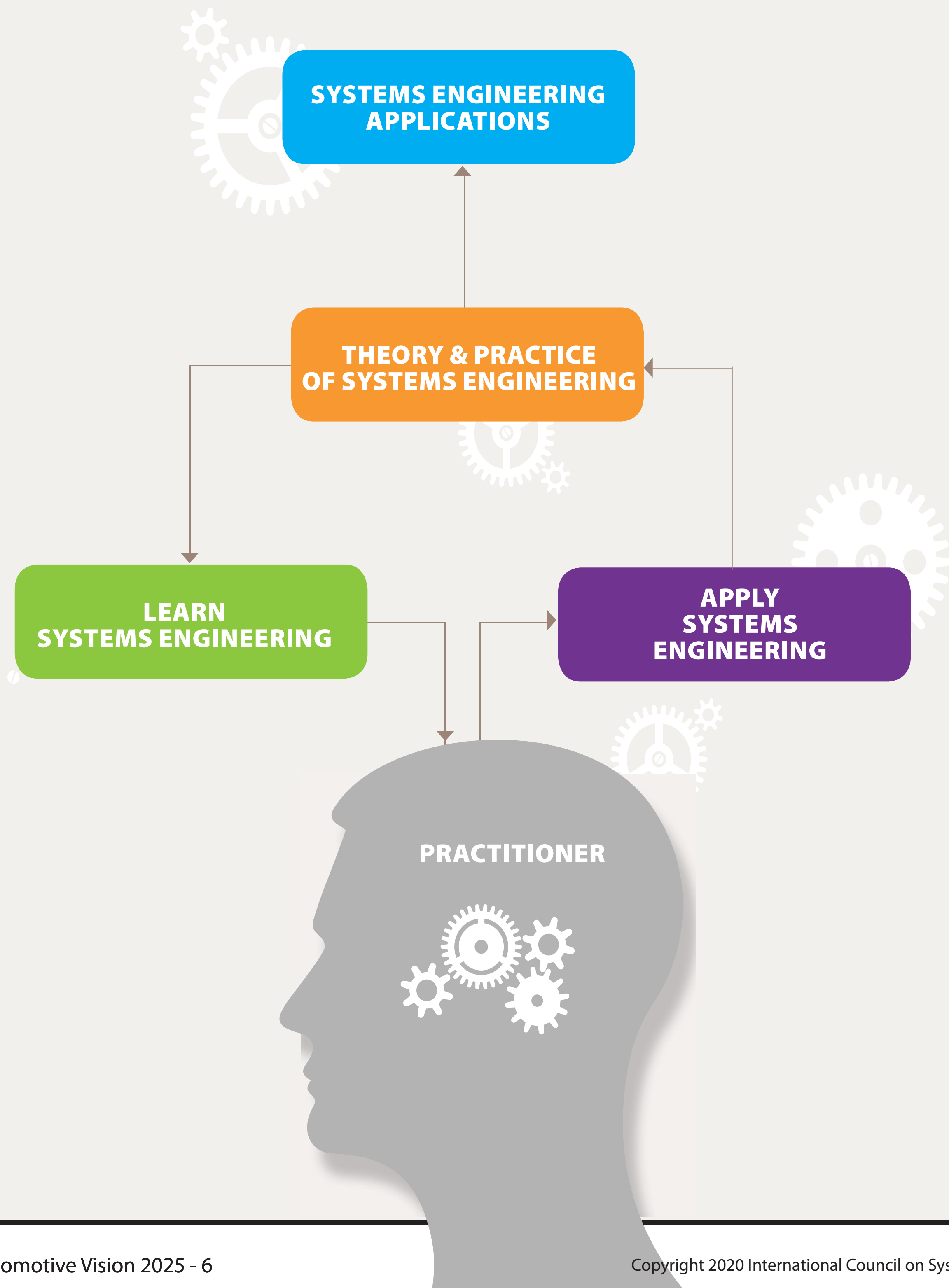
SYSTEMS ENGINEERING FOCUSES ON ENSURING THE PIECES WORK TOGETHER TO ACHIEVE THE OBJECTIVES OF THE WHOLE ACROSS THE SYSTEM'S LIFECYCLE

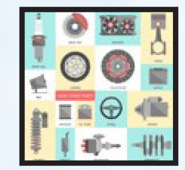
Contents



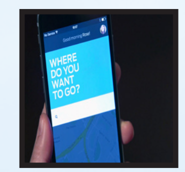
STATE OF AUTOMOTIVE SYSTEMS ENGINEERING



AUTOMOTIVE SYTSTEMS ENGINEERING IMPERATIVES

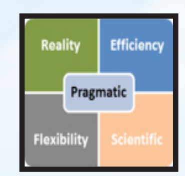


Expanding the **APPLICATION** of systems engineering to non-traditional domains.

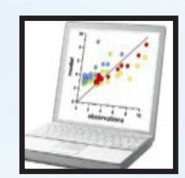


Applying systems engineering to help shape policy related to **SOCIAL AND NATURAL SYSTEMS**.

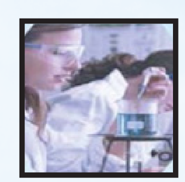
Embracing and learning from the diversity of systems engineering **APPROACHES**.



Expanding the **THEORETICAL** foundation for systems engineering.



Advancing the **TOOLS** and **METHODS** to address complexity.



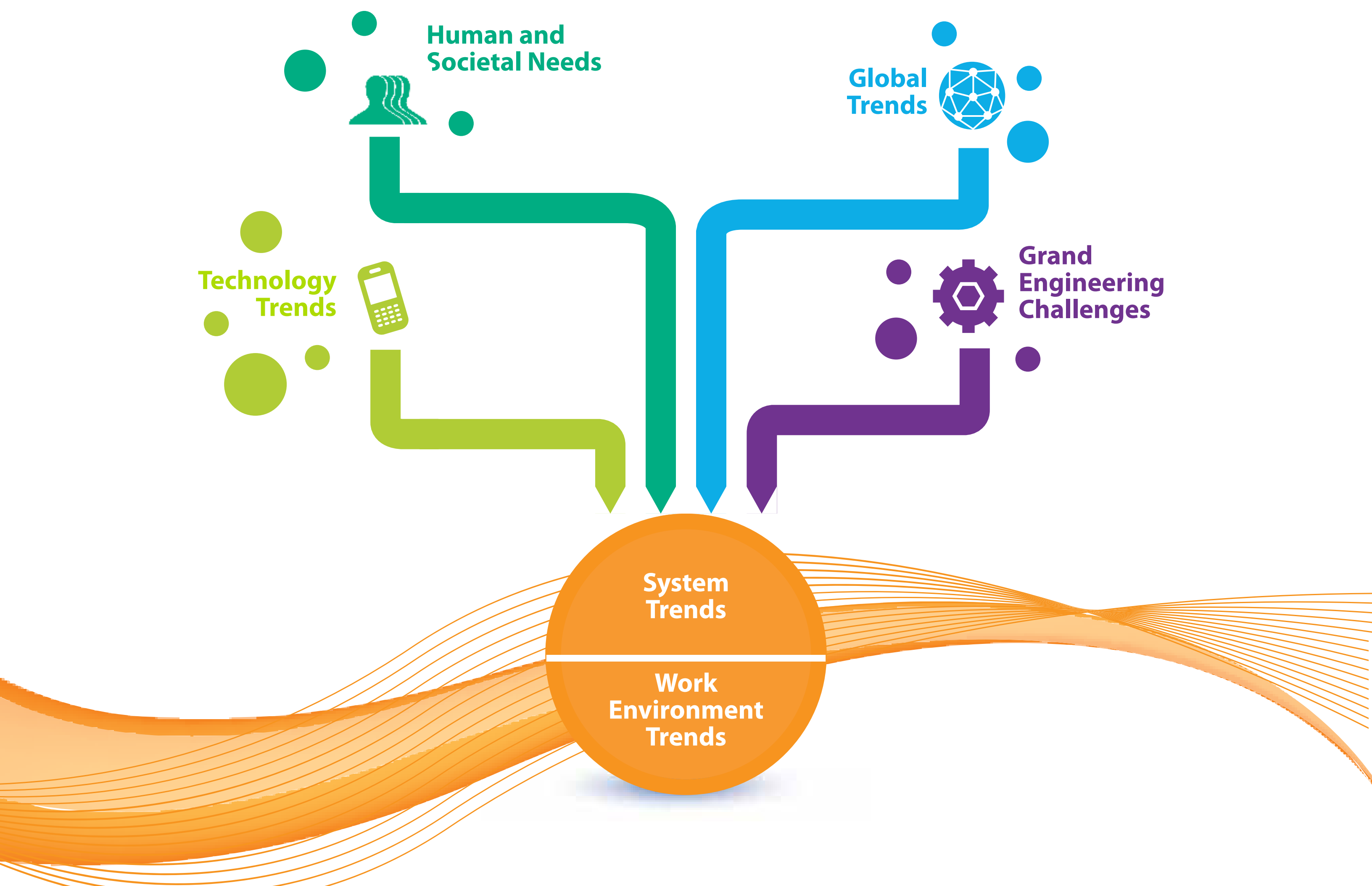
Enhancing **EDUCATION** and **TRAINING** to grow a **WORKFORCE** that meets the increasing demand.

1 The Global Context

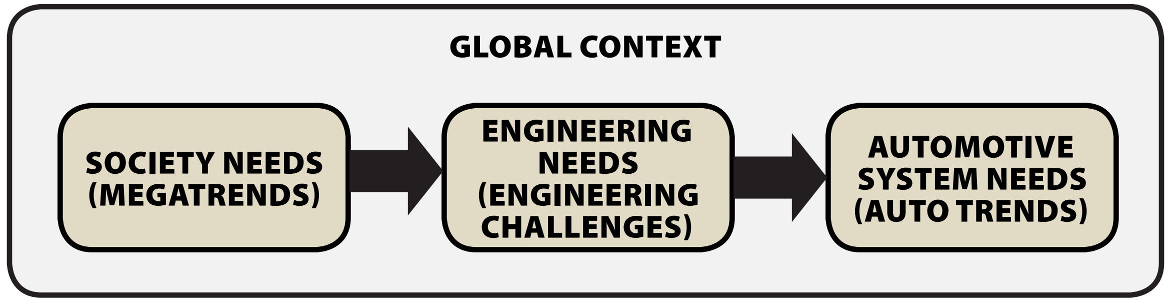
INCOSE released their vision for systems engineering in 2025. This vision document is now being used as a framework document from which to create industry specific, systems engineering vision documents. The purpose of these industry specific vision documents is to: support internal Company dialogue, identify opportunities for internal and external corporate collaborations and to provide a mechanism for a greater discussion among systems engineering professionals.

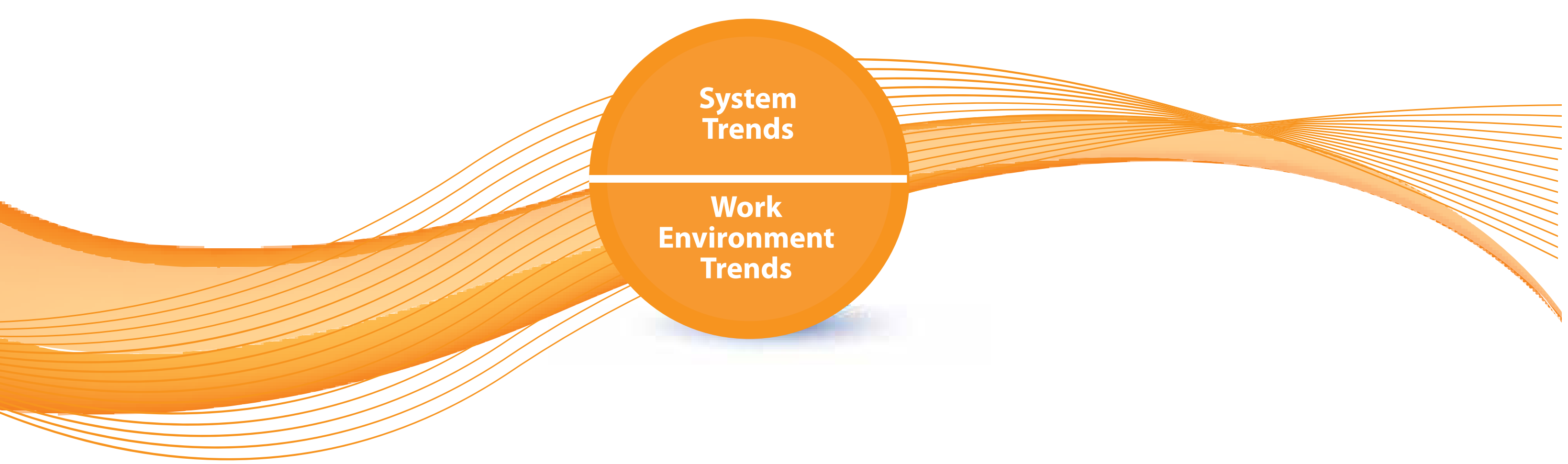
The following document leverages the INCOSE systems engineering vision 2025 framework to retain alignment with the fundamental principles and challenges outlined within that document. It then specializes the content of the vision to provide a focused perspective relevant to the automotive industry and the challenges and opportunities unique to the automotive domain in the next decade.

Global Context:
This first section of the automotive systems engineering vision 2025 defines the global context for the growth, needs and value proposition that systems engineering must address over the coming decade.



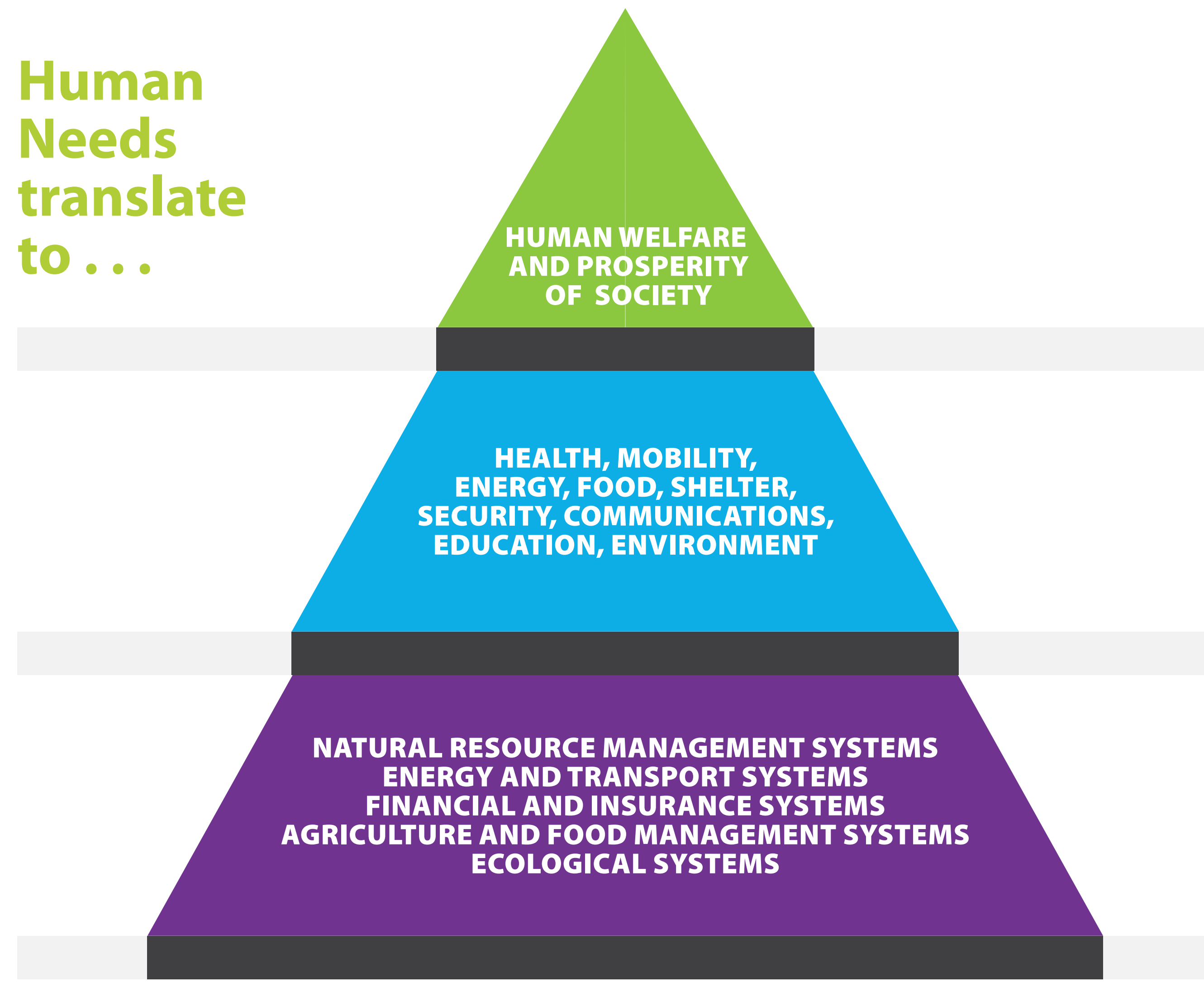
1.1 Outline: Global Context



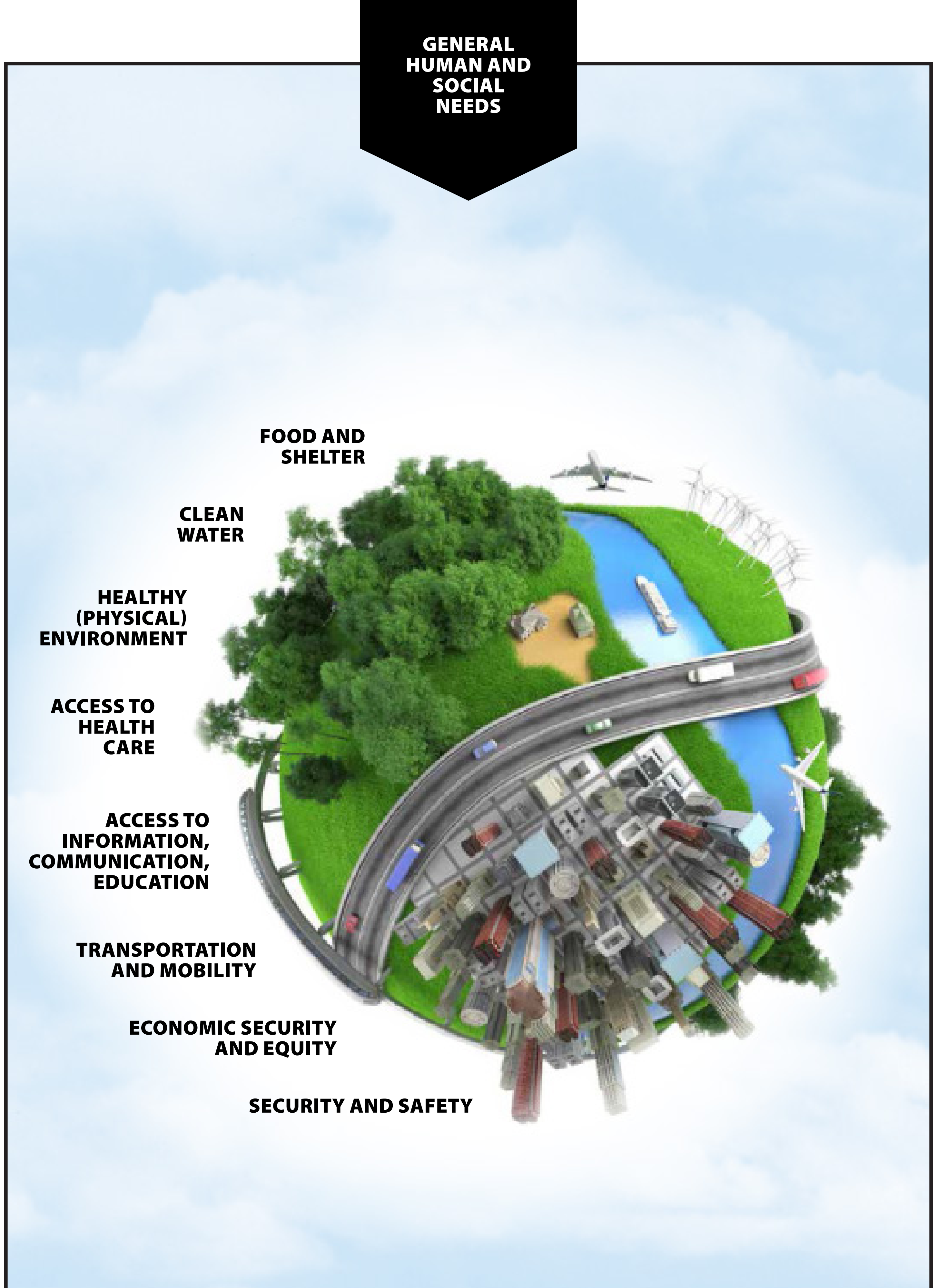


1.2 Human and Societal Needs Give Rise to Engineering Challenges

Humanity has always attempted, through engineering and technology, to make the world a better place. With our ever-evolving society, however, come newer and ever greater challenges. When we look for ways to meet fundamental human needs, we see that the solutions often lead to large and complex engineered systems of systems that can only be realized in the context of societal behavior.



NEEDS DRIVE SYSTEMS –> SYSTEMS SATISFY NEEDS



1.3 Global Megatrends that Shape the Automotive Systems Environment

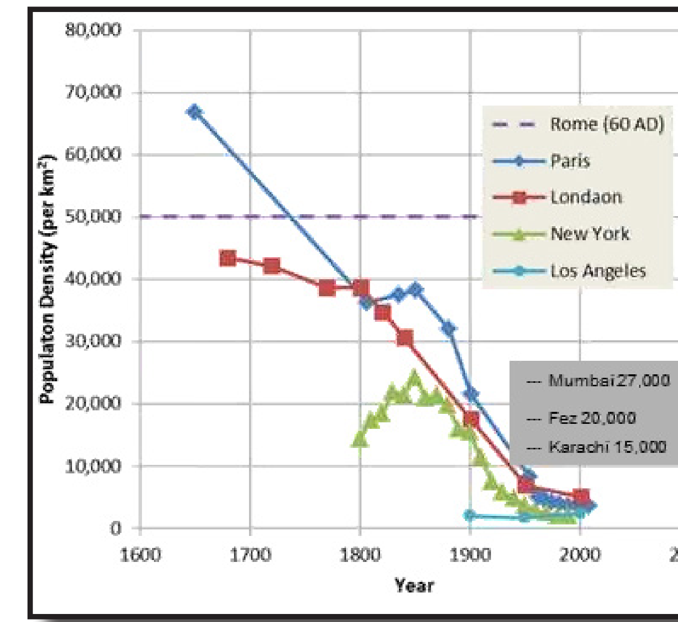
There are six major global trends that will significantly impact future automotive industry that can be categorized as follows;

Megatrend 1:
Population Growth and Urbanization

In general the population dense within major cities has changed dramatically over time from very dense city centers to far less density cities. There are however 28 megacities with populations of above 10 million people. This number is expected to rise to 41 megacities by 2030. Ultimately each geographic region has decided the appropriate level of population density it is comfortable with or capable of maintaining based on local systems dynamics. Population density is a choice; it expresses a balance between living space, access to amenities and time spent in different pursuits. .An increased focus on global transportation systems in response to urbanization has provided opportunities for developing fully integrated transportation systems.

Personal Mobility:
The commuter of the future may have a "personal mobility portfolio", with the car being only one part of it. An automobile might be there to drive for pleasure on the weekend (the affection for the car will probably not go away completely). As mobile internet becomes ever-more powerful it will be totally normal and convenient to step out on the street and make an immediate decision. You could hail a self-driving shared vehicle. You could jump into the car of a social-media friend, who just happens to be driving by and going in the same direction. Or you will take public transportation if is the best option. The car will be totally integrated into a greater mobility network. There will be a network of different options to integrate services in places such as airports, all of them combined in one application on our communication device. We basically tell the application where we want to go and, based on our preferences, three different optimized transportation modes will be offered, similar to the three different routes that a GPS navigation system offers us today.

Car sharing will become a significant part of the mobility solution- using an automobile without the vehicle owner ship costs. One customer frustration barrier yet to be addressed is vehicle repositioning after use. Today, shared bicycles need to be shipped back to their points of origination by large diesel trucks. Alternately, the customer is expected to return these at the end of the rental agreement. Future trends could see autonomous vehicles (AV) driving themselves on specially selected lanes to return themselves.



Self-driving Technology:
Self-driving or autonomous vehicles are widely considered the way of the future. While the technology is rapidly advancing, new business models and public policy associated with this new technology remains a large unknown. Autonomous vehicles could lead to what has been termed "The end of driving", however this will lead to more mobility for children, the elderly, and the disabled. Driving, however, always has been and should remain a fun and engaging activity. People buy their cars because they are a pleasure to drive. Many OEMs see increasing levels of automated technology such as Piloted Driving and increasing levels of automated assistance as the real future. Providing incremental

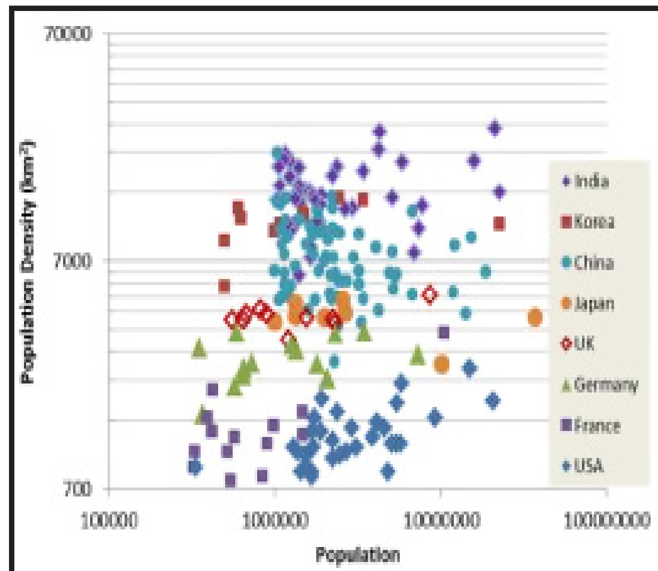
levels of automated assistance to relieve the tedium of being in stop-and-go traffic and having to park in tight spots and help with reacting in difficult safety related scenarios are some obvious trends that are already seen on the near horizon. Whichever direction the automated/autonomous driving functionality ultimately goes, it seems automobiles as a form of personal transportation will be around for quite some time to come.

Increased Population Density:
Several key heuristics are still valid when it comes to understanding the systems dynamics at play with population centers: Marchetti's rule on time a person is willing to spend on routine travel, Zahain's rule on amount of income to spend on travel, data on a person's tolerance for the amount of walking and waiting they are prepared to accept, and the actual amount of CO_2 produced per person using car and mass transit transportation modes (data suggests that cars are often more efficient than mass transit). These factors along with additional basic economic theory can help the systems engineer develop some reasoned, data driven insights into future city transportation planning and the probable outcome. The available data (there is always a need for better data) suggests that there are different models for developed world versus developing world.

Asia Growth:
An interesting example of how these systems properties may playout will be in Asia. Some of Asia's major policy drivers today are: reduce oil dependency, mitigate greenhouse gas emissions and improve air quality while maintaining social stability. Decision makers in Asia would like to see their transportation oil consumption eliminated, reduce lifecycle carbon dioxide emissions per unit of distance by 85 percent, and curb inner-city PM 2.5 air pollution to zero. Because several of Asia's authorities hold enough regulatory and financial power to ensure market commitment to their directed goals, top-down approaches will be implemented to guide and drive implementation strategies.

Many of Asia's future transportation systems will strive for zero tailpipe emissions and be composed of mainly unmanned connected cars. On-demand car sharing and carpooling will probably dominate urban commutes resulting in limited need for urban parking spaces.

The driverless car could well extend that flexibility in dramatic fashion, combining some characteristics of automobiles and public transportation and allowing people more choice in the way they live, whether it involves more compact, high-density cities, more dispersed low-density settlements — call it sprawl if you like — or, perhaps most likely, all of the above.



In order to internalize the vision, national and local policy makers would:

1 - Emission Standards:
Steer industrial development, mainly by creating stringent standards and requirements that slowly eliminate combustion-engine-type vehicles' profitability;

2 - Energy Solutions:
Allocate and direct financial investments toward new-energy solutions, including global financial mechanisms and investments; and

3 - Commuting Reduction:
Carefully plan cities so that the daily average commute will be reduced to some 2 kilometers. Policy makers would require tailored tools based on global best practices, such as city transport emissions planning tool kits, information disclosure platforms that would reflect market implementation, clear and strict enforcement mechanisms, local pilots for evaluating new schemes and solutions, and cross-sector and multi-stakeholder workshops and roundtables in which problems could be raised and promptly addressed for ensuring smooth development.

Personal Mobility:
A Transit Synergized Development (TSD) is a strategic model of sustainable urban development targeting the next generation of transit-ready cities in China. TSD is predicated on the implementation of one-square-kilometer districts around mass transit stops, creating energy-efficient, economically vibrant and highly livable urban neighborhoods.

TSD transforms the transit nodes of a city, arguably its socioeconomic centers and energy and resource hot spots, into a network of Energy Hubs, district energy systems that work with the city's power grid to promote energy efficiency and resilience; a network of Innovation Hubs that collaborate with industries to rapidly prototype new technologies, products and services and promote economic growth; and a network of Social Hubs that foster high-quality urban environments and high quality of life, enhancing the city's image and attractiveness to businesses and talent.

In targeting the densest and most valuable areas of a city, TSD aims to be largely market-driven, relying on collaboration between private and public sectors as well as innovative institutional and policy mechanisms.

Megatrend 2:
Growth of the Middle Class
And Aging Population

Growth of a global middle class - which is now nearing the one billion mark. The share of the population that falls into the wealth middle class in global terms has doubled in Latin America, has almost trebled in Eastern Europe and has increased seven-fold in Asia. The flows between wealth classes are particularly interesting. The middle class includes both 65 million people that have been demoted from the "wealth upper class" since 2000, and 491 million new entrants (courtesy the guardian). The gap between the rich and the poor continued to grow and both factors will have profound economic implications. Technology change which raise the demand for skilled workers will continue to drive this divide.

Aging Population:
The aging population in countries such as the US is expected to raise dramatically by 2025. The number of people aged 50 or over is expected to grow to 133 million by 2030. This will create stress on housing, transportation, health care.

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Megatrend 3:
Environmental Factors such as Air Quality

Greenhouse gas concentrations are expected o continue their increase over the next decade unless global, aligned and synchronized actions are taken to decrease emissions in a sustainable manner. Without such global actions the impacts to the environment are expected to manifest themselves as;

Increase in Earth's temperature
More dramatic patterns of precipitation
Rising sea levels
Increased acidity of our oceans
Reduced snow caps at the poles.

CO_2 regulation trends and diversification of renewable energy sources are forcing original equipment manufacturers (OEMs) to offer alternative fuel vehicles. This comes with associated R&D costs and is heavily influenced by trends such as the rise of shale oil and gas and the volatility in carbon fuel costs versus the inexorable drop in unit costs for sources such as solar energy.

Emissions Standards:
According to a recent report from the U.S. Environmental Protection Agency (EPA), the auto industry exceeded domestic greenhouse gas emissions standards by a "wide margin" in 2013, with cars getting an average of 1.4 more miles per gallon than required. The EPA is continuing to tighten greenhouse gas compliance regulations on cars and small trucks setting a Corporate Average Fuel Economy (CAFE) target of 54.5 mpg by 2025.

The CAFE standards covering vehicles made between 2012 and 2025 are projected to save 12 billion barrels of oil, and will cut 6 billion metric tons of greenhouse gases, according to the EPA.

Advanced manufacturing trends are supporting the increased use of ultra-lightweight vehicles. This is in response to supply-side considerations (high supply chain and raw material costs, advancements in materials science) as well as the demand side (meeting urban needs and calls for lighter, more efficient vehicles).

Megatrend 4:
Consumer Attitude Shift From Ownership to Services

Though global car sales are expected to exceed 107 million by 2020, up from 80 million in 2013, this is primarily driven by the developing world. Elsewhere, consumers will move away from buying to leasing and renting and it will gain momentum in new megacities as well as smaller ones. Car pooling and ride sharing is increasing. New business models will emerge that support new mobility models such as Uber where unique mobility applications will be used to schedule a transportation solution for your unique travel needs. Consumers may not accept the 4% utilization rate for their personal ownership vehicles that spends the majority of its life in a garage overnight or in a workplace parking lot.

Car Ownership:
The developed world exhibits declining interest in car ownership; moving to urban living and moving toward bigcities versus walkable towns. This change will require the need for large infrastructure investments.

The developing world shows aspirations for vehicle ownership, which is a typical characteristic of emergent car communities. In these environments, the city space vs. time vs. amenity trade-off is strongly in play.

Megatrend 5:
Changing Workforce Demographics: Employment Expectations, Personal Motivations, and Talent Shortage

The future workforce will be motivated by a more complex set of personal, project and global factors than today. Work-life balance, project responsibility and ownership, and ability to impact global issues will be more dominant than basic par structures today.

The ability to contribute meaningfully to the global context and work within a collaborative team environment will be basic expectations.

In addition, the fundamental work environment will be expected to offer a rich set of configurable options such as: corporate infrastructure that supports flexible work week schedules in any global location of choice, reconfigurable office spaces that promote project team dynamics and collaboration, and amenities such as on-site restaurants, cyber-cafés, and laundry service.

The global workforce will also become more mobile, expecting to move more often between Companies, Regions and Countries. Engineering competencies in particular will be in great demand as university supply is outstripped by global demand. An increasing bimodal distribution will develop between deeply technical, specialty-driven engineers who develop the implementation details of the emerging technical solutions, and system-of-systems (SoS) engineers who can design and develop system solutions across multiple subject domains, providing the blueprint and roadmap for successful system designs.

Megatrend 6:
Ubiquitous Connectivity and Cybersecurity

Ubiquitous Connectivity and Cybersecurity: Consumers are moving towards hyper-connectivity, increasingly demanding the ability to stay connected at all time. Companies are adding networking connectivity to product lines to enhance their value. In automotive, by 2020 90% of all new cars sold are anticipated to be "connected". Data isn't free, but a fundamental shift occurs from charging per gigabyte (GB) to charging purely by the service that the (included) data enables.

Where the automotive industry has traditionally been focused on manufacturing, deriving competitive advantage from platform scale and reuse with brand differentiation, the involvement of innovative, non-automotive technology companies and mobile service providers in this realm challenges conventional modes of operation and development cycles. The industry is moving rapidly from purely manufacturing to a hybrid industry that delivers innovative mobility and connected services solutions, which in turn has a impacts the business models, competition landscape, and infrastructure needed in 2025.

Cybersecurity Threats:
With increased Internet access comes an increase in possible hacking points, called the "attack surface". Many of these vulnerabilities will be a natural consequence of planned new customer feature introduction. Some vulnerabilities will be due to product defects, poor design (insufficiently robust architectures), and low-level operating system weaknesses. Future automotive software-intensive solutions will need safety and security to be designed-in from the initial concept

1.4 Engineering Challenges: Engineered Systems are Key to Satisfying Human and Societal Needs

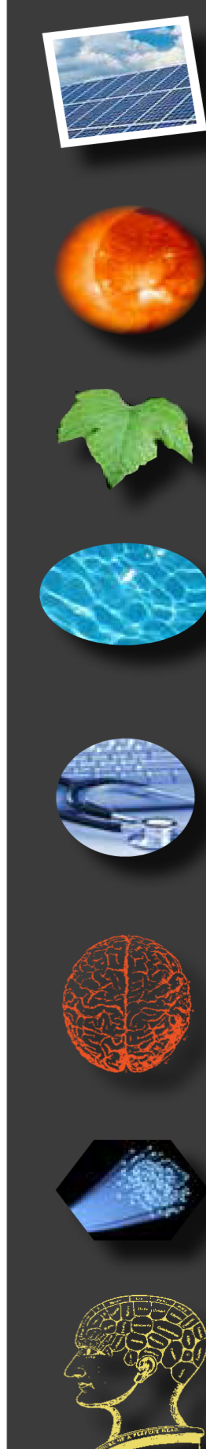
The US National Academy of Engineering (NAE) identified Grand Engineering Challenges for the 21st Century. Linking these to human and societal needs highlights the diversity and landscape of domains to which the discipline of systems engineering should contribute. Large and often complex engineered systems are key to addressing the grand challenges and satisfying human, social, physical and psychological needs. These systems solutions must be embedded in the prevailing social, physical, cultural and economic environment. They must also be tailored to the relevant local or regional capabilities and resources. In order to be successful engineering these solutions we must take into account safe, robust, lifecycle analyses and sustainable implementation approaches; we must also consider the complex dynamics of social and government environments.

Passenger Health Needs:
Many of the NAE challenges have implications within the extended automotive transportation systems of the future. Advanced health infomatics is already being supported with in-vehicle driver and passenger monitoring systems. Advanced decision making and data search algorithms that leverage the hierarchical brain processing model are already used for cloud based data analytics along with neural network based on-board/off-board voice processing algorithms. Future cloud based "Big Data" analysis will drive advances in fuel economy, security, safety and personalization.

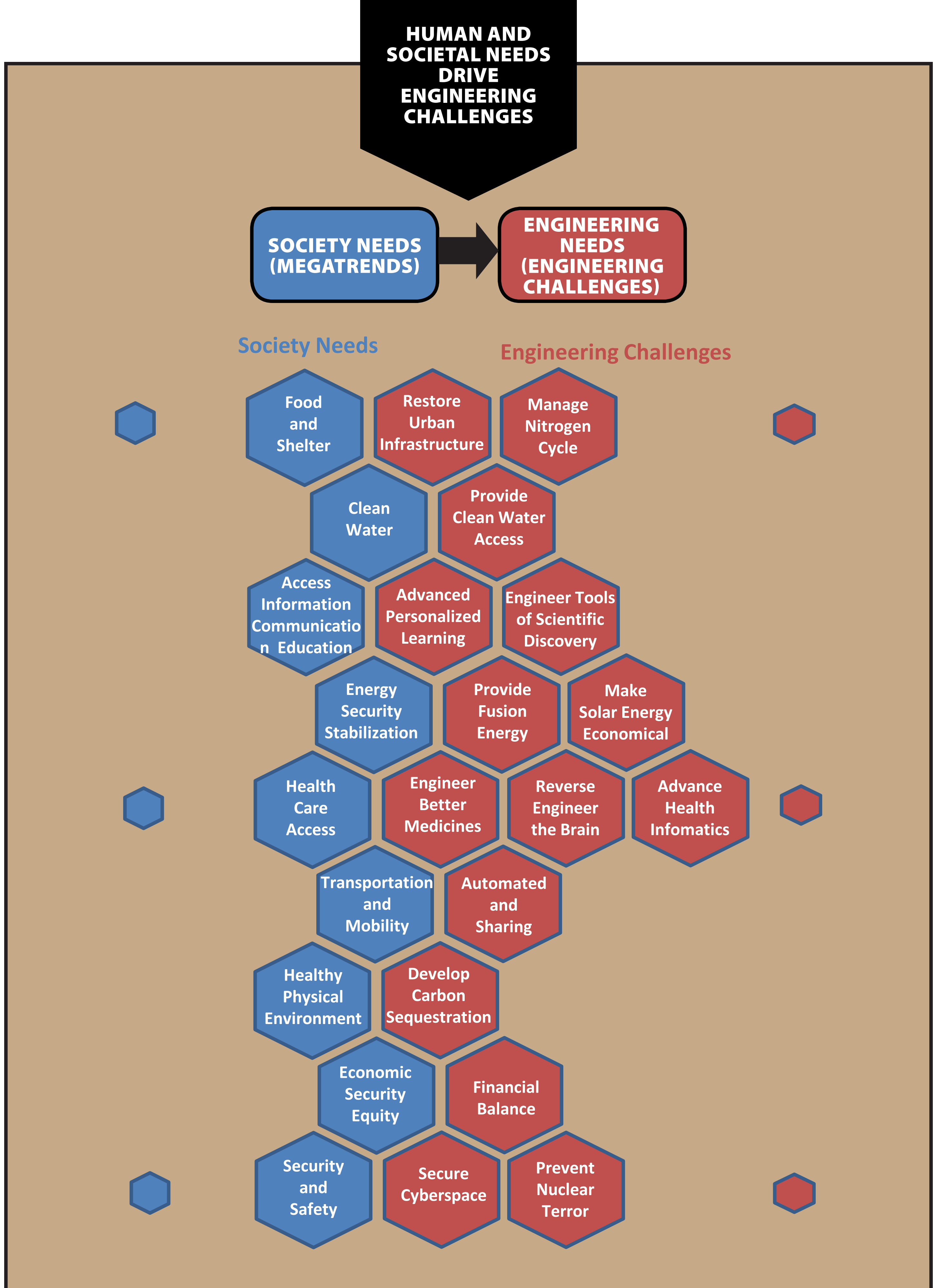
Cybersecurity has already touched in-vehicle systems, where communication networks have been attacked to gain access to key vehicle resources. As V2x systems continue to expand, the cyber-physical "attack surface" will extend creating ongoing challenges for systems engineers developing secure and safe vehicle systems.

Virtual Reality Tools:
Increasingly, enhanced virtual reality systems will be required to design and evaluate automotive system solution alternatives that can meet the complex and competing demands of mobility, energy economy, safety and security.

NAE ENGINEERING GRAND CHALLENGES



1. Make solar energy economical
2. Provide energy from fusion
3. Develop carbon sequestration methods
4. Manage the nitrogen cycle
5. Provide access to clean water
6. Restore and improve urban infrastructure
7. Advance health informatics
8. Engineer better medicines
9. Reverse-engineer the brain
10. Prevent nuclear terror
11. Secure cyberspace
12. Enhance virtual reality
13. Advance personalized learning
14. Engineer the tools of scientific discovery



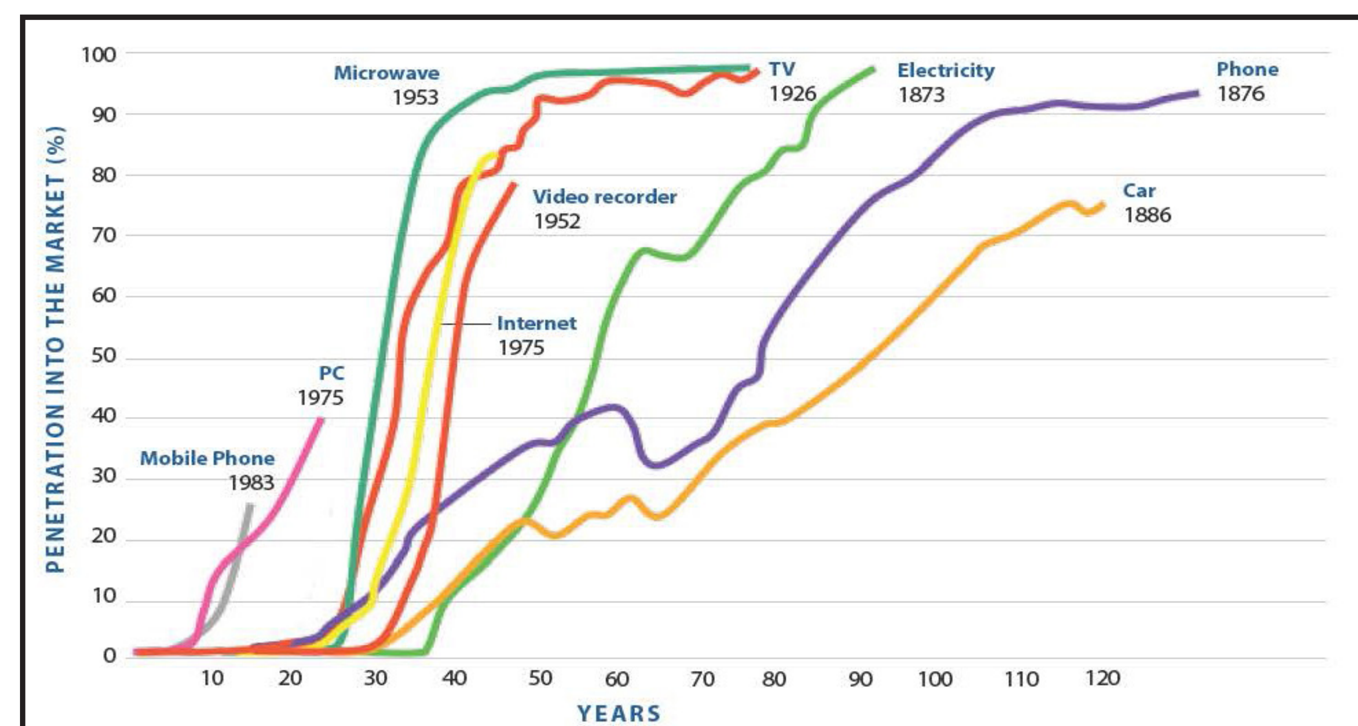
1.5 Automotive Technology Trends: Development and Infusion Impact the Nature of Future Systems

Expect technology driven changes to every aspect of the vehicle's function. We will see laser headlights with 500 meter lighting distance (Audi, BMW), external airbags on the front of cars to protect pedestrians (Volvo, Mercedes Benz, BMW), and under the vehicles floor-pan to create emergency braking drag.

We can expect to see 30-50% reduction in carbon emissions, especially in trucks with innovations including more aerodynamic design, more efficient tires, suspensions which generate electrical power and light weight materials.

Technology advances in both traditional basic automotive components, materials and subsystems in combination with advances in adjacent consumer and infrastructure technologies will provide a rich environment for emergent innovation. With technology infusion and advances in almost every area of the traditional and non-traditional domains, there will also come greater stress on time-to-market and the development of robust solutions of technology fusions once considered impossible. The innovative systems and services of the future will need to meet ever increasing customer demands for simplicity, reliability, safety and security

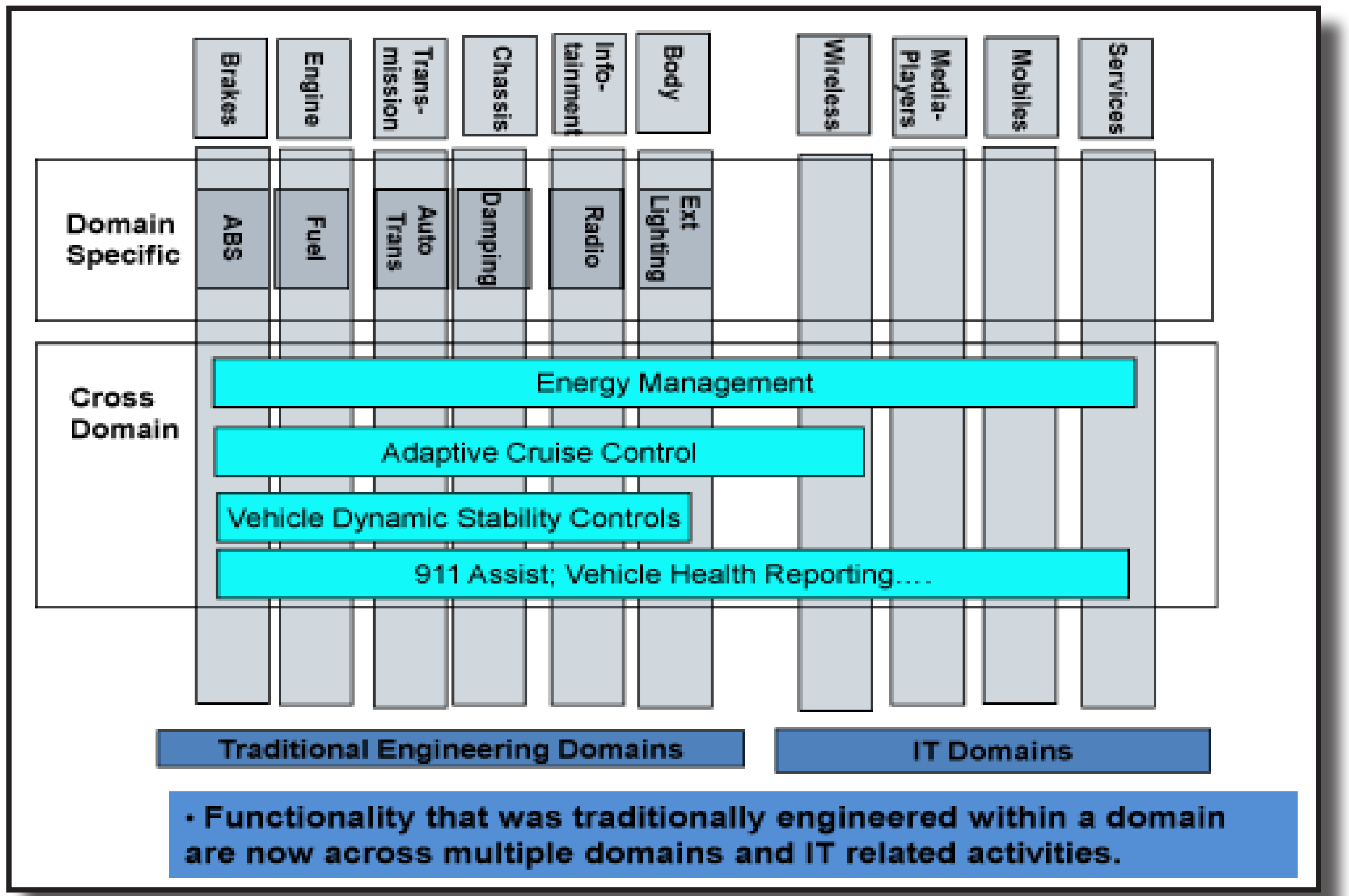
Automotive Systems Safety and Security:
A large percentage of new vehicle system technologies and functionality is software intensive. These technologies have progressed from isolated electronic solutions within a specific automotive domain, through mechatronic system solutions that cross multiple domains, and are now progressively becoming highly distributed networks of software intensive systems. These highly distributed systems are connecting onboard and off board services and data pools that have never before been integrated into a real-time dynamic controls solution. Increasingly we are also seeing onboard control systems interacting with a multitude of other vehicles in a new social and economic transportation systems. This unprecedented growth in depth of new EE & SW technologies, the fusion of technologies and the breadth of system implementation has created fantastic vehicle systems solutions which come with some significant new challenges.



Cross Functional Domains:
Each additional level of domain, organizational, enterprise and interoperable system that is required to deliver a vehicle solution introduces new system use cases, failure modes and associated hazards The in-vehicle software solutions have grown from 1 million lines of code to 100 million lines of code in a decade. The number of sensors, distributed features and signals have also grown significantly. The set of primary customer use case needs to be fully understood and analysed using advanced model based tools to perform virtual simulations and analysis.

With the introduction of "build-in, brought-in, beamed-in" software solutions comes the threat of "hacked-in" software. The increasingly complex system-of-system (SofS) solutions are creating new system boundaries, interfaces and intrusion points.

The threat of attack on these future systems is increasing, further exacerbated by ubiquitous connectivity and over-the-air (OTA) updates. These new SofSs provide potential opportunities for security vulnerability that if identified and leveraged could compromise vehicle system integrity.



Modeling Methods:
Techniques such as model-in-the-loop (MiL), software-in-the-loop (SiL), processor-in-the-loop (PiL) and hardware-in-the-loop (HiL) must now be leveraged fully to design, verify and validate complex solutions. Additionally, the fundamental set of system control actions and their potential failure modes must be analyzed. From that safety/security mechanisms can be designed-in to manage them in a systematic and comprehensive manner."

Malicious attacks might attempt to take control of aspects of the vehicle system performance, control or simply deliver annoying loads that disrupt normal vehicle operation in an unknown manner. Cyber-physical security lessons learned from the aerospace and military domains will need to be understood and applied at design time to the automotive vehicle systems ensuring maximum protection from such malicious attacks.

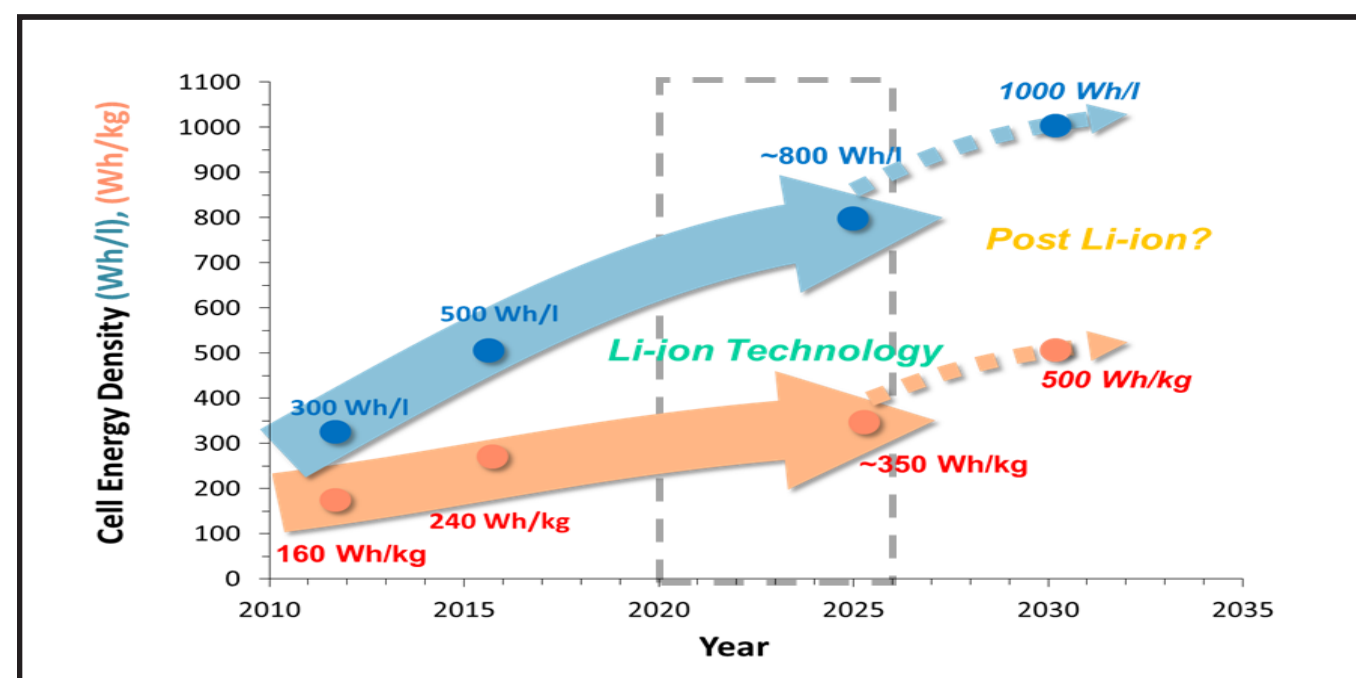
Vehicle Electrification:
Low voltage electrical networks have existed in cars since the advent of the self-starter in 1912. The typical network includes a 12V battery, an alternator, and an increasing number of powered controllers and actuators. Most automotive low-voltage batteries are electrochemical-based and designed primarily to support non-propulsive actuators. To incrementally support propulsive actuators and meet driving performance and fuel economy attributes, not only are very different kinds of energy storage and delivery technologies needed, but also a coordinated control system.

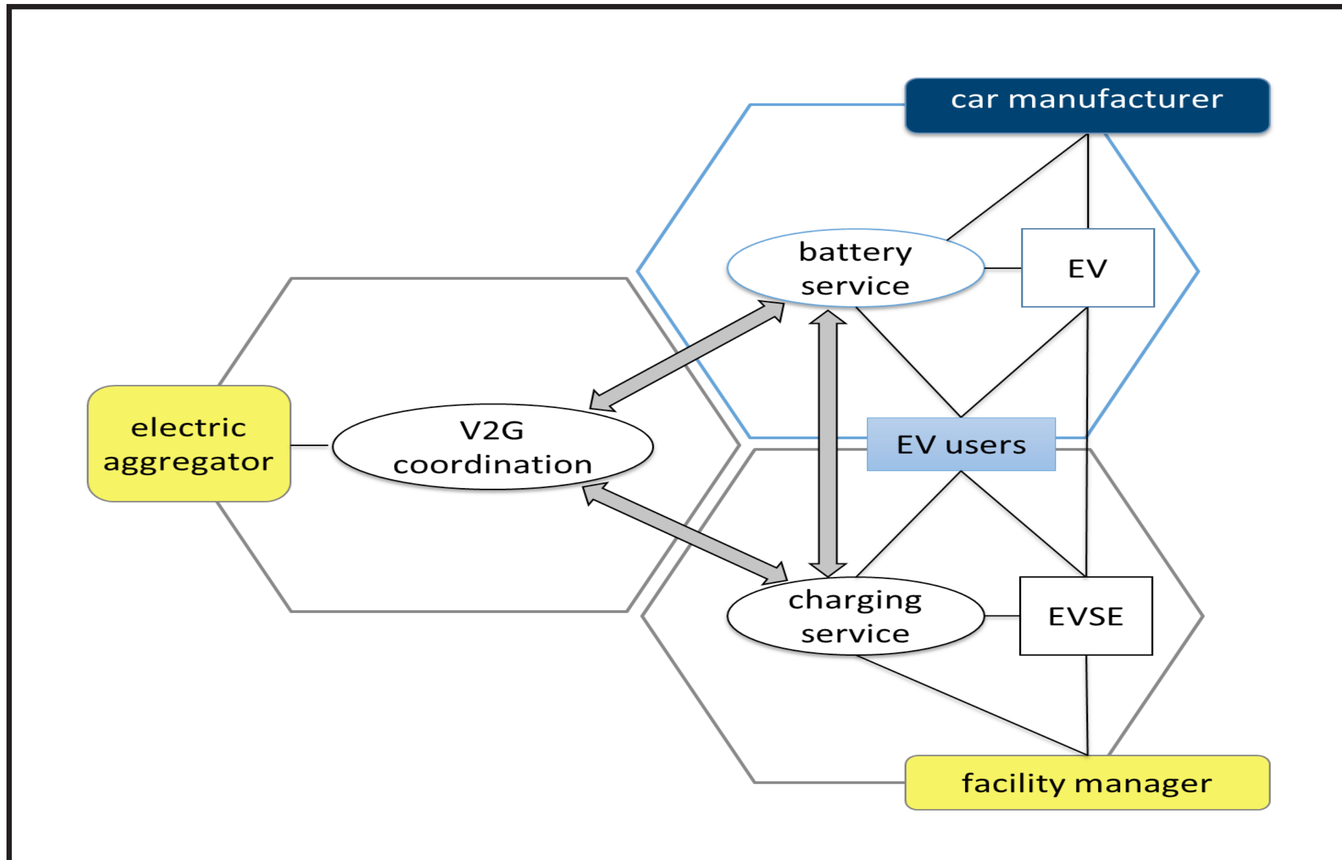
For example, the battery may be controlled by a battery management controller that computes the instantaneous power and capacity using on sensors that monitor the battery and environment temperatures and other properties. The increased heat generated from some of these systems also has to be managed via a cooling system, which in itself has its own controls and components…all while respecting safety and aging concerns. In the end, the battery subsystem alone represents a major cost, and for EVs it may be one of the heaviest and most expensive in the car. Thus improvements are needed and driven by joint efforts of automotive and other industries, relying on a huge research efforts in the race for sustainable, safe, and affordable energy solutions.

Electrified vehicles typically have a second electrical network, operating at a higher voltage (typically 48-400V). A higher voltage network brings potential safety issues such as more severe electric shock, a risk that must be considered in all lifecycle phases, from manufacturing to maintenance to crash. This leads to things like regulation changes to cover many of these safety concerns, which impact far more than just the automotive OEMs but concerns all stakeholders.

Electric motors have been used for many years in a variety of applications. Nevertheless, automotive integration has led to deep adaptations with many innovations. Specific performance in speed range, efficiency, cooling, and cost have improved through automotive applications. Electric motors are also leveraged in one of a variety of configurations, often noted as P0-P4 in literature, depending on whether they are applied to the front, rear, or both axles, and their location and purpose (e.g. in-wheel or not, capturing regenerative energy, driving tractive motors, extending vehicle range, meeting high performance targets).

Vehicle electrification has also led to new vehicle interfaces and standards. A prime example is the introduction of plug-in electric vehicles (PEVs), which involve a connection to the electric grid. This interface presents news challenges as it has to





enable safe power transmission that meets volt¬age, frequency, and other constraints, all of which may vary depending on the region and limited by what the local utilities can deliver. Grid-supplied alternat¬ing current (AC) has to be rectified into direct current (DC) suitable for battery charging. Lower-power chargers are embedded in vehicles while high-power EV supply equipment (EVSE) incorporate this converter and supply DC power to the vehicle. This has created a growing market for EVSE products, which creates its own need for interoperability and standards including even the expected but nevertheless tough issue of socket standardization. Considering a large introduction of PHEV, a system of systems approach is then appropriate to address the interactions with the electric grid when deployed at scale.

Alternative Fuels:
Despite growth in EVs and HEVs, the use of regionally available carbon based fuels will likely increase in low cost countries. Alternatively, the use of new fuel cells such as hydrogen fuel cells will increase. Hydrogen-powered vehicles convert hydrogen into electricity in a fuel cell producing only water vapor coming out the tailpipe. There are still challenges to overcome, such as where to get the hydrogen from and how to fund the infrastructure required to deliver it to the customer.

Solar power, pneumatic energy, photovoltaic and ultra-capacitor power suppliers are still under research and development and could provide part of the automotive solution portfolio of the future. In addition, NASA has an ongoing research project trying to figure out how to beam energy down from solar collectors in space. There's a notion that all cars could then collect energy from space as well, transmitted the same way. Each approach requires significant engineering analysis, design and understanding.

Lightweight Materials:
To meet future fuel economy regulations, vehicle light weighting will be a major contributor toward fuel efficiency and emissions targets. The success of engine technology such as direct injection, turbocharged engines and high compression engines, has contributed significantly toward the future fuel economy and emissions goals. However, the challenge remains to get to 54.5 MPG by 2025. This can only be achieved thru a combination of vehicle downsizing in conjunction with significant application of lightweight materials. The chart below is a high level table showing the weight savings opportunities for various materials available to the automotive OEM's along with the advantages and challenges each materials system poses.
In the near term, there will be continued focus on incorporating more advanced (hot stamped) ultra-

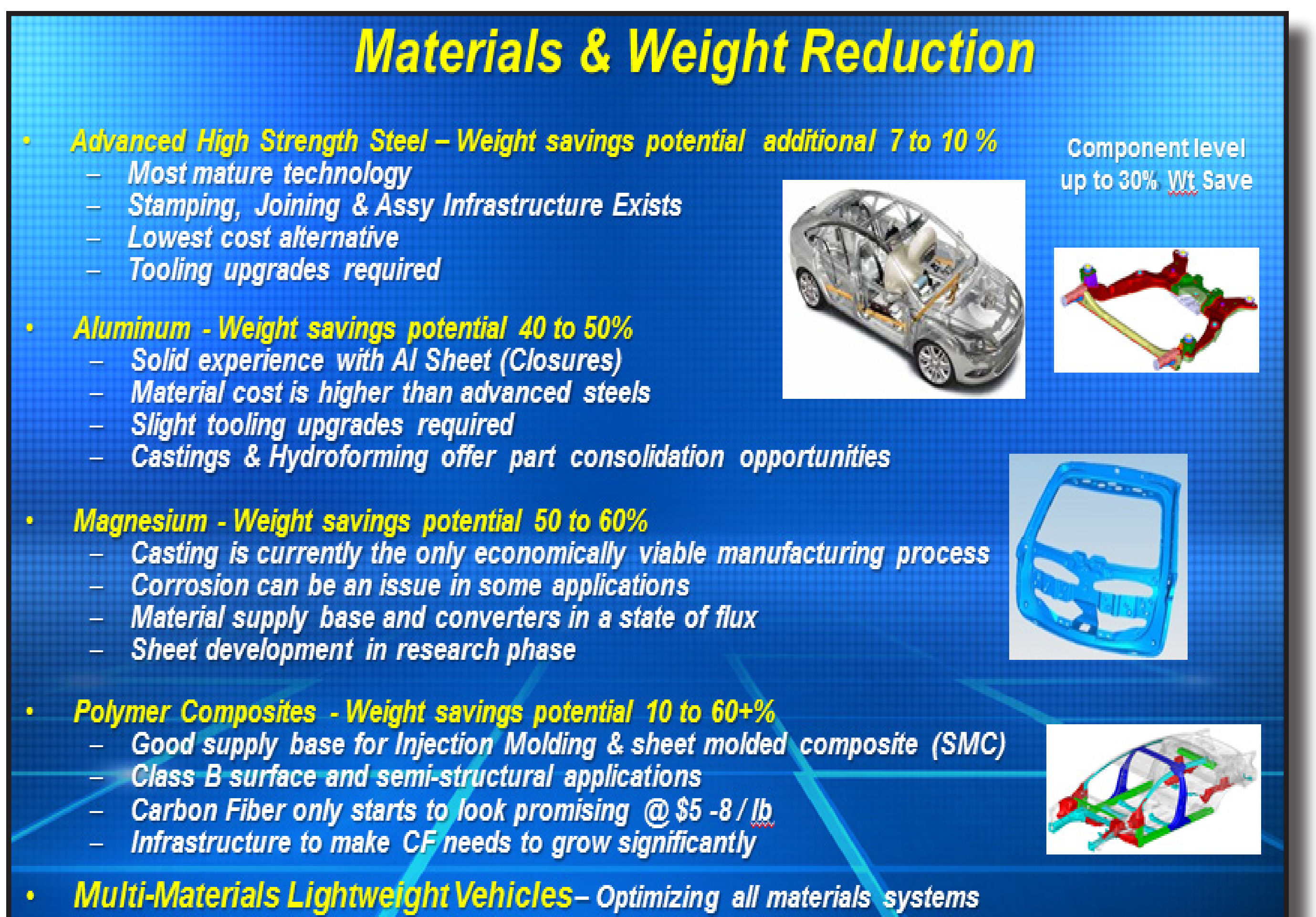
high strength steel (UHSS), defined as steels with high (>1500 MPa) tensile strength. Steel will continue to be a dominant player in A, Sub B, B and C class vehicles. As the steel industry continues to develop the 3rd generation of UHSS, we expect to see small, measurable and incremental weight savings in the 7-10% range for various applications of UHSS. The crossover point for more aluminum in passenger cars will start with the C/D and D-class size vehicles. The logical next step to light weighting of the C/D and D class vehicles will be the application of aluminum for closures (hoods, decks, doors and fenders). There are several reasons for this, most notably is the fact that closures are all "bolt on" components which is less of a disruption to the automotive press shop and body shop where the infrastructure is built around steel stampings and conventional welding (resistant spot welding – RSW) processes. The introduction of aluminum closures will be the most common near term weight saving enabler for the smaller aforementioned vehicles. Aluminum body structures and closures in general offers weight saving in the 40% to 50% range compared to steel although cost is still a challenge. OEMs and suppliers are looking for ways to offset the cost by using aluminum stampings in conjunction with castings and extrusions; the latter two processing techniques allow for part consolidation and reduced tooling cost. The development of the all-aluminum body Ford F150 was evolutionary in that Ford had extensive experience in aluminum thru vehicle launches such as; the Jaguar XJ, Aston Martin Vanquish and the 2005 Ford GT aluminum supercar. The key to delivering the aluminum F150 was working closely with the aluminum industry to add significant capacity at aluminum sheet production facilities to meet the demand of the F150. Strategically, it was the right material (aluminum) applied to the right product (F150) at the right time (to meet 2017 FE targets).

When considering the use of magnesium (Mg) and carbon fiber composites (CFC), the same materials availability issues limits wide spread application. The use of magnesium offers weight savings potential of up to 50% thru the use of high pressure die casting for interiors, powertrain and even select body structure applications. The primary source for Mg is China and US tariffs add significant cost to Mg as a commodity making it too expensive for certain applications. Nonetheless, Mg offers many opportunities and there are developments underway to produce Mg sheet which can be stamped into more complex shapes.

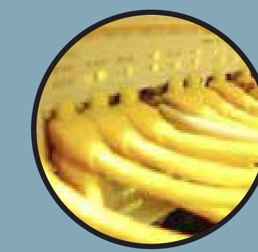
There is significant talk about the use of CFC as a light weight material, but the limited production of lower cost carbon fiber (CF), limits the applications to a few select automotive applications. CFC's, depending on the processing method, can deliver a range of weight savings from 10% to as much as 60%. Full vehicle applications will be limited to low volume niche and specialty vehicles, like the 2017 Ford GT supercar. Higher volume application will be targeting multi-purpose use, for example, as a B-pillar inner reinforcement where the CFC not only delivers weight savings, but via its higher strength, add to the safety and energy absorption in crash critical areas. This combinatorial and strategic use of high cost materials like CFC for body, chassis and powertrain applications will evolve over time but is unlikely to lead to a massive material substitution like what was delivered in going from stamped steel to stamped aluminum on the 2015 F150.

Lastly, the development of mixed material lightweight vehicles (MMLV's) is clearly the trend in delivering high volume lightweight solutions that will meet the needs of all OEM's to meet fuel economy and emissions targets. The strategic use of UHSS, Aluminum, Mg and CFC for body, chassis, powertrain and interiors will deliver the necessary light weight solutions over time. The key is to work in conjunction with material suppliers (steel & aluminum industry), develop advanced manufacturing processes (stamping, casting, extruding and injection molding) and state of the art integrated computational materials engineering (ICME) tools to improve material properties, reduce processing costs, optimized component design, and deliver value to our customers.

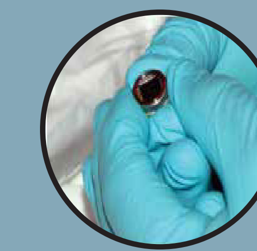
Steel Replacement:
Carbon fiber, aluminium or other lightweight material might replace steel. The design will be a mix of efficient contours (low aerodynamic drag) and emotional styling. Some sort of morphing shape is a possibility. MIT has looked into some very promising vehicle concepts that allow for small footprint in the city and a safer and more dynamic configuration for the open road. These future lightweight cars would be virtually indestructible. They will have safety features that can scan the roadway looking for potential hazards, pre-collision technologies that avoid or minimize impacts, internal and external airbags that protect driver, passengers



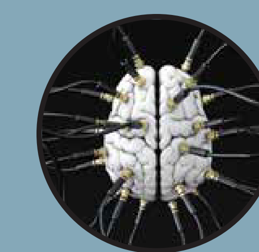
INFLUENTIAL TECHNOLOGY DEVELOPMENTS



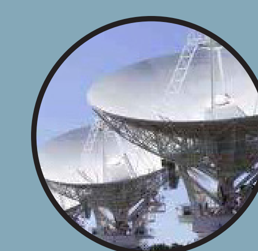
COMPUTATIONAL POWER
. . . continues to increase while computers are getting smaller and more efficient. Extensive reasoning and data management capabilities are now embedded in everyday systems, devices and appliances, yet data centers exhibit very high power densities requiring more sustainable power and thermal management systems.



SENSOR TECHNOLOGIES
. . . provide information to a multitude of systems about location, human inputs, environmental context and more. For example, GPS now provides complete and accurate information about a system's geographic position - information that was previously unobtainable. Advances in medical systems, Geographic Information Systems and many industrial systems are based upon ever better and more efficient sensor technologies.

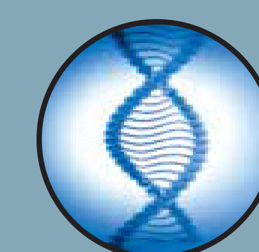


HUMAN-COMPUTER INTERACTION
. . . technologies enable the exploration of virtual environments allowing engineers to interact more deeply and comprehensively with systems before they are built. They also advance human control by integrating multiple information streams into manageable pieces.

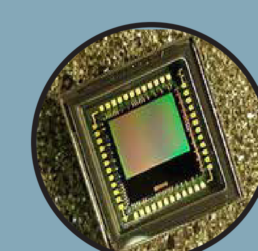


COMMUNICATION TECHNOLOGIES
. . . bring our world closer together and enable systems that are aware of and can respond to much greater environmental stimuli and information needs.

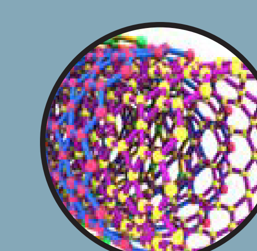
SOFTWARE SYSTEMS
. . . embody algorithms that manage system state but also reason about the system's external environment and accomplishment of objectives. As systems become more "intelligent" and dominate human-safety critical applications, software certification and system reliability and integrity become more important and challenging.



BIO-TECHNOLOGY
. . . contributes to health and human welfare, but can have unintended consequence



MINIATURIZATION
. . . of system components provides increased capabilities in smaller and more efficient packages but can contribute to hidden levels of system complexity.



MATERIAL SCIENCE
. . . new capabilities lead to systems with improved properties, such as weight and volume, electrical conductance, strength, sustainability or environmental compatibility.

1.6 Automotive System Trends

System performance expectations and many system characteristics will reflect the global societal and technological trends that shape stakeholder values. Examples of system stakeholders are:

System Users:
- The general public
- Public and private corporations
- Professionals

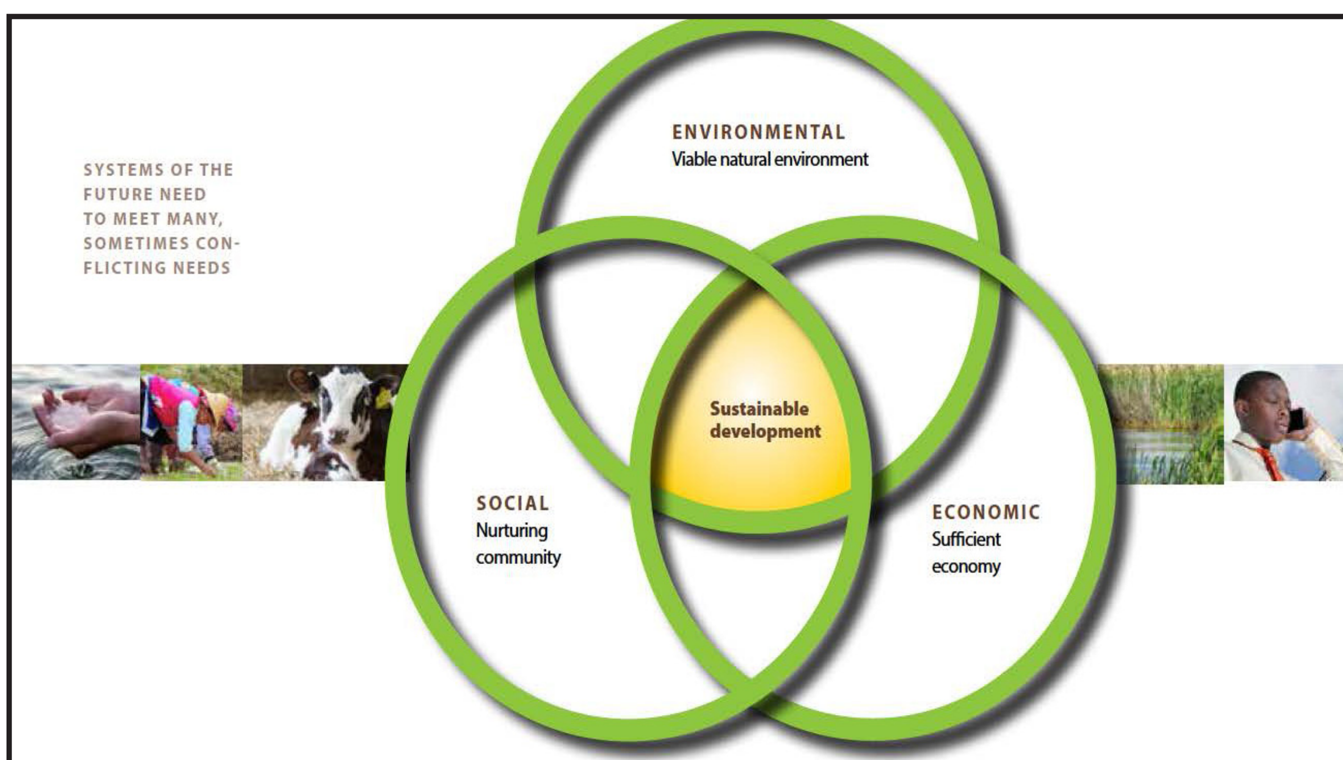
System Sponsors:
- Funding organizations
- Investors
- Industrial leaders and politicians

Policy Makers:
- Politicians
- Public/private administrators

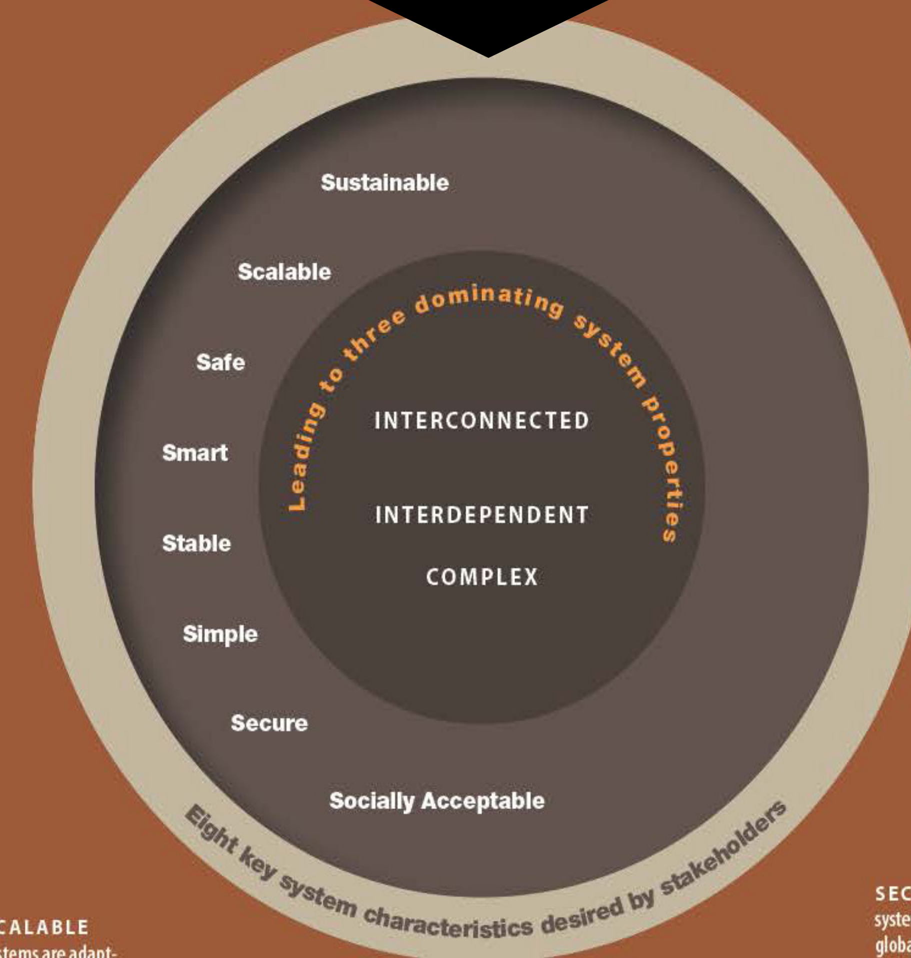
Across a wide variety of domains, stakeholders are demanding increased functionality, higher reliability, shorter product lifecycles, and lower prices. Stakeholders are also demanding environmentally and socially acceptable solutions that assure safety and personal security while delivering more value to the users. In maximizing value to stakeholders, systems engineers have to cope with greater levels of complexity and interdependence of system elements, divergent goals, as well as cost, schedule and quality demands.

Automotive System Trends and Characteristics: The demand for greater mobility, personalized transportation portfolios and flexibility around data access, usage and storage will drive highly complex SoS solutions. These SoS solutions will integrate technologies, methods, information and data models from previously unconnected, unaware systems. The use cases demanded of these highly integrated and increasingly complex SoS will also be themselves highly complex, distributed and dynamic in nature.

The simple act of entering a vehicle, starting it, driving to a final destination, parking and turning it off will evolve into a far more elaborate set of activities. Consider an individual in 2025 who wants to travel from his home to his parents' house located at a city-destination in another state. He can plan his desired modes of transport using a simple mobile application on his favorite device.



SYSTEM CHARACTERISTICS



SUSTAINABLE systems take into account: acceptable cost of total ownership; full product life cycle management; management of product diversity; pre-planned product evolution; upgrades while operational; & conservation of natural resources.

System engineers must be able to balance sometimes contradictory demands.

SCALABLE systems are adaptable to a range of performance and system capabilities without breaking their fundamental architecture. This is an important trait because of the high cost associated with initial infrastructure investments or non-recurring engineering.

System engineers must deal with scalability and adaptability from the project start and reconcile the conflict with product optimization for single applications.

SAFE systems, driven by software-intensive designs, are increasingly being used in applications in which system safety is a significant concern.

System engineers must be able to assure ever-increasing levels of safety and resilience in the face of increasing systems complexity.

SMART systems are able to cope with a changing and unknown environment, assist human operators, or self-organize to provide unanticipated products & services .

System engineers must integrate social, functional and physical demands to create valuable system solutions.

STABLE systems of the future must be stable and reliable in order to: meet key operational requirements and availability needs; achieve customer acceptance; operate efficiently; avoid liability; and provide expected system value.

System engineers must validate systems to be consistent with customer expectations across a wide variety of use cases and stress conditions.

SIMPLE systems are maintainable and avoid operator error.

System engineers must strive to find solutions that have simple architectures and interfaces, are understandably failure tolerant & easy to use.

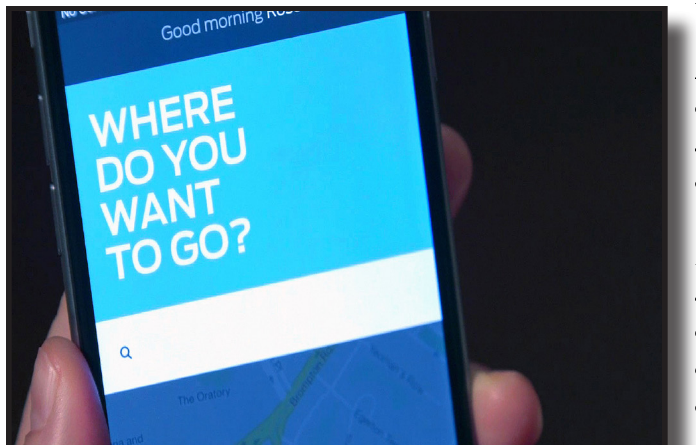
SECURE system complexity, global connectivity and IT-dependence give rise to system vulnerabilities. The challenges for averting unwanted intrusions or for mitigating the results of intrusions have grown enormously.

System engineers must analyze cyber threats and contribute to global security policies ensuring cyber security and cyber defense against both ad hoc and organized threats.

SOCIALLY ACCEPTABLE social, environmental and economic concerns interact.

Stakeholder acceptability of systems is increasingly influenced by socio-economic issues and concerns of sustainability.

Ride Sharing Applications:
The application will identify multiple modes of possible transportation to get him from his home to the target city. These choices might involve pick up from his home by an automated, driverless vehicle (his choice of electric, fuel cell, gasoline power source). This "taxi-service" or shared mobility device could then drop him of at a waiting shared bus-mobility-unit. The driverless bus-unit would then proceed to take him to an airport or directly to the outer limits of the target city. The bus terminus would then provide his previously booked mode of transportation to enable his travel from the outskirts of the megacity to the downtown (pedestrian zone). If he takes an electric bicycle or segway unit he can travel directly into the inner pedestrian zone and deposit the cycle outside his parents' home.



The bicycle would then be picked up by an autonomous collection and redistribution system, preparing the vehicle for the next customer. All Mega-city taxes, congestion charges and fuel taxes would be automatically included within the transportation application device.

The access to the pre-planned set of mobility units would make the trip very efficient; both in time and in costs. The environmental impacts to and within the megacity would be significantly reduced from older modes of transportation. The consumer will need to make multiple vehicle transitions but this could become a "fun" activity and break the boredom. If the customer wanted to concentrate and complete some work during the trip they could order a limited set of transportation devices and maximize their time working (as long as they don't get car-sick).

System of Systems (SoS):
These distributed and connected SoS solutions will include Vehicle-to-Vehicle (V2V), vehicle-to-roadside Infrastructure (V2RI), vehicle to citywide infrastructure (V2CI) and vehicle-to-cloud (V2C). Vehicle-to-vehicle and vehicle to xInfrastructure (V2xI) communication will provide opportunities for each customer's vehicle to continuously communicate via local on-board vehicle transceivers.

The communication can be directly to other vehicles, to a central cloud based data analysis center, to infrastructure on the highway, etc. The communications can also be used to read road signs, traffic signals and emergency information long before the driver could perceive or process the data. This capability should provide improvements in real-world safety.

Advanced automotive and general systems engineering will be required to design, develop and implement these types of system-to-system communication and control structures. The cloud based data compilation and information or control signal determination will require careful thought and the combined engineering skills of controls engineers, auto systems engineers, technology engineers, data analysis engineers, software engineers and IT infrastructure engineers.

Ultimately the transmitted data from thousands of vehicles will be processed in cloud based systems to determine if emergency information should be transmitted or broadcast to multiple vehicles that are about to encounter a hazardous environment such as a blizzard or major traffic incident. The data could also be used for rapid response and automated decisions between vehicles to alarm drivers if immediate actions are required.

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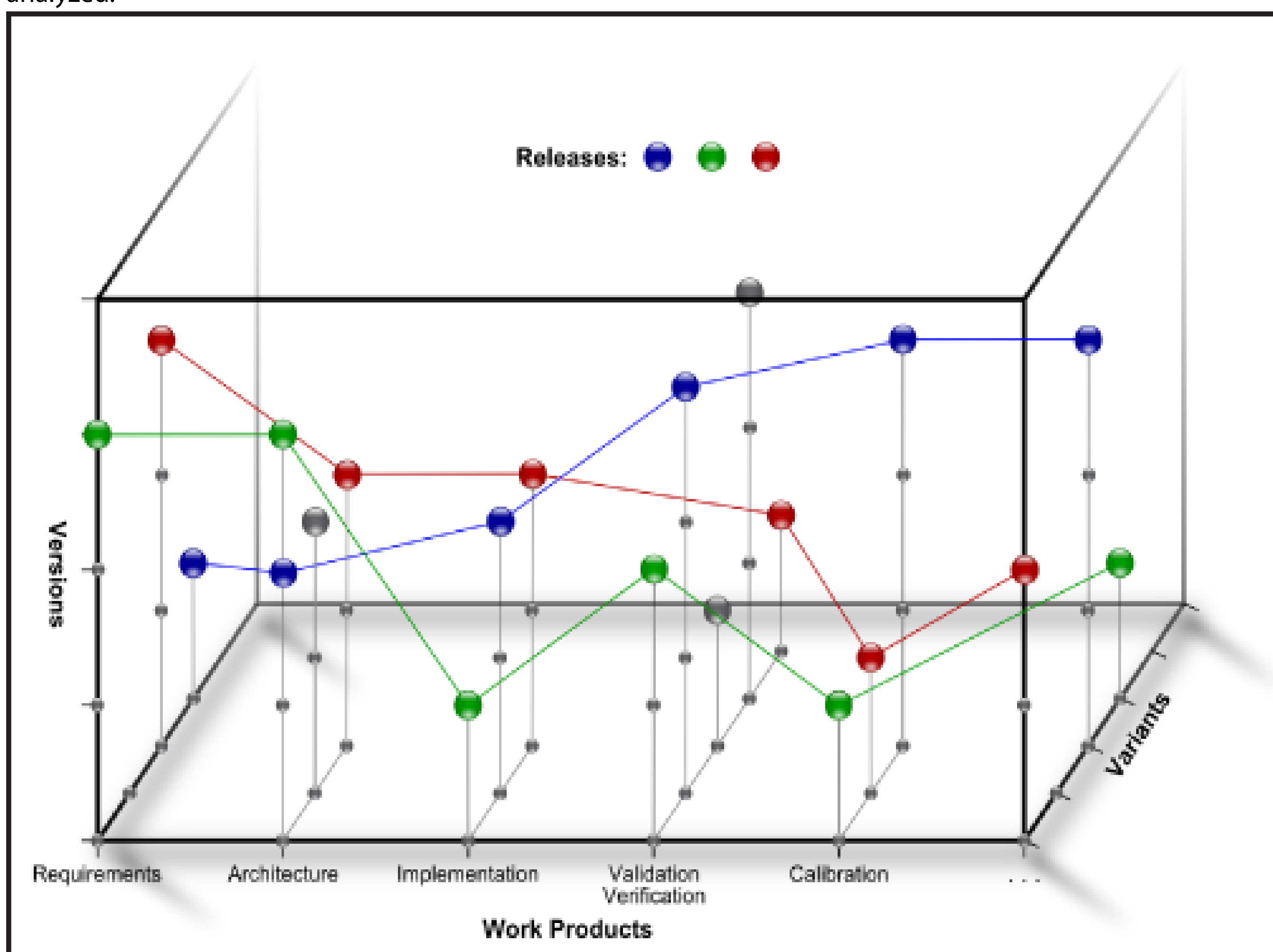
Trends of Emerging System Properties:
Inter-connectivity and interdependence are characteristics that, by themselves, provide no intrinsic value. Value is gained by building systems with these characteristics to address stakeholder desires. In doing so, complexity, both necessary and unnecessary, enters the system designs because of the increasing number of new system interfaces and new failure modes inherent at each interface.

Interconnectivity produces vulnerabilities and risks that need to be analyzed and exposed for systems managers, sponsors and public policy decision makers. These properties will drive future systems design regardless of different markets and applications domains.

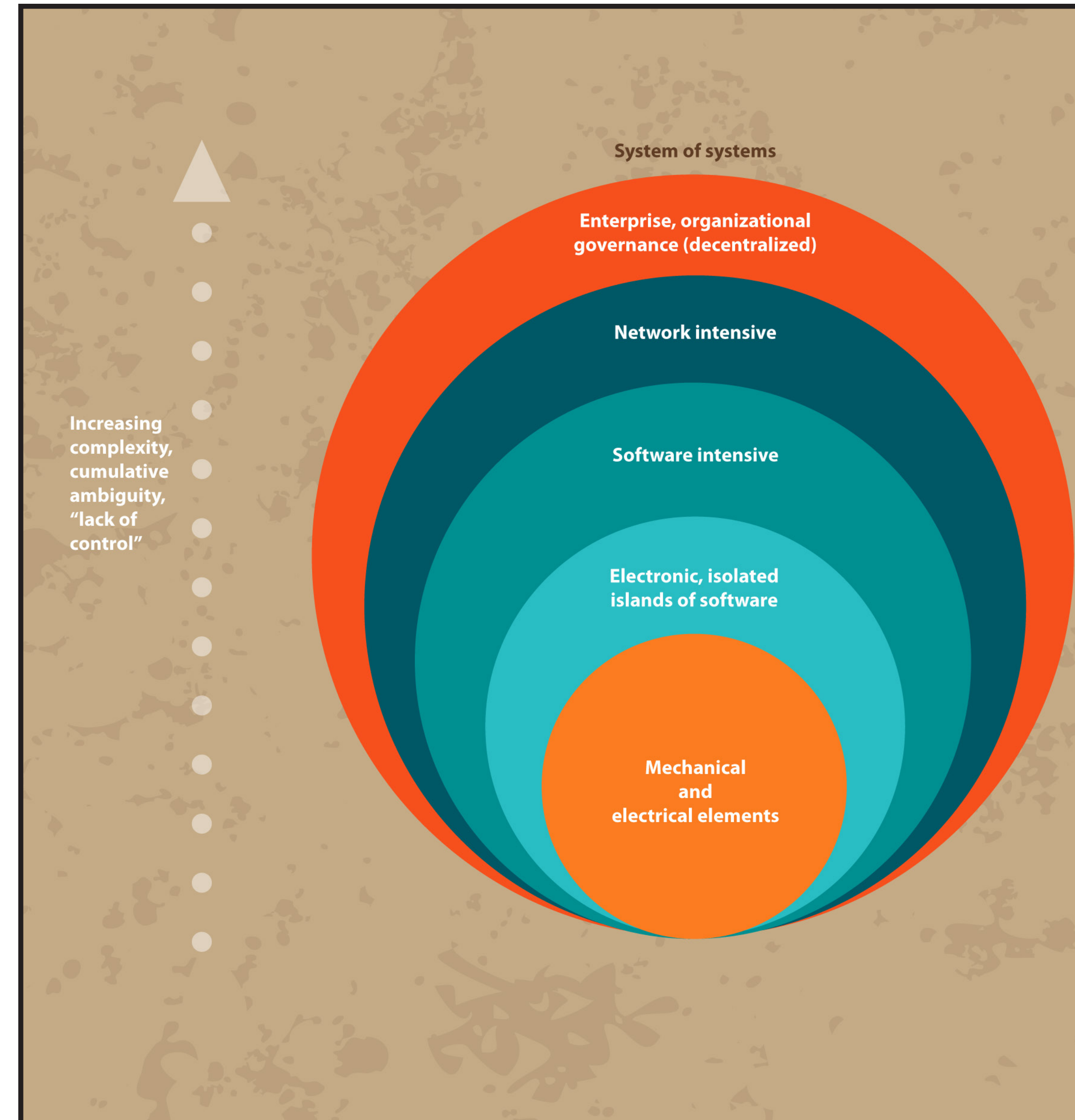
These automotive specific, SoS advances will provide improved driver and pedestrian safety but will also introduce a new set of cybersecurity threats, failure modes and risks never previously envisioned or analyzed.

Variant Management:
The fundamental emerging system property will be driven by the massively complex feature and function interactions. These will be created when building transportation system solutions that have integrated multiple, highly distributed-hierarchical control systems solutions that combine legacy on-board controls with newly designed distributed system controls and highly adaptive system of system controls.

The final complexity challenge will be managing to maintain, upgrade and extend these complex system solutions over time without breaking them, degrading their performance or unintentionally introducing customer facing system failure modes.



THE ROOTS FOR GROWING LEVELS OF SYSTEM COMPLEXITY

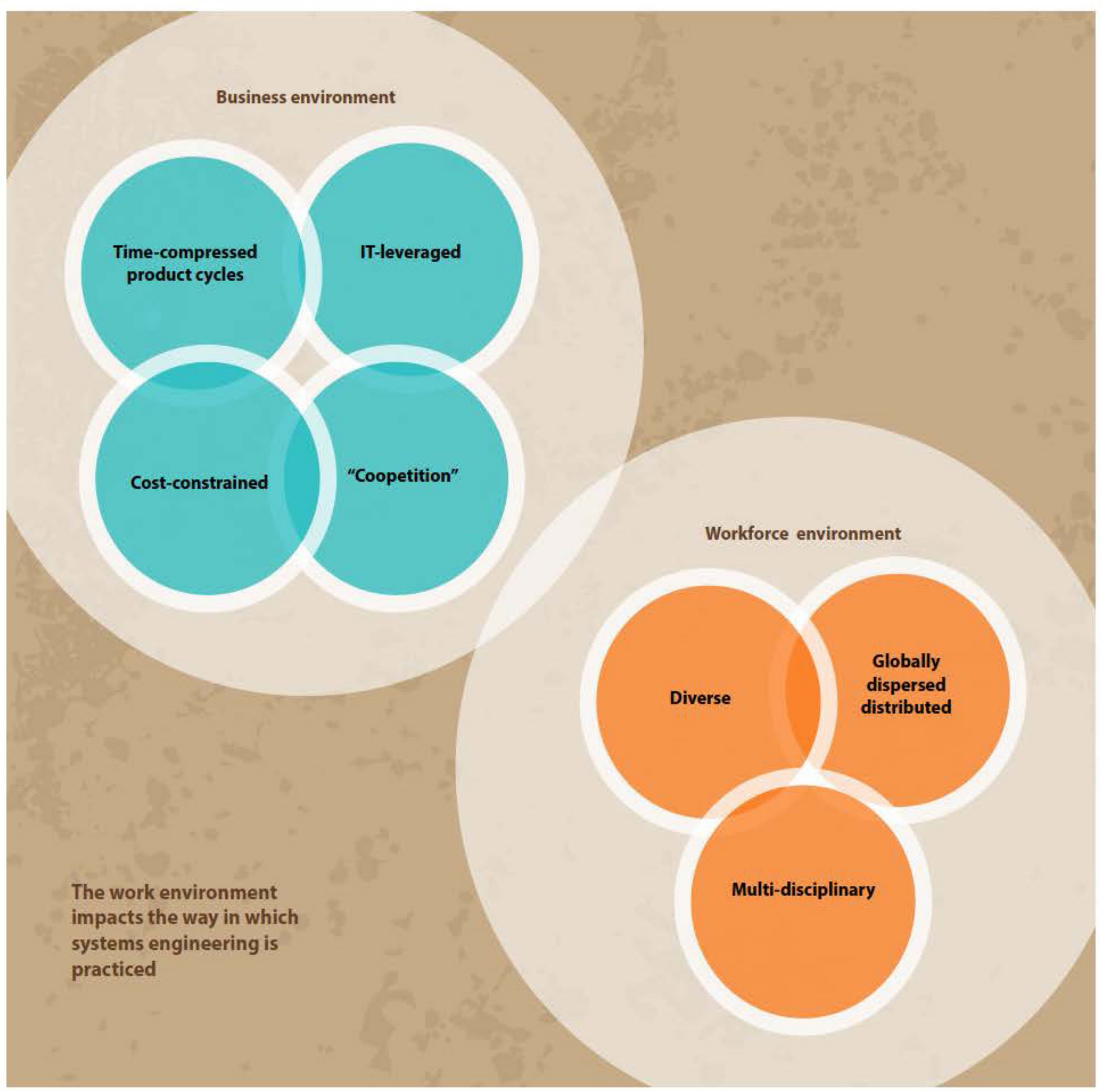


1.7 The Automotive Work Environment

Global competition among the automotive manufacturers and their Tier 1 suppliers will continue to grow. Industry collaborations and product platform element sharing will increase. The OEMs will increasingly compete on the ability of their respective work force to innovate, design and develop compelling vehicle system solutions and deploy these solutions in shorter time frames.

The Tier 1 relationships with the OEM community will also adapt and evolve to become a strategic competency resource providing far more value to the system solution than was previously defined by constrained sub-system definitions. The tier 1 workforce will become an integrated, mobile extension of the OEMs workforce adding a dynamic, virtual competency framework.

The automotive systems engineering workforce of the future will be a global, seamless integration of well-trained systems engineers across OEMs, tier 1s, and adjacent industries such as aerospace, medical, IT services and consumer electronics. The collective knowledge of cross industry experts will be required to design and develop, using agile methods as the compelling features of the future work processes.



KEY ASPECTS OF THE EVOLVING SYSTEMS ENGINEERING WORK ENVIRONMENT

Adapted from the AFIS Vision

New Engineering Generation:
This new generation of highly mobile systems engineers will rapidly be replacing the "Baby Boomers" and "Gen Xs". Increasingly, the global workforce will be educated to higher levels of standardized coursework, often delivered via on-demand internet delivery and collaboration environments. The standardization and mobility of the workforce will provide both opportunities and challenges to the automotive OEMs and tier1's. Large populations of highly skilled engineers will be accessible in all global regions making hiring a truly global endeavor. Each open job position will be advertised on a global basis with interviews taking place via video conference; once employed the engineering activities can be performed remotely and results of designs, investigations; simulations will be integrated and reviewed virtually. Only final vehicle build and validation will require a physical presence of the vehicle acceptance and sign-off test engineer. Entire careers could evolve without many engineers actually physically meeting.

Job mobility and turnover may see a large permanent upshift – the leading indicators can be seen in parallels in the IT field. The challenge will be in the retention of highly skilled engineers who have multiple competing OEMs pursuing their unique and usually scarce resources.

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SUMMARY

THE GLOBAL CONTEXT

GLOBAL CONTEXT

SOCIETY NEEDS (MEGATRENDS) → ENGINEERING NEEDS (ENGINEERING CHALLENGES) → AUTOMOTIVE SYSTEM NEEDS (AUTO TRENDS)

SOCIETY MEGATRENDS

- POPULATION GROWTH & URBANIZATION
- GROWTH OF MIDDLE CLASS & AGING POPULATION
- ENVIRONMENTAL FACTORS SUCH AS AIR QUALITY
- CHANGING ATTITUDES TOWARDS CAR OWNERSHIP
- CHANGING WORKFORCE DEMOGRAPHICS:
- GROWING MOBILITY, CONNECTIVITY, & SECURITY

ENGINEERING NEEDS

- PERSONAL MOBILITY
- INCREASED POPULATION DENSITY
- ASIA GROWTH
- TRANSIT DEVELOPMENT
- AGING POPULATION
- ENVIRONMENTAL CONCERNS
- CAR OWNERSHIP
- SUPPLY CHAINS
- CYBERSECURITY THREATS
- PASSENGER HEALTH NEEDS
- SAFETY AND SECURITY
- COMPLEXITY GROWTH

INFLUENTIAL TECHNOLOGY

- COMPUTATIONAL POWER
- HUMAN COMPUTER INTERACTIONS
- SENSOR TECHNOLOGIES
- COMMUNICATION TECHNOLOGIES
- SOFTWARE SYSTEMS (ADAPTIVE)
- BIO-TECHNOLOGY (MACHINE)
- MINIATURIZATION
- MATERIAL SCIENCE

AUTOMOTIVE TRENDS

- RIDE SHARING APPLICATIONS
- SELF-DRIVING TECHNOLOGY
- TRANSIT DEVELOPMENT
- EMISSION STANDARDS
- CAR OWNERSHIP
- HORIZONTAL ORGANIZATION
- VIRTUAL REALITY TOOLS
- SAFETY AND SECURITY
- CROSS-FUNCTIONAL DOMAINS
- MODELING METHODS
- ALTERNATIVE FUELS
- LIGHTWEIGHT MATERIALS
- SYSTEM OF SYSTEMS
- VARIANT MANAGEMENT
- CHANGING WORK ENVIRONMENT
- PRODUCT GLOBALIZATION

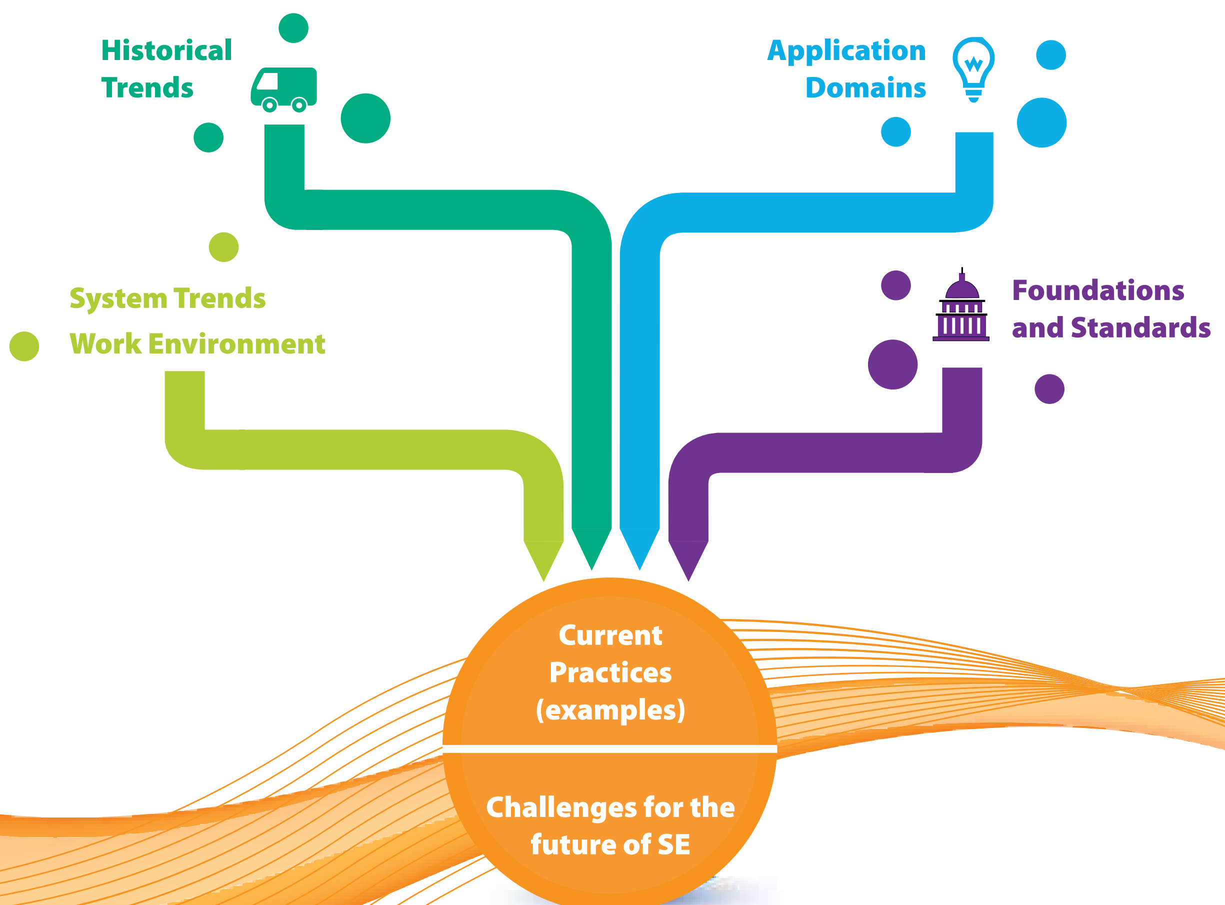
2 The Present State

To understand the desired future state of automotive systems engineering, it is essential to understand the current state. This section highlights key aspects of the current state of practice to help predict and guide its future directions.

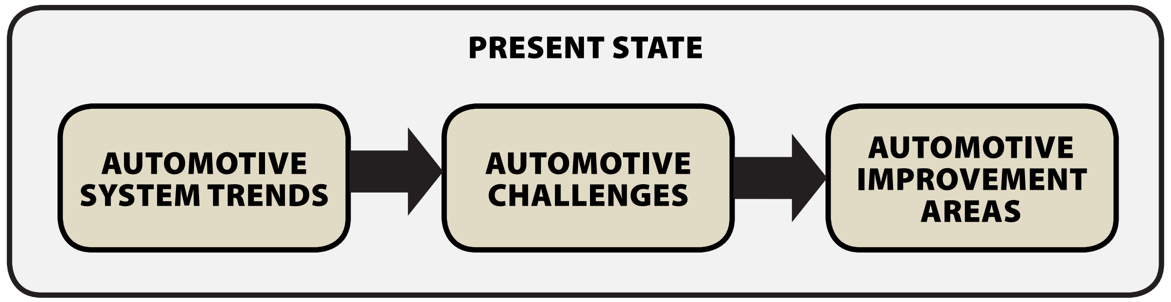
The previous section provides a global context for systems engineering across multiple industries, by characterizing systems that systems engineers support and the work environment in which systems engineering is practiced.

Today's automotive systems engineering practices and challenges are greatly influenced by the changing global context. The practices have evolved differently; both depth, breadth and approaches, within different traditional automotive domains such as chassis, powertrain and electrical systems.

The relatively newer domains of automotive embedded software, consumer electronics, consumer services and infotainment have been developing at a rapid pace for the past 20 years with no end in sight.



2.1 Outline: Present State



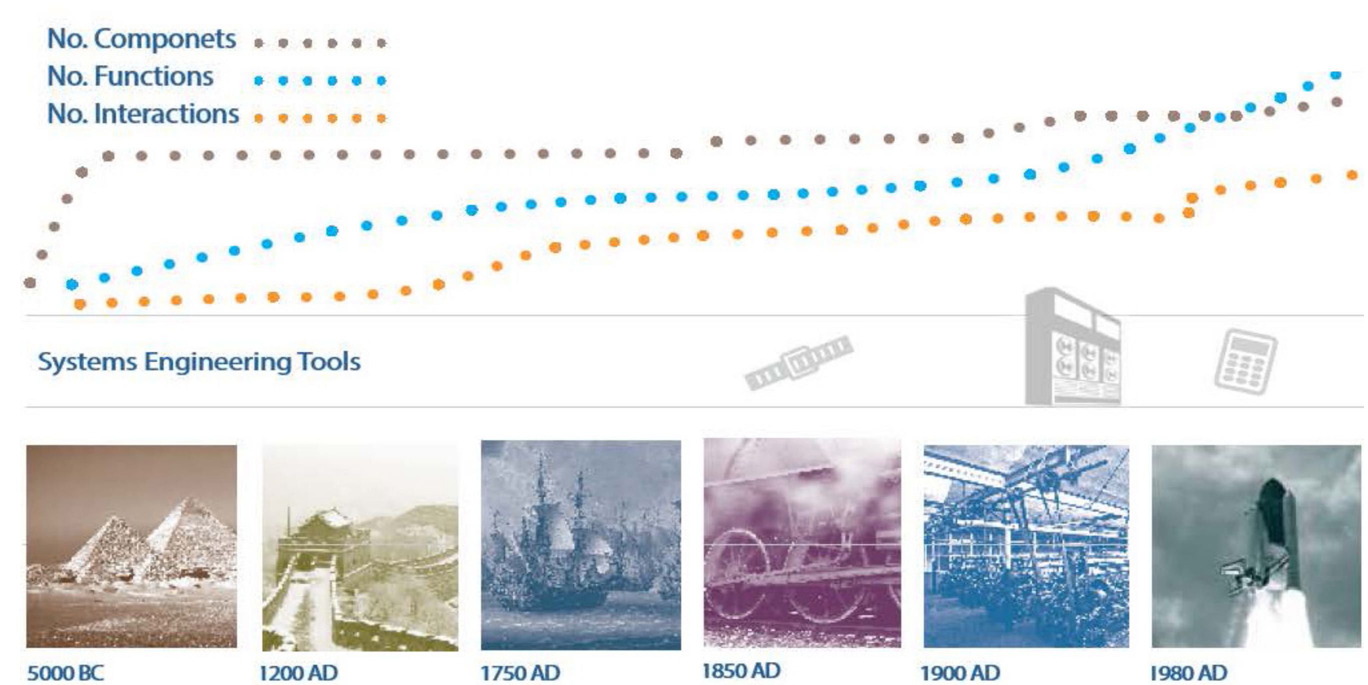
2.2 Historical Trends

Some consider automotive systems engineering to be a young discipline, while others consider it to be quite old. Whatever your perspective, automotive systems and the practice for developing them has existed a long time. The constant throughout this evolution of systems is an ever-increasing level of complexity.

Automotive Complexity Trends:
Automotive complexity can be observed in terms of the growth of customer features (or functions) that have been offered over time. The buildable set of different vehicle configurations that are offered has exploded from hundreds of build combinations to hundreds of thousands, if not millions. Traditional mechanical complexity growth was driven by customer features such as engine size choices, vehicle body style choices and drivetrain configurations: all-wheel drive, rear wheel drive. Electrical systems provided greater choices with customer features such as anti-lock brakes, traction control, and different levels of infotainment systems. More recent trends are seeing the marriage of on-board software systems with off-board software systems and the exchange of massive amounts of data to provide a dynamically changing, real-time customer experience. All of these customer features have driven increases in the number of vehicle systems, systems interfaces, calibrations, components and the amount of software code required to implement the total vehicle system.

Each of these indicators of complexity has increased dramatically over the last fifty years, and will continue to increase due to the capabilities that customers, Governments and other major stakeholders are demanding and that advancing technologies can support.

Tool Complexity:
Other factors have impacted automotive systems engineering. Advancements in technology not only impact the kinds of systems that are developed, but also the tools used by automotive systems engineers. System failures have provided lessons that impact the engineering practices required to develop high quality and always available systems, including factors related to the changing work environment and operating environments. These factors remind us that automotive systems engineering is a human endeavor that requires global teamwork and collaboration. A look back in time can provide insight into the factors and trends that will impact the future directions of automotive systems engineering.



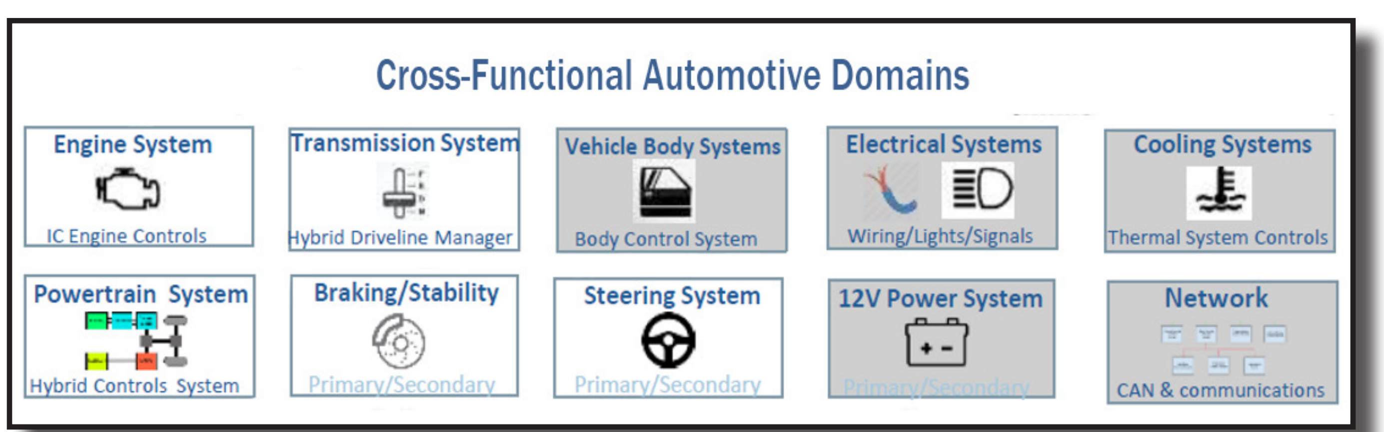
2.3 Automotive Application Domains

Automotive systems engineering is practiced in many different industries such as aerospace, defense and consumer products. It is also practices across very different domains of competency within the automotive industry. Areas such as powertrain, chassis, body and electrical engineering have developed systems engineering best practices at different rates and to address different and sometimes very specific problem spaces.

Within the automotive industry, powertrain engineering was typically the first domain to embrace on-board computing and digital controls. These were introduced in an attempt to manage fuel delivery and emissions compliance. The powertrain domain soon entered the challenging space of drive by wire and all of the safety related system design activities required to support the coordinated implementation of control systems across the engine, transmission and transfer case systems. Chassis engineering was also an early adopter of systems based design principles when developing and implementing brake control systems like ABS and traction control.

These systems depended heavily on cross domain interactions and controls to manage vehicle level torque requests that sometimes operated in competing directions of torque request. More recently the integration of consumer devices and services onto the vehicle platform has required a new domain of expertise to be leveraged during the designs of vehicle-infrastructure solutions. Cloud based services are now designed for use with in-vehicle features and functions to deliver unprecedented levels of vehicle performance and accessibility.

Cross-functional Domain:
Cross-functional domains have different names in these different automotive domains, and each application domain has unique drivers that impact the systems engineering practice. The extent to which the industry is market-driven or government-contracted whether a product is delivered as a subsystem of a larger system or whether it is delivered as an end product or a service, are all factors that influence the practice.



2.4 Foundations and Standards

Grown from the need to deal with complexity in the aerospace and defense industries, systems engineering practices have been based primarily on experience - trial and error. Over time, heuristics were developed to tackle complex problems systematically and holistically and these practices have been codified in standards and handbooks focusing on specific domains. The Society of Automotive Engineering (SAE) has provided a focal point for many automotive specific guidelines, standards and best practices.

Organization and Councils:
Today's researchers are revisiting current systems engineering practices to ground them in a sound foundation built on mathematical theory and science.

Further development of this theoretical foundation is needed to allow systems engineering and automotive systems engineering to expand into new domains and deal with increased complexity, without having to repeat a costly trial-and-error learning process. Specific areas of interest for the automotive engineer is research that cover the area of SoS. This is a rapidly growing need driven by emerging mobility, services and connected vehicle systems.

IEEE

SAE INTERNATIONAL

AUTOSAR

INCOSE

ISO

NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

2.5 Practices and Challenges

Current automotive systems engineering practice is typically unique within each OEM and tier 1. The extent to which systems engineering is incorporated into the OEM's product development processes varies. Each OEMs development lifecycle is based on well-defined, and proven processes and activities.

The utility of these development lifecycles, including research and advanced innovative cycles have demonstrated significant value to stakeholders. However, in the future, the automotive systems engineering community must tackle many new fundamental inter-disciplinary and integration-related challenges. These system of system challenges will require a rethinking of the traditional systems engineering practices and the incorporation of new, agile and cross domain systems engineering activities. The ability to "innovate and incorporate" new customer features into a production vehicle will become even more critical to profit and loss than ever before. Those OEMs and tier 1's that can design efficient, agile and flexible innovation, development and production lifecycles will become the successful players in 2025.

It is the systems engineer who holds both deep domain experience and cross domain experiences who will define and lead this execution.

SEVEN KEY AUTOMOTIVE ENGINEERING CHALLENGES

1. **Managing complexity growth: driven by increased customer features; safety systems, automated driving, mobility and connectivity.**
2. **Maintaining a competent engineering workforce: changing technologies and associated competencies require retraining, new HR hiring policies, and competitive working environments.**
3. **Reacting to shrinking product development lifecycles: consumer electronics and software applications require rapid product updates.**
4. **Development and introduction of new Model Based Systems Engineering Tools: that support system and component reuse, object level versus document centric development and enables global collaboration.**
5. **Retention of Corporate knowledge: at SoS, system, subsystem, component levels. Engineering workforce is aging and new workforce will be more mobile.**
6. **Reorganization of existing Corporate structures: to support competitive automotive systems engineering structures and practices.**
7. **Creating compelling Systems Engineering career paths: that recognize and reward the seasoned, proven systems engineers and encourage organizational movement.**

CURRENT PRACTISE EXAMPLES

MODELING, SIMULATION, AND VISUALIZATION

When Boeing unveiled its latest jet, the 787 Dreamliner – it was a virtual rollout. Boeing virtually created parts, and integrated and assembled the system prior to cutting metal.

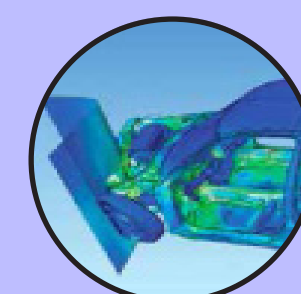
Visualization and simulation helped identify incompatibilities in interfaces and assembly processes early in design before hardware costs were fully committed, avoiding costly redesign late in the system design lifecycle.

Source: http://www.pbs.org/newshour/bb/science/jan-june07/airplane_01-09.html

SYSTEM OF SYSTEMS ENGINEERING

The Thameslink Rail Capability Programme is a £5.5Bn rail upgrade program to improve North-South commuter traffic into London. It is led by Network Rail and overseen by the UK Department for Transportation. Systems engineering approaches have been applied to ensure that the rolling stock, signalling new stations, and railroad can meet all needs (including number of passengers, target journey times, and system safety).

Understanding this complex system of systems requires the use of comprehensive systems approach to analyze not only the traditional technical issues, but also the policy issues and the human behavior of the users.



DESIGN TRACEABILITY BY MODEL-BASED SYSTEMS ENGINEERING

The software and electronics of modern automobiles are becoming increasingly complex. Ford Motor Company has been applying model-based systems engineering to manage design complexity including architecture, requirements, interfaces, behavior and test vectors.

Ford has established digital design traceability across their onboard electrical and software systems by applying multiple integrated modeling technologies including UML, SysML, Simulink with an underlying CM/PDM system.

Source: Presenter Chris Davey. http://www.omgwiki.org/MBSE/lib/exe/fetch.php?media=mbse:03-2013_incose_mbse_workshop-ford_automotive_complexity_v4.0-davey.pdf

PRODUCT-FAMILY AND COMPOSABLEDESIGN

Scania trucks is a Scandinavian company that provides customizable solutions for long haul, distribution, construction and special purpose trucking. Clients have the ability to customize their vehicle by selecting the cab, engine, chassis, engine, transmission and accessories.

Scania's composable approach starts at the component level – with common engine cylinders, push rods and combustion chambers to drive up parts interchangeability, and drive down variations for maintenance.

Source: http://www.scania.com/ products-services/trucks

2.6 Systems Engineering Improvement Areas in Automotive

Based on what has been covered thus far, a set of improvement areas in automotive systems engineering begins to emerge.

Some are familiar but now carry more importance than before due to social, economic, and technology factors that either threaten the sustainability of current methods or have new types of solutions not previously available.

Other improvement areas are new to the scene, having presented themselves in the last 5-10 years, such as those relating to connectivity, functional safety and cybersecurity.

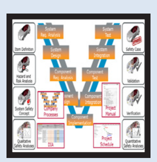
The following figures depict current-state summaries of these improvement areas as a preface to looking at and contrasting the present state with the desired future state in Section 3.

PRESENT STATE DESCRIPTIONS

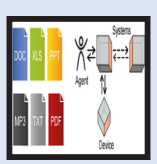
Expanding Across Automotive Domains
Presently, the lack of establishing a defined standardized discipline across automotive domains has limited the ability of practitioners to utilize their practices

Improving Decisions for Stakeholder Needs
Presently, decision making is often made without leveraging a well-defined approach to understand the diverse set of stakeholders' needs and the implications of various policy options.

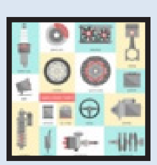
Managing Complex Systems and Behaviors
Presently, customers are demanding capable, safe, and secure systems that are driving complexity with increased electrical, software, and control systems which is increasing development time and more complex failure modes.



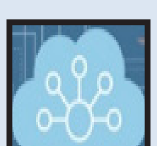
Ensuring Automotive Functional Safety and Robustness
Presently, unknown hazards of sophisticated complex features that balance the trade-off between performance, function, efficiency, & safety with reduced effectiveness of robustness tools on complex software intensive systems.



Leveraging Enhanced Tools versus Limited Office-Based Tools
Presently, reduced capability of office applications leverage computing and information technologies to some degree but they make heavy use of limited localized domain office applications for documenting system designs.

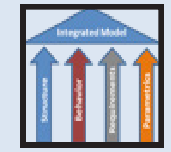


Integrating Multi-discipline Processes
Presently, processes are often not well integrated with time consuming manual program management and discipline-specific processes such as hardware, software, test, manufacturing, operations, and logistics support.



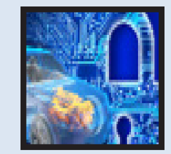
Enhancing Connected Systems
Presently, limited technical guidance is available to engineer complex systems of systems and assure qualities of service with emphasis on IT based architecture frameworks and interoperability standards.

PRESENT STATE DESCRIPTIONS – CONTINUED

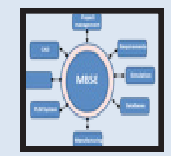


Improving Architecting
Presently, systems architecting is often ad-hoc and does not effectively integrate architectural concerns from technical disciplines such as hardware, software, and security, nor does it fully integrate other stakeholder concerns.

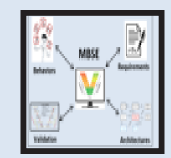
Expanding Fault Resistant Architecting
Presently, inadequate fault detection, isolation, and recovery is based on a prior designation and characterization of off-nominal behavior when designing systems so they can recover from failures and continue to operate.



Reducing Isolated Cybersecurity
Presently, security are increasingly being compromised due to the digitally interconnected nature of our infrastructure and evolving nature and increasing sophistication of the threats to our cyber-physical systems.

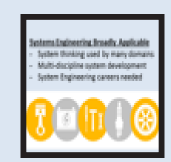


Supporting Better Design Decisions
Presently, a limited number of design alternatives primarily based on deterministic models of performance, physical constraints, cost, and risk.

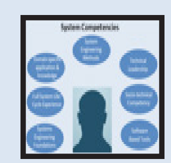


Coordinating MBSE Modeling
Presently, model based simulation occurs in a disjointed manner and each domain area creates and uses project specific simulations to analyze and develop project specific attributes.

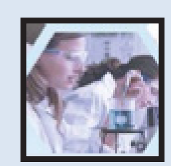
Connecting Theoretical Scientific Based Methods
Presently many systems engineering educational programs focus on practice with little emphasis on underlying theory, which should be built on systems science to ground our understanding of the system under development.



Broadening the System Engineering Roles
Presently, the competency of today's system engineer vary significantly in the depth and breadth of their knowledge with isolated specific domain-based backgrounds and organizations.



Establishing Essential Knowledge Competencies
Presently, the competency vary significantly in the depth and breadth of their systems engineering knowledge and informal methods and practices applied based on their domain specific engineering background.



Building the Workforce
Presently, the worldwide demand in all application domains is increasing the need for high quality education and training and many practicing engineers have not had formal education, but have learned "on the job".

SUMMARY

PRESENT STATE OF AUTOMOTIVE SYSTEMS ENGINEERING

- Automotive systems engineering continues to evolve in response to an accelerating growth in distributed automotive system and consumer electronics complexity.

- Automotive systems engineering is recognized as an essential set of competencies required to deliver high quality customer and environment friendly products.

- Automotive systems engineering is also recognized by other industries, academia and government as beings a leading growth area for the application of both real-time hard controls and consumer electronics soft controls in the delivery of advanced, coordinated in-vehicle and cloud based solutions.

- Automotive systems engineering practices vary across auto-engineering domains and across the automotive industry.

- Many auto-systems engineering practices are based on heuristics, but a theoretical foundation is being established. There is a need for greater cross fertilization across domains and across OEMs/Tier 1s.

- The need for ever increasing global integration of reuseable vehicle assets requires a more formalized, consistent and flexible automotive systems engineering workflow.

- The future success of the automotive industry will be fundamentally based on its ability to;

- Hire and retain engineers with a cross section of systems engineering skills

- Establish an industry-wide, systems engineering competency standard that can help drive global Schools and University to develop and deliver aligned class content.

- Develop University systems engineering courses that are dynamic, integrate the science of systems engineering and are based on projects that solve immediate, real-time automotive design and development challenges.

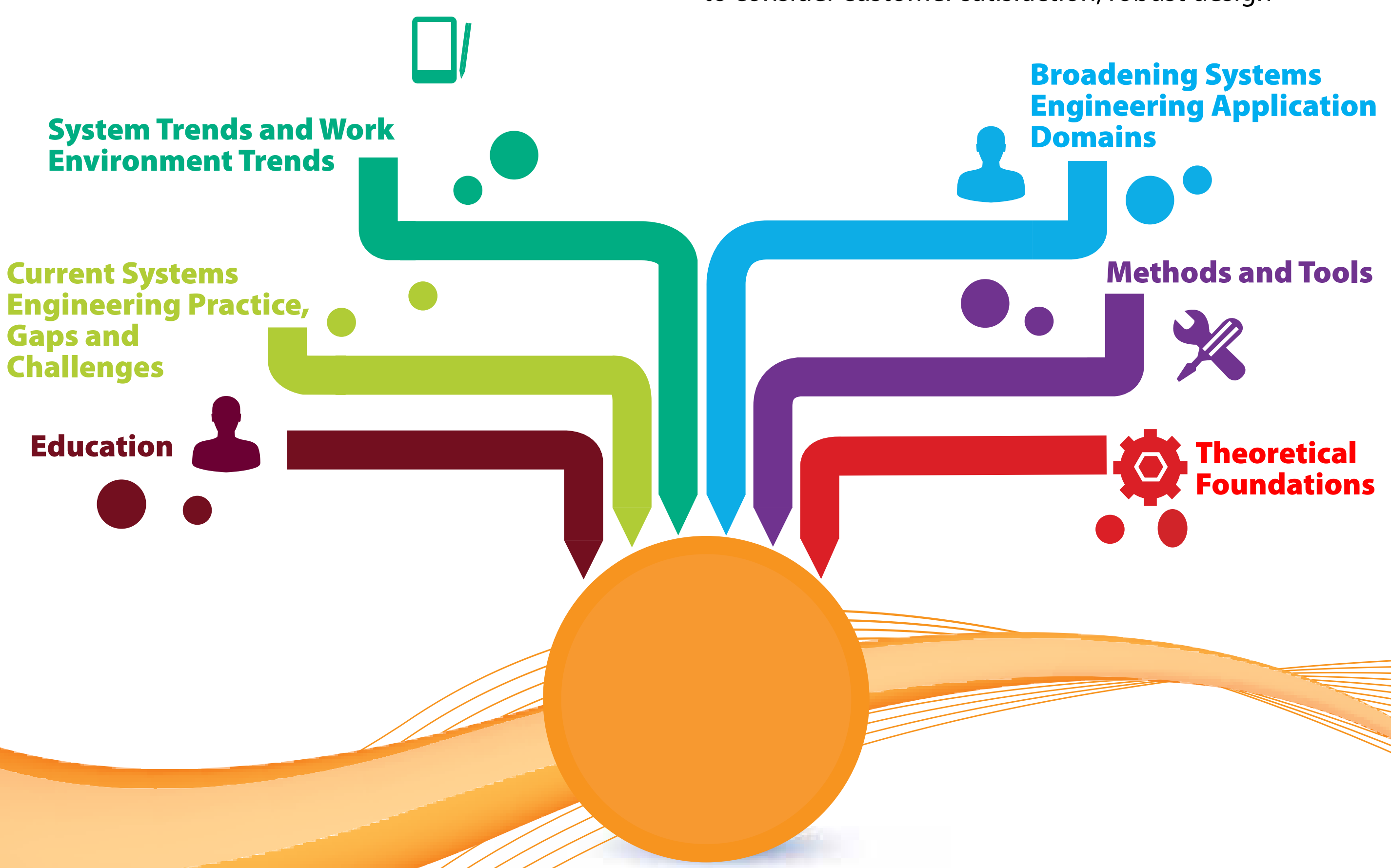
3 The Future State

By 2025, automotive systems engineering will have made significant strides in meeting the challenges and needs described in the global context for automotive systems engineering. Its relevance and influence will go beyond traditional in-vehicle systems development and extend into the broader realm of connected services, mobility, artificial intelligence and cloud based big data systems.

The influence and impact of automotive systems engineers will also reach across social systems such as health care, local state/global government and policy making systems. Automotive systems engineering will grow and thrive due to its multi-disciplinary and cross cutting perspective that is critical to successful, SoS designs in 2025.

The Automotive Systems Engineer of the future will increasingly be central to innovate the next generation of mobility solutions as automotive complexity increases exponentially.

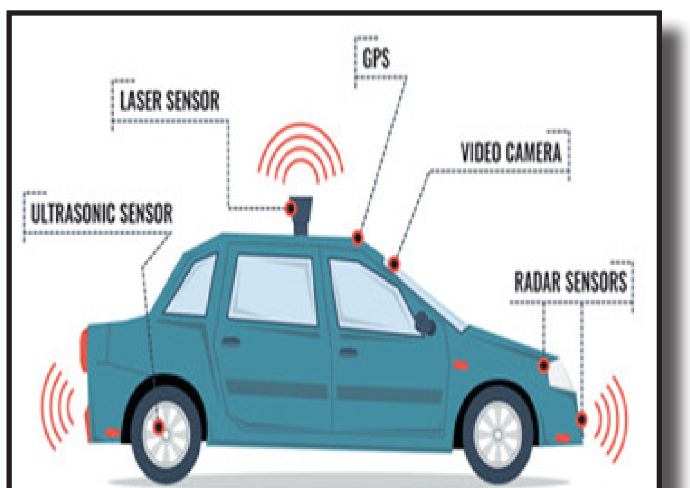
System of Systems (SoS):
In order to achieve this, it will be necessary to perceive all customer features, vehicle systems, support infrastructure and design decisions in the larger context of global SoS engineers will develop broad skills and experiences through planned development rotations across key application domains to conceptualize, innovate and design; and finally implement and integrate the next generation of mobility solutions. They will have the discipline and rigor of traditional automotive engineering; to consider customer satisfaction, robust design



principles, quality methods and vehicle feature integration.

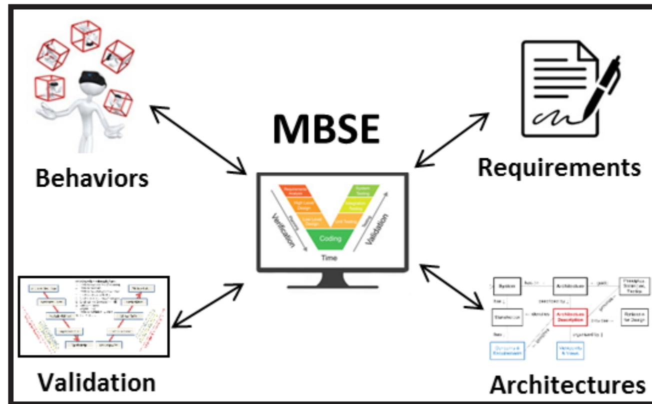
However, systems engineers will also have expanded competencies in SoS identification, bounding, alternative solution development, advanced tradeoff skills based on decision theory, virtual validation skills to run simulation based design evaluations and the ability to communicate with systems engineers. It will also be critical to success to work with and learn from adjacent industries such as start-up technology firms, IT service providers, data analytic companies, intelligent transportation systems, biomedical systems, aerospace systems and policy makers.

Automotive Systems Engineers will be recognized broadly by governments and cross-industry as a discipline of high value to a wide spectrum of application domains because the above contributions, combined with assessment and management of risk, are key to competitiveness in many industries.



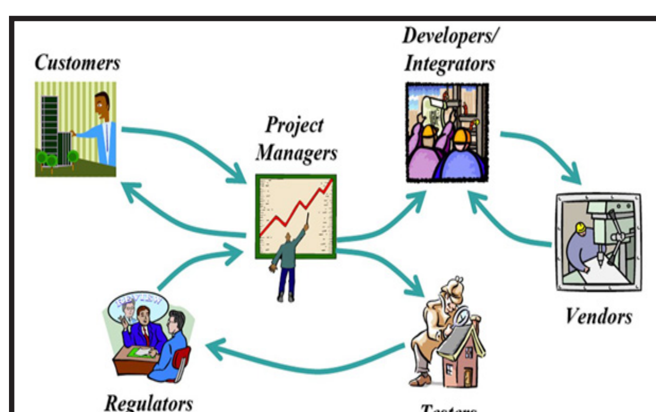
Automotive systems engineering's contributions to the management of complexity, while achieving faster time to market through competitive pressures and reduction of defects, will result in vehicles with improved accident avoidance and safety, greater time and energy efficiency, and improved maneuverability on city streets."

Transformative Technologies:
Transformative technologies are difficult to predict but one can be certain that disruptive technologies such as 3D printing, autonomous transportation systems, and new kinds of materials will impact both the nature of automotive systems as well as the way in which automotive systems are developed.



Automotive systems engineering practices will adapt to and be transformed by new technology as efforts become pervasively digital and globally distributed. This change will intrinsically link the design-supply-manufacturing-sales and servicing infrastructures in an increasingly functionally dependent manner. Real-time access to global datasets that relate the vehicle to customer-experience to environment will enable unprecedented consumer value and efficiencies for those automakers that can harness the multi-level SoS architectures.

Changes in the social, economic and political environments in which emerging technologies are infused will impact the market drivers for automotive system capabilities as well as the work environment where it is performed. These efforts will assist in the assessment of public policies designed to mitigate the negative aspects of technology on our social-physical systems and help shape the global societal trends of the future.



Theoretical foundations will advance to better deal with complexity, variant management, and the global demands of the discipline. This strengthened foundation will form the basis for systems education as well as the methods and tools used by practicing systems engineers for architecting, design and holistic understanding.

Improved Methods:
Methods and tools, based on solid theoretical foundations, will advance to address the market demands of innovation, productivity, and time to market as well as product quality and safety by harnessing the power of advancements in modeling, simulation and knowledge representation; thereby meeting the needs of an increasingly diverse stakeholder including the auto industry, governments and tech companies, while making the offerings affordable and attainable to all customers.

Internet of Things (IOT):
The methods and tools will also keep pace with system complexity that continues to be driven by customers demanding ever increasing system interconnectedness, autonomy, ready access to information, and other technology advances associated with the digital revolution, such as "The Internet of Things" (reference IEEE Computer, Feb. 2013). Automotive systems engineering will lead the effort to drive out unnecessary complexity through well-founded architecting and deeper system understanding.

Education and Training:
Education and training of automotive systems engineers and the infusion of systems thinking across a broad range of the engineering and management

workforce will meet the demands for a growing number of systems engineers with the necessary technical and leadership competencies. Institutional investments from governments, industry and academia will develop, improve and infuse solid systems thinking, as-wells-as automotive systems engineering talent and practices.

3.1 Outline: Future State

GETTING TO THE FUTURE STATE

AUTOMOTIVE CHALLENGES → PRESENT STATE IMPROVEMENTS → FUTURE STATE 2025 VISION

3.2 Applications

3.2.1 Application Across Domains

PRESENT:

Isolated System Domains

Traditional Domains:
Automotive systems engineering is a semi-formal recognized discipline within different automotive domains. The automotive OEMs define their product development processes to include traditional system activities such as requirements decomposition and cascade.

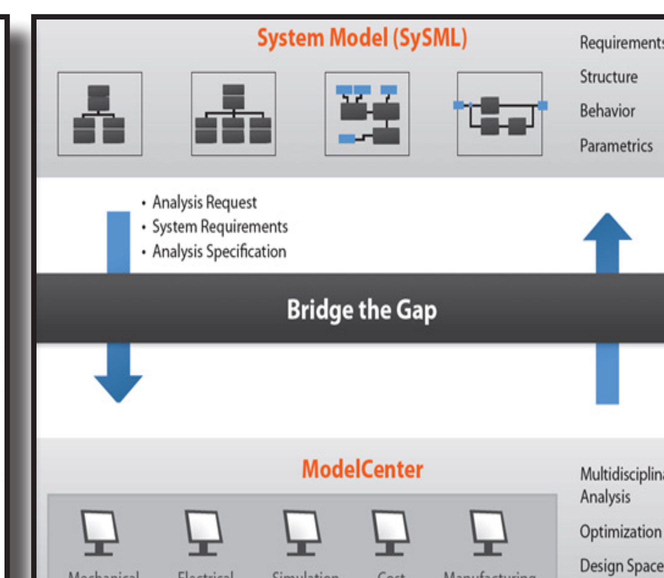
Isolated Subsystems:
At the domain level of chassis, powertrain, body and electrical engineering system activities are typically defined and organized differently. This results in inefficient and sometimes confounding work product sharing and collaboration.

FUTURE:

Collaborative System Domains

Applied Across All Domains:
The desired approach must be able to standardize the practices enabling scalability and exchangeability of work force and information across traditional and non-traditional domains & industries. This is broadly recognized by global economic and business leaders as a distinct value-added discipline related to a wide variety of automotive areas systems and services.

Coordinated Subsystems:
Utilizing cross-functional automotive practitioners results in the sharing and maturation of more robust practices and foundations. The formal standardization of system practices both within the automotive organizations and across adjacent and supplier industries supports the full mobility of the global workforce.



The automotive OEMs define their product development processes to include traditional System engineering activities such as requirements decomposition and cascade.

The lack of recognition as a formal, standardized discipline in, and across these domains has limited the ability of practitioners to share and mature their practices. This results in inefficient and sometimes confounding of work product sharing and collaboration. Recently, the automakers have recognized the need to standardize and operate as a formal discipline across multiple traditional and non-traditional domains such as consumer electronics, transportation, IT infrastructure systems, and biomedical systems.

Automotive systems engineering will also contribute to assessments and analysis of socio-physical systems such as the global climate system to inform stakeholders and decision makers of the emergent impacts of organizational and public policy actions.

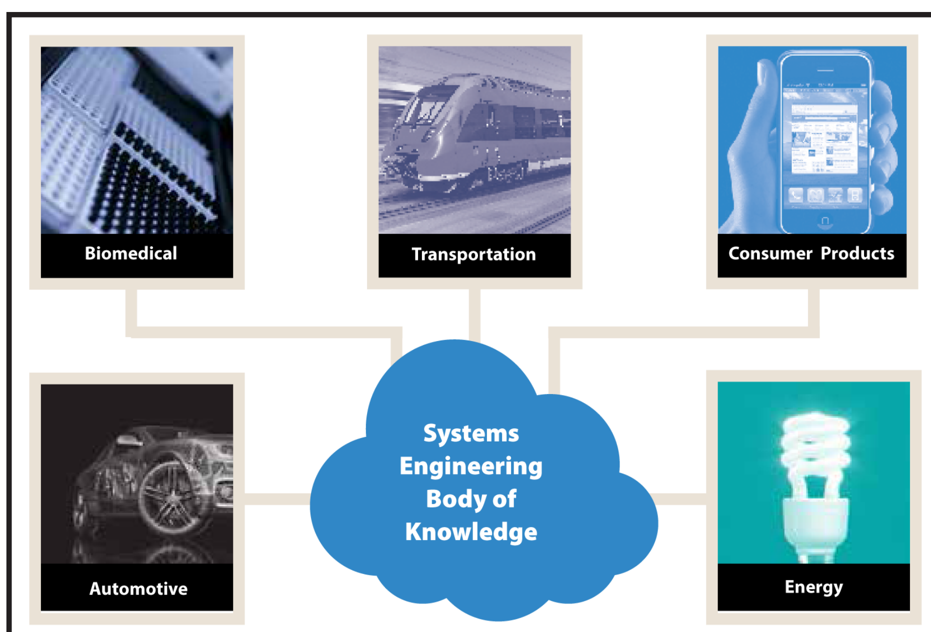
Electrified vehicles and true networks of driving solutions; autonomous vehicles and large scale vehicle sharing infrastructure will position the automotive systems engineer to actively participate and help shape the global dialogue on future. This is broadly recognized by global economic and business leaders as a distinct value-added discipline related to a wide variety of commercial products, systems and services, as well as government services and infrastructure.

This broad community of practitioners results in the sharing and maturation of more robust automotive systems engineering practices and foundations.

The formal standardization of systems engineering practices both within the automotive organizations and across adjacent industries supports the full mobility of the global workforce.

THE AUTOMOTIVE SYSTEM ENGINEERING DISCIPLINE WILL EXPAND ITS APPLICABILITY AND RECOGNITION ALONG SEVERAL FRONTS

- Non traditional domains such as consumer products, biomedical, health care, automotive, and energy production
- Geographic scope, both regionally and nationally
- Enterprises from small to medium to large
- Governmental projects and policy at international, national and local levels



3.2.2 Applying to Policy Decisions

PRESENT:

Limited Policy Influence

Limited Stakeholder Needs:
Public policy decisions are often made without leveraging a well-defined approach to understand the diverse set of stakeholders' needs and the implications of various policy options.

FUTURE:

Leveraged for Diverse Decisions

Comprehensive Stakeholder Needs
This approach takes its place with other systems related, iterative disciplines such as economics, human ecology, geography and economic anthropology to structure more objective cost-benefit and risk assessments of alternative policy.

Modeling and simulation is widely used to support integrated planning for a better representation of real-world constraints and solutions. Complete extended, automotive ecosystems are modelled to integrate and analyze the design-development-manufacture-sales-service and customer experience lifecycle.

Fully dynamic ecosystem models that provide a rich context of interactive system analysis; providing predictive assessments and optimizations across typically disjoint systems. Capabilities for generating characterizations and visualizations for complex policy issues are greatly improved and are approachable by policy makers and other stakeholders.

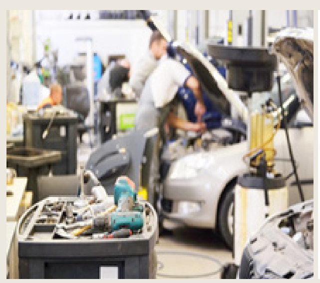
Observational data sources and models are assessed for uncertainty and applicability for specific decision-making needs. Tools and methods better integrate physical and socioeconomic information into holistic and sustainable solutions.

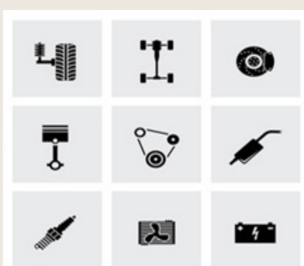
3.3 Transforming

3.3.1 Value Driven Practices for 2025

SYSTEMS ENGINEERING METHODS WILL BE SCALABLE TO SYSTEM AND ORGANIZATIONAL COMPLEXITY AND SIZE, AND TAILORED TO THE APPLICATION DOMAIN. METHOD SELECTION AND ADAPTATION WILL BE VALUE DRIVEN TO OPTIMIZE PROJECT SCHEDULE, COST, AND TECHNICAL RISK. METHODS AND TOOLS WILL SCALE FROM SMALL AND MEDIUM SIZED ENTERPRISES TO MULTI-BILLION DOLLAR PROJECTS.

TAILORED TO THE DOMAIN





SCALED TO PROJECT SIZE

SCALED TO SYSTEM COMPLEXITY

The practices will continue to evolve from those of today to meet the demands of complex systems and work environments of the 21st century. Leveraging information technology and establishing the theoretical foundations for value-driven automotive systems engineering practices will pave the way for meeting these demands to enhance competitiveness, manage complexity, and satisfy continuously evolving stakeholder needs.

The methods will be tailored to the domain and scalable to project and system size and complexity. Collaborative engineering across national boundaries, enterprises, and disciplines will be the norm. The practice will deal with systems in a dynamically changing and fully interconnected system of systems context.

Architecture Design:
Architecture design and analysis practices will enable integration of diverse stakeholder viewpoints to create more evolvable systems. Design imperatives, such as cybersecurity, post-release expendability for product resilience, and security considerations will be built into the solution from the beginning.

Composable design methods will leverage reuse and validated patterns to configure and integrate components into system solutions. Decision support methods will enable the rapid analysis of large number of alternative designs, and optimization of complex systems with multiple variables and uncertainty.

A virtual engineering environment will incorporate modeling, simulation, and visualization to support all aspects by enabling improved prediction and analysis of complex emergent behaviors.

3.3.2 Managing Complex System

PRESENT:

Increasing Complexity

More Complex Behaviors:
Today, automotive customers are demanding increasingly capable, safe, and secure systems giving rise to increased automotive complexity. The increased electrical, software and control system complexity is increasing development time and introducing new and more complex failure modes within the automotive context.

Increasing Software Interactions:
Software & Controls system interaction based failure modes are becoming more predominant over traditional mechanical engineering failure modes. There is broad recognition that there is no end in sight for the growth in vehicle-system complexity.

FUTURE:

Managing Complexity Growth

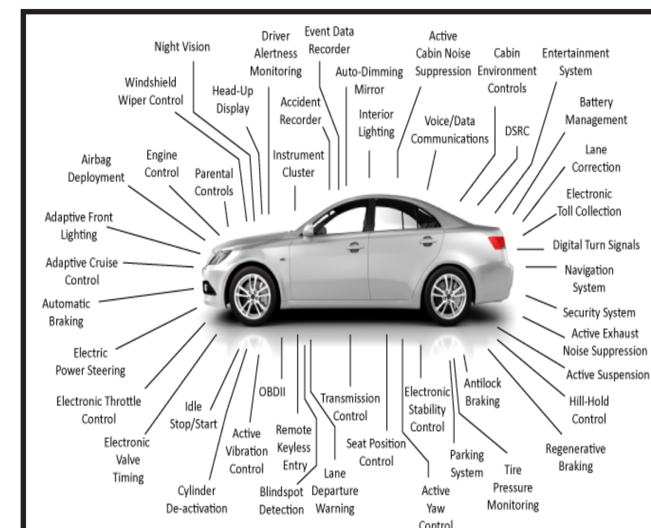
Identify Unanticipated Behaviors:
In 2025 and beyond, standard measures of complexity will be established; methods for tracking, handling, and mitigating complex system behaviors will be commonplace. The practices will include both formal and semi-formal methods for identifying emergent and unanticipated behaviors. Understanding & managing this complexity growth is fundamental to the OEMs success.

Integrated/Modeled Software Interactions:
MBSE will be a fundamental integrated capability that will be used to design, evaluate, assess, and produce new feature and function content.

Reuse strategies will become key to managing complexity; architecture views/perspective, design patterns, product line engineering and contextual information methods will underpin complexity management approaches.

Analytical techniques will be commonly used to explore huge system state spaces to identify and eliminate undesirable system states.

Techniques will be developed to correlate a diverse range of system parameters as indicators of system health, similar to how a person's temperature and white blood count are used to indicate the presence of an infection. Developing systems that are more tolerant, secure, robust, resilient, and adaptable will be a fundamental part of these practices in order to capitalizing on this understanding."



3.3.3 Applying Automotive Functional Safety

PRESENT:

Ensure Functional Robustness

Unknown Hazards of Sophisticated Features: Today EE-SW & Control systems are delivering sophisticated and complex features that balance the trade-off between performance, function, efficiency, & safety. These highly interactive system designs, while complex, only represent the beginning of large system of Systems.

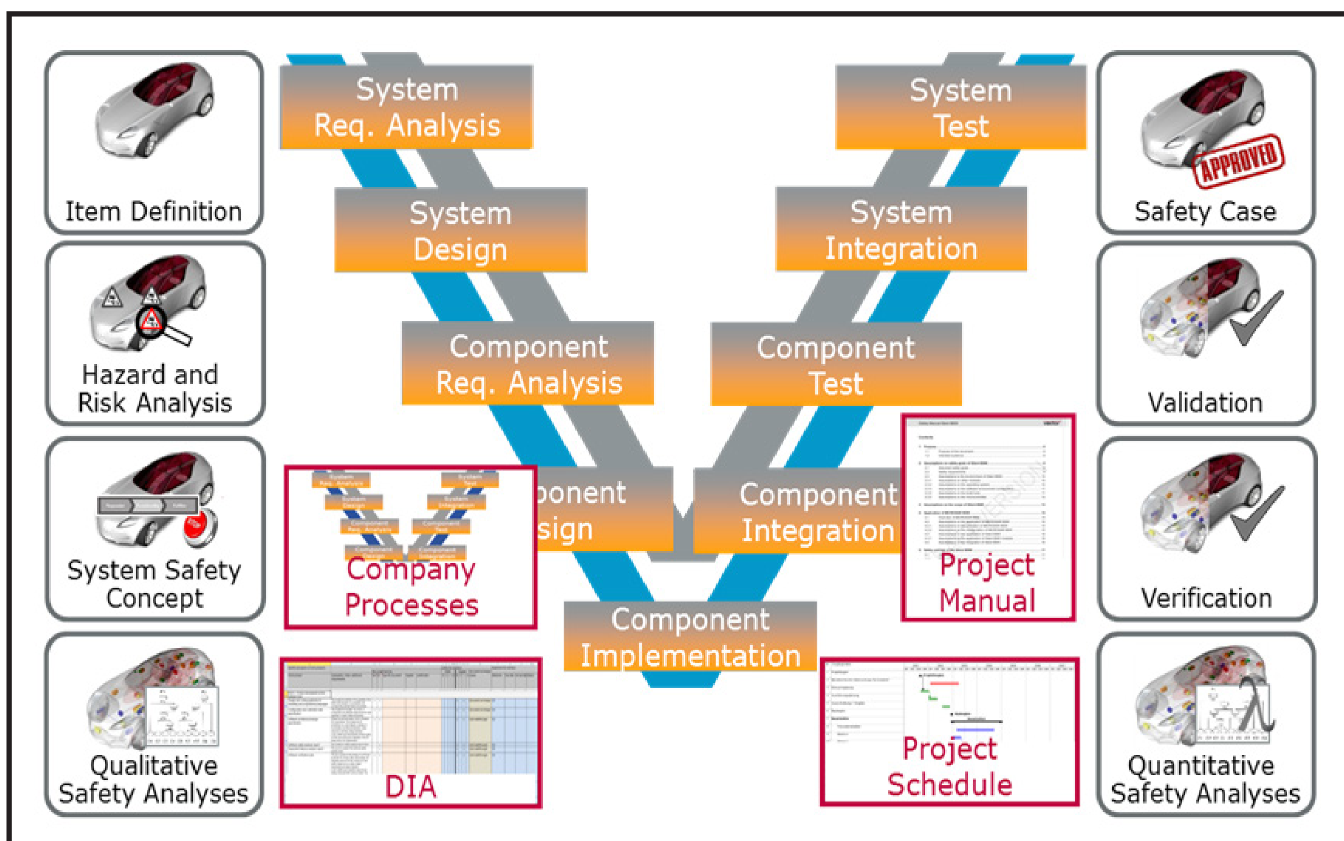
Reduced Effectiveness of Traditional Reliability: Recognition that traditional reliability and robustness tools are not as effective on complex software intensive systems.

FUTURE:

Standardize Functional Safety Method

Formalized Hazard based Risk Assessment: In 2025 and beyond standard controls based system safety analytical practices are in place. Large scale software intensive autonomous vehicle systems are developed using holistic system-theoretic accident models combined with hazard based risk assessment techniques that leverage traditional reliability tools.

Formalized Simulation Environments: Large scale, integrated simulation environments; Model in the Loop (MIL), Software in the Loop (SIL), Processor-in-the-Loop (PIL) and Hardware-in-the-Loop (HIL) are used extensively to confirm safe system operational behaviors.



The approach to automotive system safety will require the adoption of existing best practices within standards such as ISO26262 and enhanced methods such as MIT's STAMP/STPA process. The Systems Engineering analysis and practices will include both formal and semi-formal methods for identifying emergent and unanticipated behaviors.

These best practices will be integrated into a model based systems engineering environment allowing the analysis to be performed directly on a system model with full traceability.

Analytical techniques will be commonly used to explore huge system state spaces to identify and eliminate undesirable system behaviors.

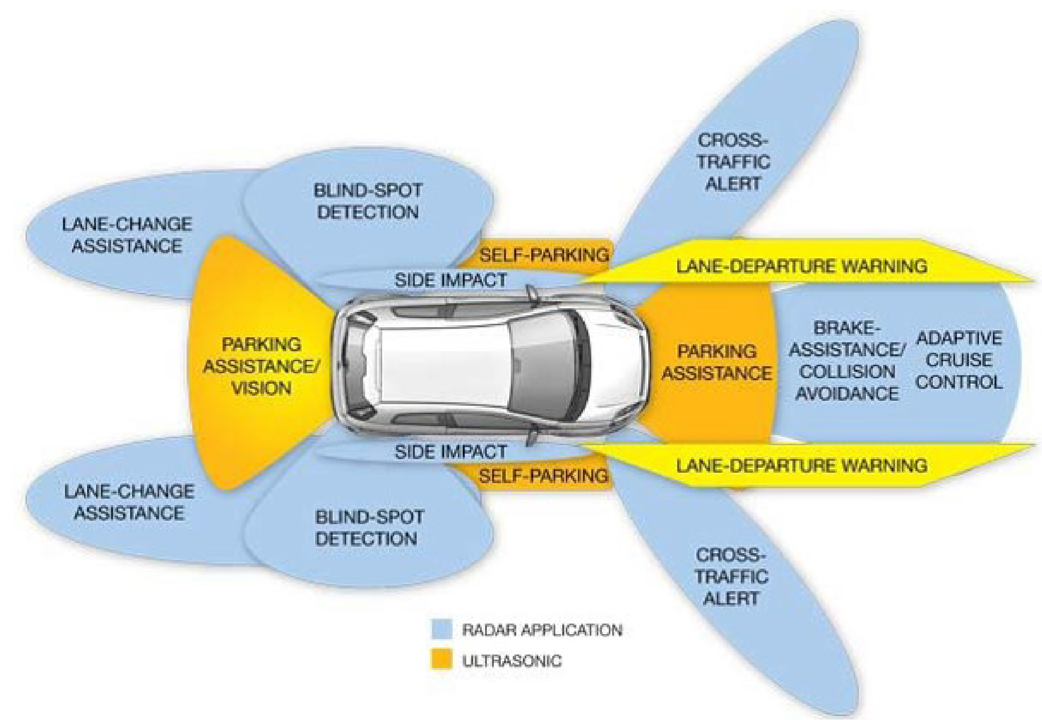
Capitalizing on this understanding to develop systems that are more fault tolerant, safe, secure, robust, resilient, and adaptable will be a fundamental part of automotive systems engineering practices:

- Organized simplicity (analytic reduction)
- Unorganized complexity (probabilistic/statistics)
- Organized complexity (SW systems) -systems theory

The increasing trend to develop advanced control systems that leverage sensor fusion and feature/function integration will require innovative design and analysis techniques to ensure system operational integrity. The images below illustrate the successive incremental use of different sensor technologies within the automated driving domain.

3D Sensor Technologies:
The total system leverages radar, lidar, sonar and ultrasonic sensors to monitor the surrounding environment and "map" out a detailed 3D space. These sensor technologies have different functional capabilities, failure modes and operational spaces. Traditionally each sensor technology would have been developed with an associated set of functions and calibrations. Over several development cycles the engineering teams would gain experience in how these "Features" operated, failed and could be maintained in the field.

With the next generation of sensor technology the engineering team would typically pilot a vehicle system with a combined set of "Features" that leverage both sensor technology sets. This approach would provide an opportunity for the engineering team to obtain experience with the integrated sensor-feature system before high volume production



application.
We are now seeing, more and more, the need to develop multiple technologies/sensor- feature sets that must be developed, integrated and rolled to volume production in shorter time frames. This consumer and regulatory driven demand for high capability safety and environmentally friendly systems has advanced the production development beyond the capability of traditional engineering analysis tools. There is an urgent need for systems engineering based analytical toolsets that support systems engineering science and the development of complex, highly distributed, service based embedded and non-embedded solutions.

In the sensor migration illustrated in the automated driving system figures there are a series of new complex hazards and failure modes that must be identified, analyzed, mitigated or eliminated with design countermeasures.
The next level of complexity will require a combination of both formal method analysis and simulation based virtual use-case testing. The ability to identify and analyze the fundamental hazards and failure modes will need to be augmented with the ability to virtually exercise the design countermeasures over a massive in-vehicle and off-vehicle use case driven space. Also key will be the ability to both virtually drive a vehicle as a participant in a set of vehicles (i.e. platooning) and as a solo vehicle operating within a larger infrastructure and the associated cloud-based dataset.

3.3.4 Leveraging Technology to Enhance Tools

PRESENT:

Limited Office-Based Tools

Reduced Capability of Office Applications:
Current tools leverage computing and information technologies to some degree and make heavy use of office applications for documenting system designs.

Isolated Domain Based Tools:
Some OEMs that have integrated EE, Software and Control systems toolsets to manage data across the cyber-physical domain (ref Davey et al). Each domain typically has developed toolsets within that domain for local optimized development.

Limited Simulation & Visualization:
The tools of 2025 will facilitate practices as part of a fully integrated engineering environment. The full integration of toolsets across the functional-CAE space and integrated with the connected services ecosystem.

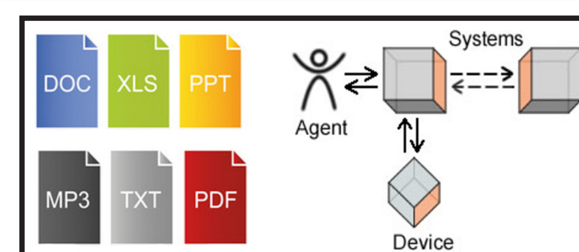
FUTURE:

High Fidelity Multi-level models

Leverage Simulation, Visualization, & Collaboration:
The tools will support high fidelity simulation, immersive technologies to support data visualization, semantic web technologies to support data integration, search, reasoning, and communication technologies to support collaboration.

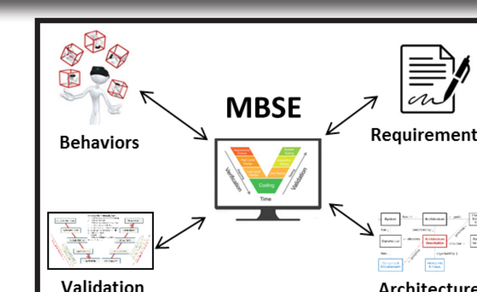
Expanded Domain via Internet-based Connectivity:
The tools will benefit from internet-based connectivity and knowledge representation to readily exchange information with related fields. The tools will integrate EE, SW, and Controls, CAD/CAE/PLM environments, project management and off-vehicle service systems into the larger ecosystems

Facilitate Multi-Level Simulation Tools:
This will facilitate a truly immersive workflow and data interaction across a broader enterprise to SoS environment. The future will be highly skilled in the use of multi-level, multi domain,



- Domain limited technology office-driven systems engineering tools.
- limited collaboration sharing of office documents.
- Office based isolated visualization.

shared drive based computing supports limited sharing and across cyber-physical local domains



- Technology driven systems engineering tools
- Net-enabled tools support collaboration.
- Immersive technologies support data visualization.

Cloud-based high performance computing supports high fidelity system simulations. Advanced query, and analytical methods to support system reasoning..

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3.3.5 Integrating Collaborative Engineering Teams

PRESENT:

Processes not Well integrated

Un-integrated Multi-disciplines:
Today processes are often not well integrated with program management and discipline-specific processes such as hardware, software, test, manufacturing, operations, and logistics support.

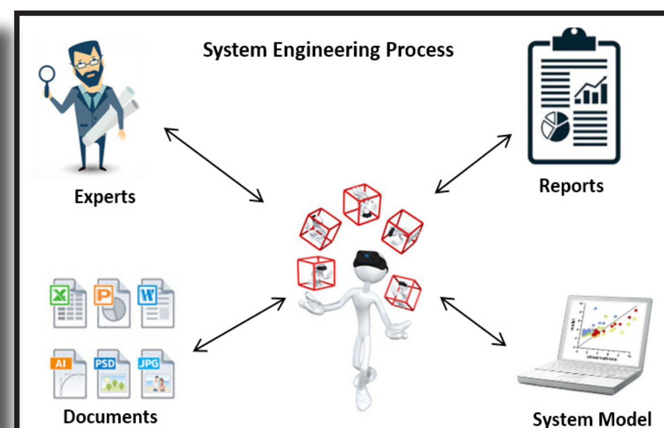
Inefficient Change Management:
As an example, program and product change processes require time consuming and manual coordination among development teams and supply chain participants.

FUTURE:

Integrated Collaborative Processes

Integrated Team & Organization Workflows:
In 2025 and beyond this will be a key integrator role for collaborative enterprise engineering that span regions, cultures, organizations, disciplines, and lifecycle phases. This will result in multi-disciplinary engineering workflows and data being integrated to support agile program planning, execution, and monitoring.

Efficient Collaborative Change Process:
The collaboration will extend across the supply chain so that customers, primes, subcontractors, and suppliers are integrated throughout all phases of development.



Automated workflow, data integration, and networked communications are critical to agile program execution, such as when implementing a global change process.

3.3.6 Designing within System-of-Systems Context

PRESENT:

Limited connected Systems

Limited Guidance for System of Systems:
Limited technical guidance is available to engineer complex systems of systems and assure qualities of service.

Emphasis on IT bases Architecture:
Current emphasis is on IT based architecture frameworks and interoperability standards.

FUTURE:

Connected Internet of Things (IoT)

Guidance for Interconnected Systems:
The Internet of Things extends the SoS challenge beyond inter-connected computers and users, to include interconnected systems and devices that monitor & control everything from household appliances to automobiles.

Diverse Stakeholder Architectures
Diverse stakeholders must demand SoS to provide information & services leveraging value from the pieces.

SYSTEM OF SYSTEMS ENGINEERING PRACTICES:
Automotive System of Systems Engineering (ASoSE) methods will be used to characterize and evolve the SoS, and include design for interoperability, extensibility, and maintainability. Importantly new analysis and prediction methods will be employed to identify emergent behaviors and ensure quality of service. Continuous build and verification methods will be used to continually monitor emergent system characteristics and attributes. These will be managed and integrated into a robust SoS solution that is instantiated using context aware dynamic build controls.

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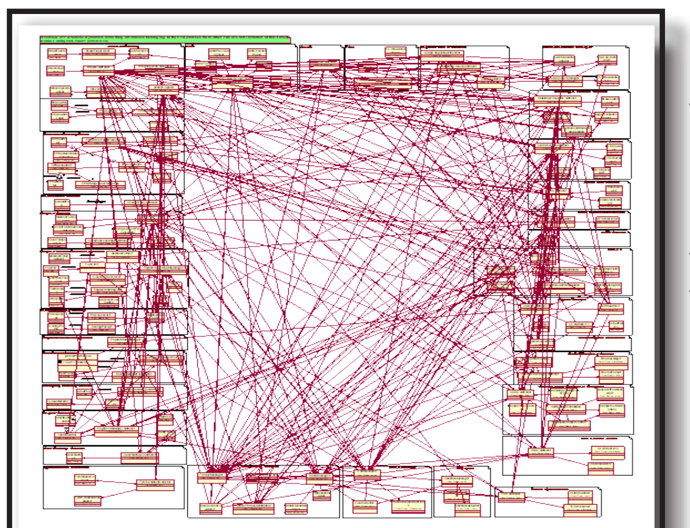
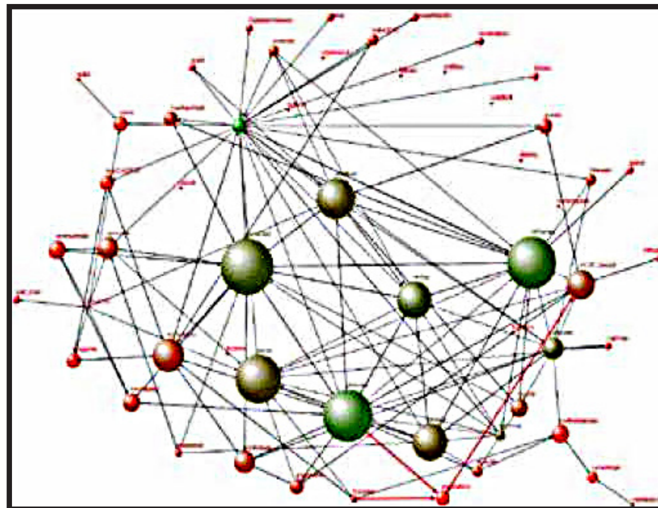
Mobile platforms are already widely used as a feature rich navigation and communication tool. Connecting a smart phone to the vehicle system and accessing both in-vehicle data and external cloud-"big data" provides endless possibilities for systems analysis and innovation. Connected cars are the next big platform for application developers.

Analyze Interactions:
Techniques for analyzing interactions among independent systems and understanding emergent behaviors in SoS must mature and become common-place (e.g., agent based simulation). New measures will be developed to characterize the SoS and its quality characteristics. ASoSE will employ new continuous verification methods as changes occur without central control. Design of experiments is one such methodology for optimizing a verification program with many parameters and uncertainty. Requirements management will evolve to address even more diverse stakeholders, in the face of uncertain organizational authority. Methods for establishing evolutionary interoperability agreements among SoS constituents will become more robust.



Model Based techniques will be required to capture, communicate and track complex system designs. Standards such as the SysML language will become important to provide a framework for cross domain model collaboration. Extensions to the standard will be created to provide specialized views for activities around functional safety, quality, and architecture design and parameter analysis. Tools will



"A SOS is an intergration of a finite number of constituent systems which are independant and operable, and which are networked together for a period of time to achieve a certain highr goal."

- Jamshidi, 2009

be needed that enable SysML model based complex simulations. Modeling tools will be required that support the definition of simulation configurations involving multiple modeling constructs. Simulation engines will need to manage co-simulations that include detailed co-simulation execution clock synchronization.

System Architecture design will become key to the definition of reusable assets that are easily configured into ever expanding feature rich customer products. The notion of software feature delivery over time will become common practice, even within the gated, milestone driven product delivery world of the automotives.

3.3.7 Architecting to Address Multiple Stakeholders

PRESENT:

Limited Ad-hoc Architecting

Ineffective Architecting and Integration:
Systems architecting is often ad-hoc and does not effectively integrate architectural concerns from technical disciplines such as hardware, software, and security, nor does it fully integrate other stakeholder concerns.

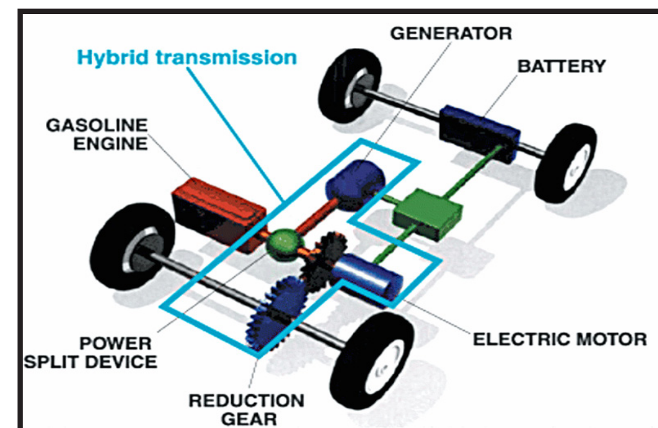
Reduced Traceability and Views:
Today's methods allow reduced traceability and view across disciplines and stakeholders.

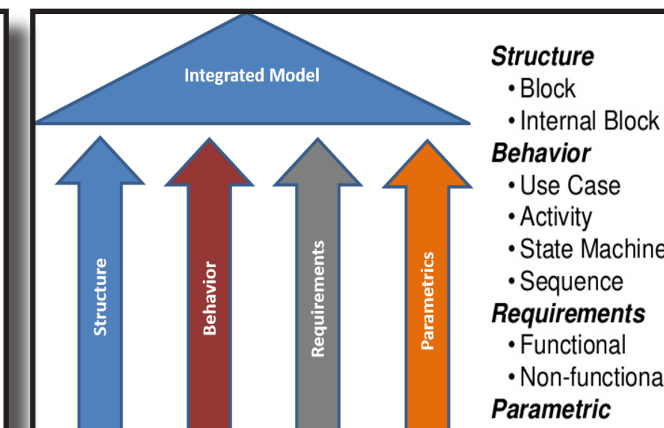
FUTURE:

Architecting cross disciplines & stakeholders

Effective Integrated System Representation:
Systems architecting methods that are well established and address broad stakeholder concerns associated with increasingly complex systems. System architecture, design and analysis is integrated across disciplines, domains and lifecycle phases to provide a single, consistent, unambiguous, system representation.

Enhanced Traceability and Views:
This ensures integrity and full traceability throughout the process, and provides all stakeholders with multiple system views to address a broad range of concerns.





Compos-able design methods in a virtual environment support rapid, agile and evolvable designs of families of products. By combining formal models from a library of component and context models, different system alternatives can be quickly compared and probabilistically evaluated.

Composable design and analysis provides a structured mechanism for capturing and reusing organizational intellectual property including component designs, test data, verification analyses and production capabilities.

Composable design approaches are industry best practices in commercial electronics and building design, and will be adopted more broadly by the community to drive cost effective solutions.

3.3.8 Architecting Resilient Systems

PRESENT:

Limited Fault Resistant Architecting

Inadequate Fault Architecting Practices:
Fault detection, isolation, and recovery is a common practice when designing systems so they can recover from failures, and/or off nominal performance and continue to operate.

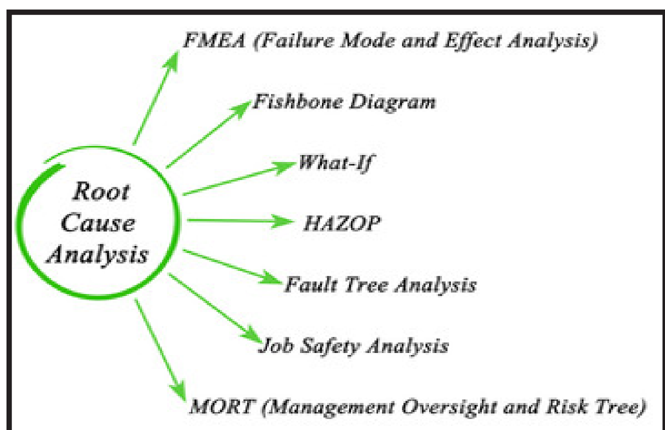
Fault Detection Based on Abnormal Behavior:
Fault detection is based on a prior designation and characterization of off-nominal behavior.

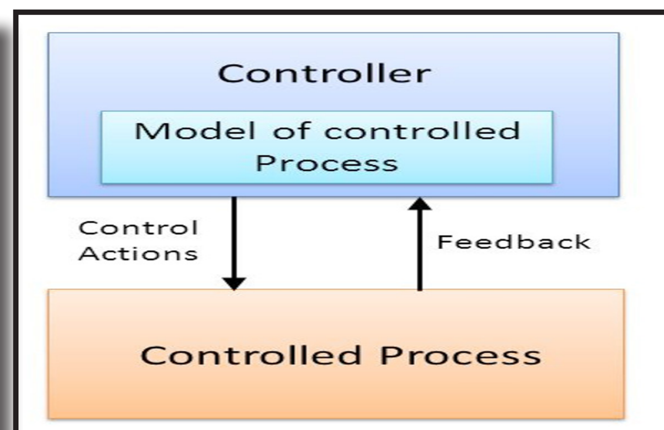
FUTURE:

Early Fault Resistant Architecting

Design Architecture for Intended Function:
Architecting will incorporate design approaches for systems to perform their intended function in the face of changing circumstances, invalid assumptions and system wide sensor contentions.

Safety Design Principles:
Automated and autonomous vehicles will leverage architectural safety and security design principles that build on aerospace and military best practices and extend these with system-theoretic accident models and processes (STAMP) ref Leveson, MIT



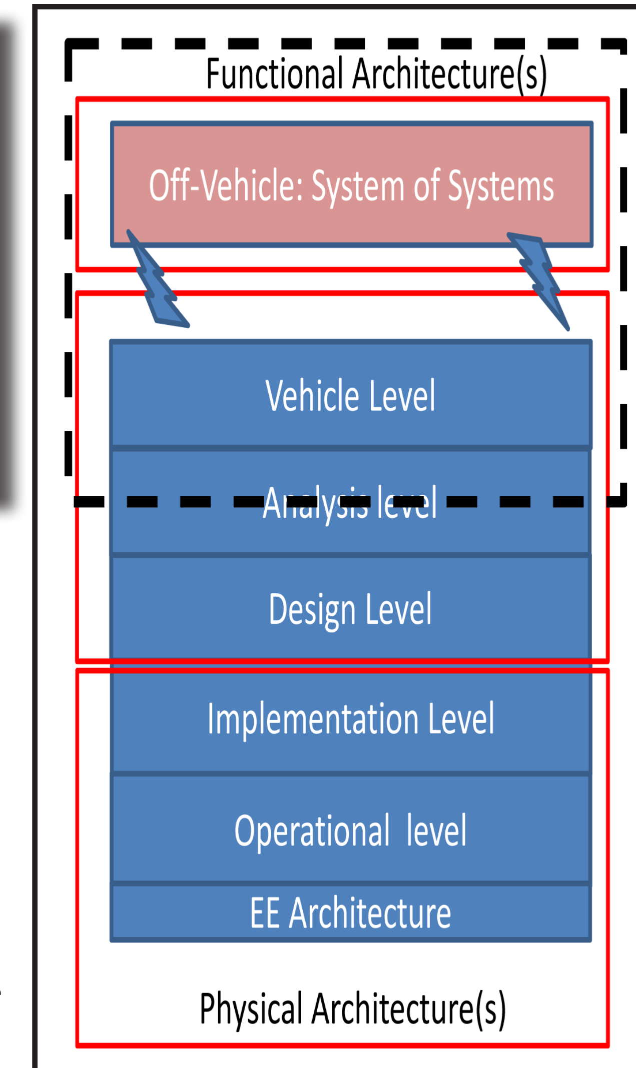


The deployment of autonomous vehicles in transportation and delivery systems illustrates the need for resiliency. Autonomous vehicles, especially those that operate in inhabited areas, must be designed to be robust to operate in a wide range of environmental conditions, adaptive to unexpected conditions, and capable of recovering from failure conditions. In this example, the vehicle must be capable of assessing its current state and the state of its environment, and develop strategies to recover and return to normal operations.

The delivery system must be tolerant to invalid assumptions related to conditions such as:

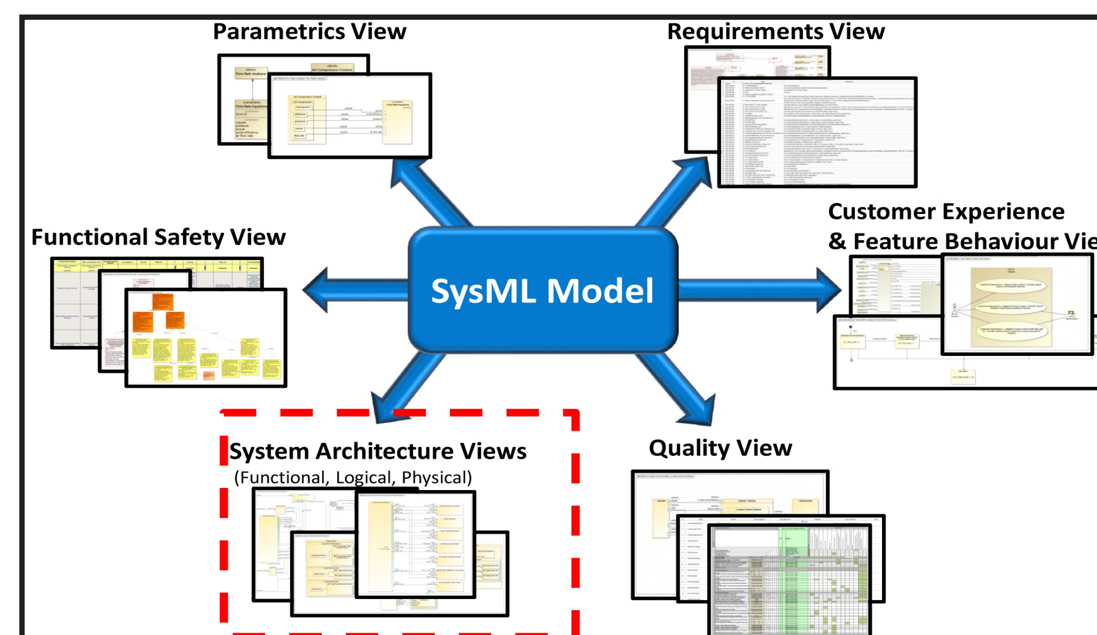
- Weather conditions
- Traffic congestion
- Inanimate surface hazards

The increased use of Architecture Analysis and Reference Architectures will be required to support robust development and delivery of increasing complex vehicle systems. The traditional vehicle architecture layers will be augmented with an off-board layer that facilitates the communication and elaboration of ecosystem services and controls.



Communication Standards:
New communication standards and protocols may be required to ensure consistent and robust exchange of data between the on-board systems and the off-board services. If external control logic is realized then the need for real-time levels of dynamic capability will become required.

Analysis tools based on standards like SysML will need to be developed and extended to manage the engineer's ability to model and analyze these new complex SoS. Domains and analysis specific extensions will be needed and implemented as standards to enable cross industry alignment and reuse.



3.3.9 Securing the System: Cybersecurity

PRESENT:

Isolated Limited Cybersecurity

Evolving Security Challenges:
Systems, personal, and national security are increasingly being compromised due to the digitally interconnected nature of our infrastructure. Engineers are hard pressed to keep up with the evolving nature and increasing sophistication of the threats to our cyber-physical systems.

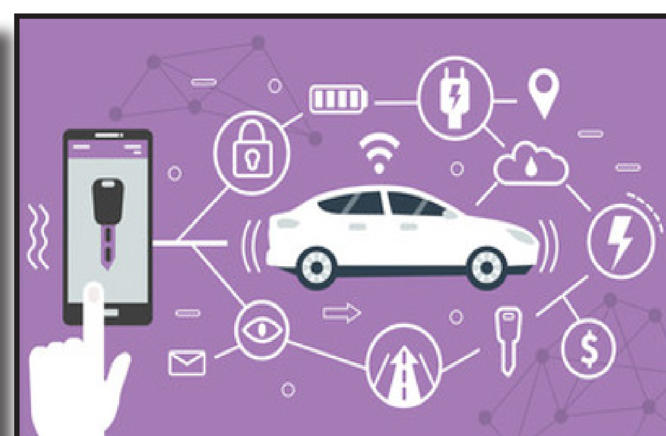
Uncomprehensive & Post Design Cybersecurity:
Cybersecurity is often dealt with as an IT infrastructure problem and not an in-vehicle malicious attack to gain access to vehicle system resources. The design of resilient vehicle- ecosystem solutions typically takes place after original vehicle designs are frozen.

FUTURE:

Early Cybersecurity Analysis & Simulation

Early Development Lifecycle Cybersecurity Analysis:
The activities that routinely incorporates security analysis and resulting requirements early in the design stages. Cyber defense capabilities are continually assessed and validated over the full vehicle development lifecycle. In addition, ecosystem infrastructure security analysis takes place asynchronously to the vehicle program development.

Comprehensive Pre-design Integrated Cyber Toolsets:
Fully integrated simulation toolsets enable probabilistic attack scenarios to be based evaluated using different product-infrastructure design strategies. Cyber-physical security is a fundamental system attribute that systems engineering understand and incorporate into designs using the strategies further outlined.



Addressing security concerns in modern systems and systems of systems requires understanding the boundary of the system and analyzing what portions of that boundary need to be protected. This protection comes at a price, often with systems engineering needing to trade performance for security.

Understanding and characterizing threats, the system boundary, and trades among key performance parameters and security, is critical for achieving the right balance of security and overall capability.

3.3.10 Leveraging Data-driven Decision & Analysis

PRESENT:

Ineffective Decision Support

Ineffective Limited Design Alternatives:
Systems engineers explore a limited number of design alternatives primarily based on deterministic models of performance, physical constraints, cost, and risk.

FUTURE:

Comprehensive Broad Deterministic Models

Explore & Leverage Wide-ranging Alternatives:
Rapidly explore a broad design space of alternatives to maximize overall value, primarily based on deterministic models of performance, physical constraints, cost, and risk based on a comprehensive set of measures including performance, security, cost, and risk.

Decision support tools must comprehensively support each aspect of the decision making process. Through composition of reference components and scenarios, a much broader set of system architectures will be defined and considered.

A decision support dashboard will assist the systems engineer in using sensitivity and uncertainty analysis to analyze a system design from all relevant perspectives across the entire lifecycle. While adding fidelity to models, adapting modeling formalisms, and combining multiple concurrent modeling efforts, systems engineers will be able to perform increasingly detailed trade studies and analyses.

Optimization tools will be used broadly, taking advantage of the vast, inexpensive computing resources in the cloud to identify system alternatives that are most likely to maximize lifecycle value under uncertainty.

Visualization tools will enable interactive analysis from many different stakeholder-specific viewpoints, allowing decision makers to gain new insights, perform what-if analyses, and make decisions with confidence.

3.3.11 Applying Virtual Engineering

PRESENT:

Uncoordinated Modeling

Disconnected MBSE Practices:
Automotive systems engineering practice leverages model based simulation in a disjoint manner.

Limited Domain-based Analysis:
Each domain area creates and uses project specific simulations to analyze and develop project specific attributes.

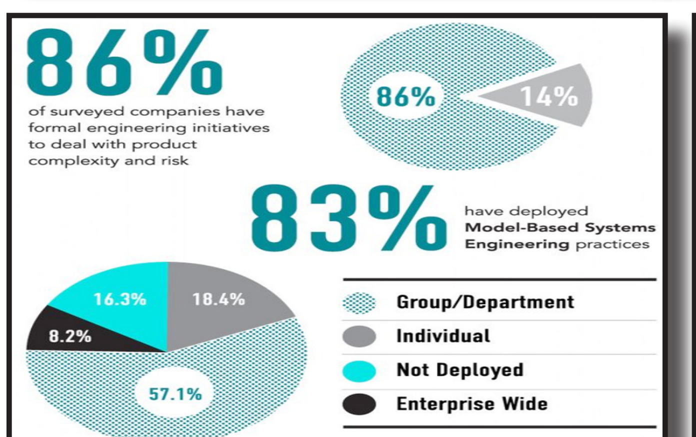
Redundant Modeling
Lack of a model management system or process for collecting model needs, clearly defining scope/purpose, and curating these models over time leads to redundant single-purpose models delivered late and with limited reuse potential.

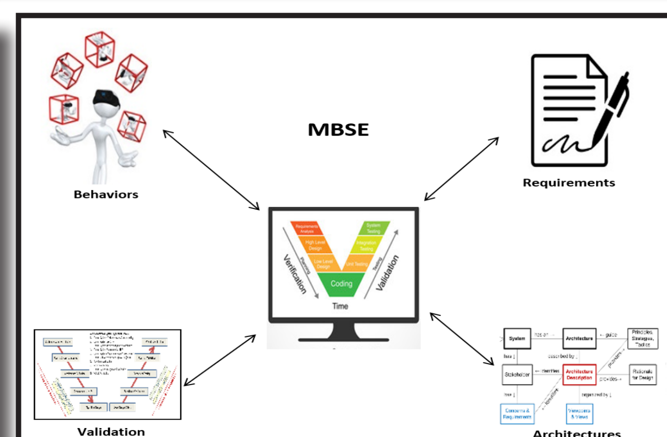
FUTURE:

Coordinated System Modeling

Connected Broad Spectrum Models:
Formal systems modeling is standard practice for specifying, analyzing, designing, and verifying systems, and is fully integrated with other engineering models. Generic, corporate models will be configured and adapted to meet the needs of the application specific domain. They will include a broad spectrum of models for representing all aspects of the system under study.

Shared Internet-driven Virtual Information:
The use of internet-driven knowledge representation and immersive technologies enable highly efficient and shared understanding of systems. In this virtual environment an engineer can potentially analyze a system across the full lifecycle from concept through development, manufacturing, operations, and support.

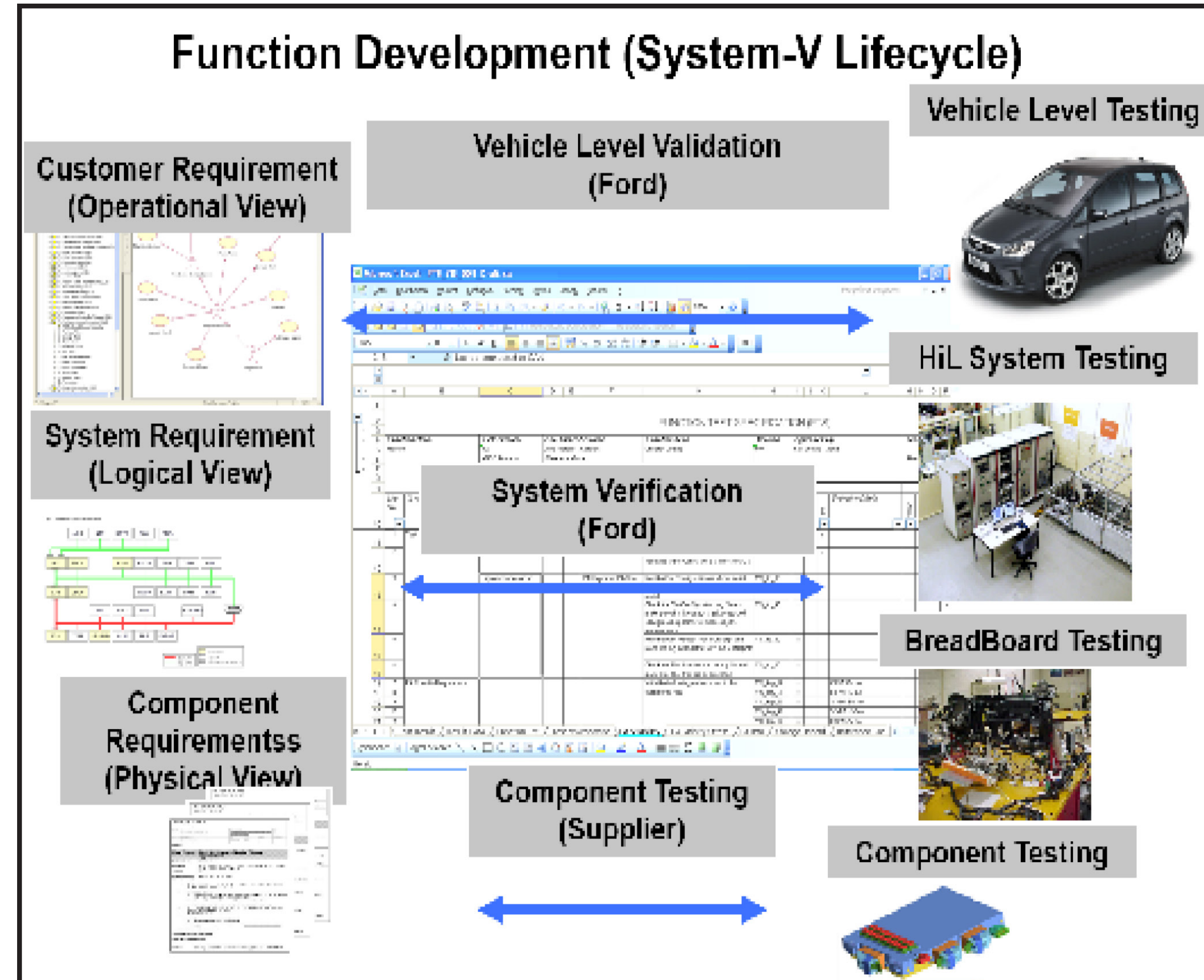




Systems modeling will form the product-centric backbone of the digital enterprise which incorporates a model-centric approach to integrate technical, programmatic, and business concerns. Model-based approaches will extend beyond product modeling to enterprise-level modeling and analysis.

Tool suites and visualization capabilities will mature to efficiently support the development of integrated, cross-disciplinary analyses. These analyses include design space exploration and optimization, interface analysis, comprehensive studies, of customer and market needs, requirements and architecture reviews, operational process analysis, and next-generation servicing solutions.

Model-based approaches will move engineering and management from paper-based to a more efficient



paperless environment, permitting the systems' capture, review and design phases to cohesively occur in digital form."

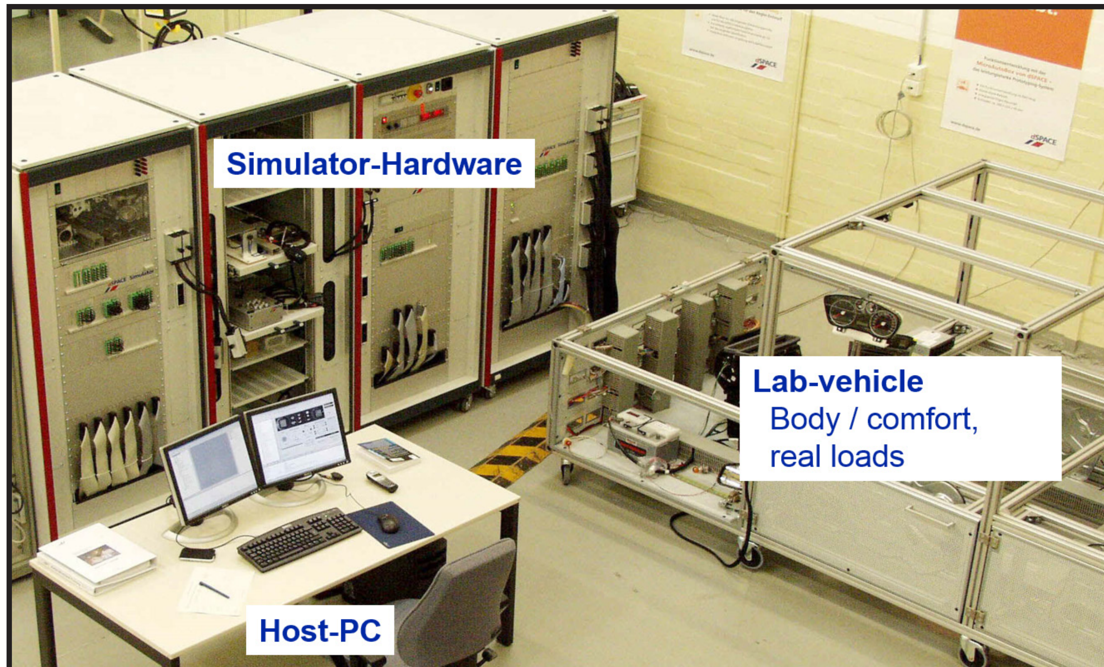
Model-based approaches will enable understanding of complex system behavior much earlier in the product lifecycle. Model-based visualization will allow seamless navigation across related viewpoints such as system, subsystem, component, as well as production and logistics.

Models will be used not only to capture design but to embody design rationale by linking design to top level customer and programmatic concerns.

Large scale virtual prototyping and virtual product integration based on integrated models will lead to significant time-to-market reductions.

Simulation and Visualization:
Modeling, simulation, visualization enable complex system understanding that helps engineers anticipate and verify solutions and their cost before building them. As systems become more complex, understanding their emergent behavior due to increasingly complex software, extreme physical environments, net-centricity, and human interactions becomes essential for successful systems development.

Integrating Model-Based Approaches:
Model-based Systems Engineering must become the "norm" for systems engineering execution with specific focus placed on integrated modeling environments. These system models must go "beyond the boxes", incorporating geometric, production and operational views. These integrated



models will reduce inconsistencies, enable automation and support early and continual verification by analysis.

Transforming Virtual Model to Reality:
A shift towards an integrated, digital engineering environment enables rapid transformation of concepts and designs to physical prototypes through the application of additive manufacturing technologies, such as 3D printers. This capability enables engineers to rapidly and continually assess and update their designs prior to committing costs to production hardware. The Boeing 777 virtual design process established a point of departure for the future of highly integrated, virtual design and production. Systems engineering practices will leverage this capability to rapidly assess alternative designs in terms of their form, fit and function.

3.4 Foundations, Roles and Competencies

3.4.1 Theoretical Foundation, System Science, and Body of Knowledge

PRESENT:

Weak Theoretical Connection

Limited Scientific Based Methods:
Automotive systems engineering practice is only weakly connected to the underlying theoretical foundation and educational programs focus on practice with little emphasis on underlying theory.

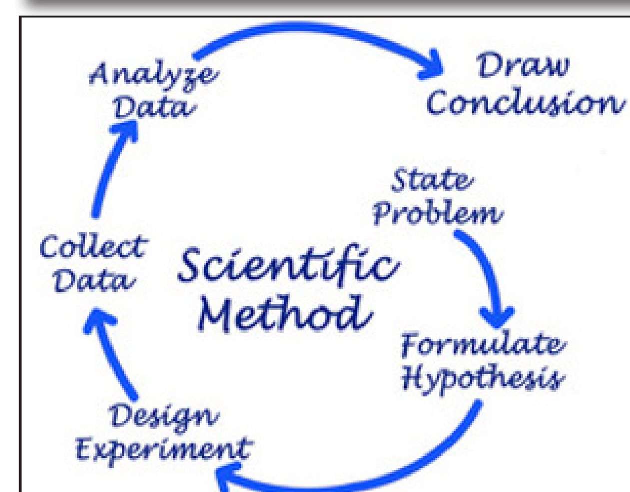
Underdeveloped Theoretical Foundation:
Underdeveloped theoretical foundation which should be built on systems science to expand our understanding of the system under development and of the environment in which it operates.

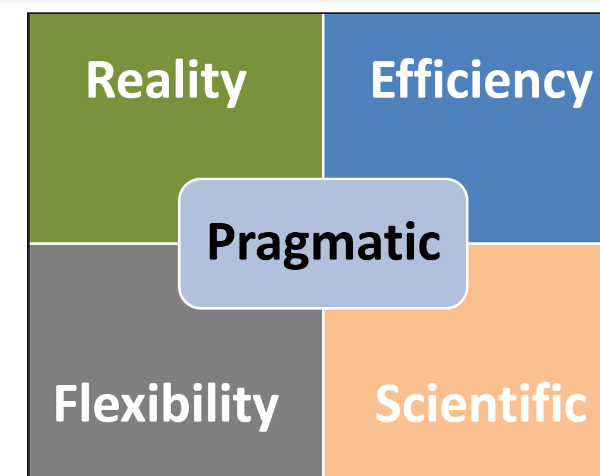
FUTURE:

Strong Scientific Methods

Apply Scientific Based Methods:
The theoretical foundation will provide a scientific basis for improved methods that must be both rigorous and pragmatic. It must allow for effective adaptation of practices to ever increasing system complexity, to a broad range of new applications.

Develop Scientific Foundations:
The foundations will encompass the mathematics of probability, decision, and game theory to ensure methods lead to the selection of a system design that maximizes value under uncertainty.

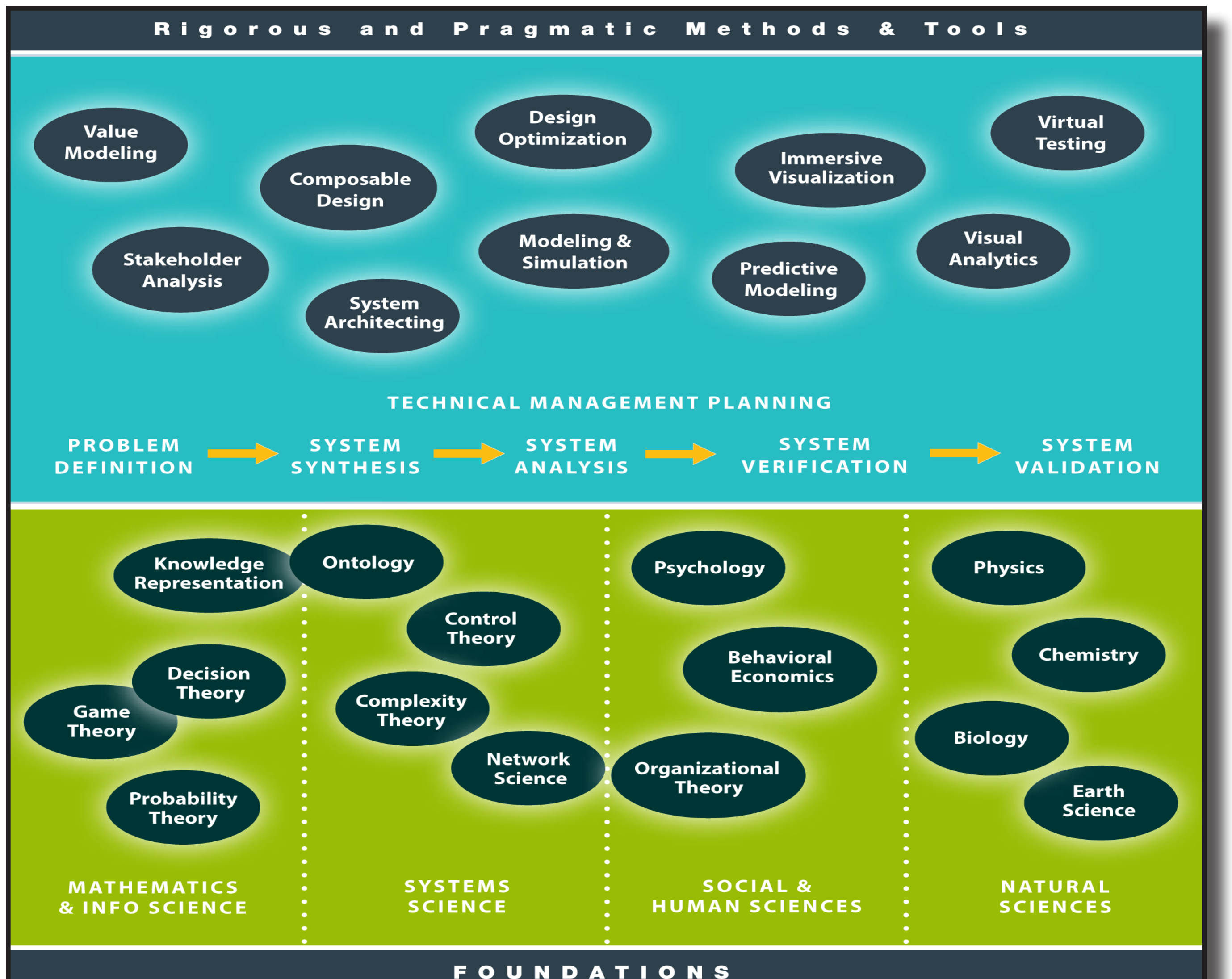




The theoretical foundation will provide a scientific basis for improved methods that will be both rigorous and pragmatic. This foundation will allow for effective adaptation of automotive systems engineering practices to address ever increasing system complexity, a broad range of new application domains, and new enabling technologies increasing system complexity, to a broad range of new application domains, and to new enabling technologies. The theoretical foundation will build on systems science to expand our understanding of the system under development and of the environment in which it operates. The foundations will encompass the mathematics of probability theory, decision theory and game theory to ensure methods lead to the selection of a system design that maximizes value under uncertainty. In addition, social, organizational and psychological sciences will support the development of automotive systems engineering methods and tools that are in tune with human nature.

Building on Body of Knowledge
Systems engineering knowledge and best practices will be grounded in a more rigorous foundation of mathematics and science. In addition to this common foundation, the knowledge and best practices will be defined and codified in domain-specific user guidelines and industry standards.

Develop Systems Science
Systems increasingly derive their behavior from complex interactions between tightly coupled parts, covering multiple disciplines. It is therefore important to develop a scientific foundation that helps us to understand the whole rather than just the parts, that focuses on the relationships among the parts and the emergent properties of the whole systems science seeks to provide a common vocabulary (ontology), and general principles explaining the nature of complex systems.



3.4.2 Broadening the Role

PRESENT:

Limited Depth and Breadth

Varied System Engineering Roles:
The competency of today's system engineer vary significantly in the depth and breadth of their knowledge.

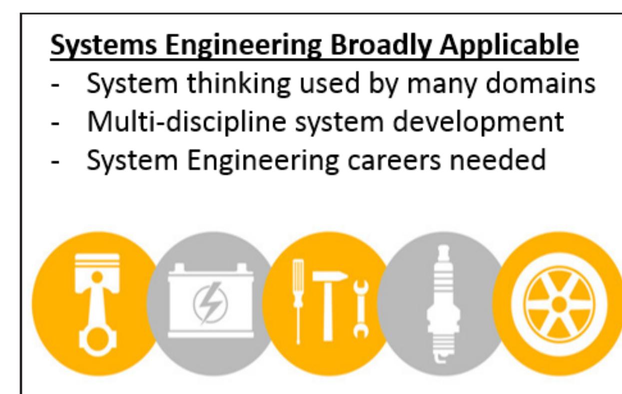
Isolated Domain-based Backgrounds:
Their competencies are often based on their domain specific engineering background, an understanding of the specific practices that are employed at their organization, and the lessons learned from applying this approach on projects.

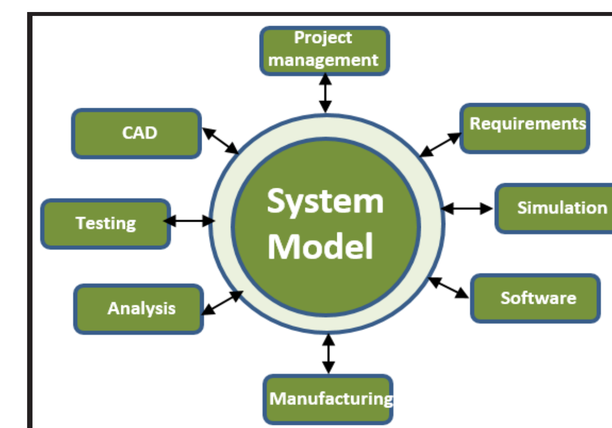
FUTURE:

Span Broader Disciplines

Establish Leadership in Diverse Environment:
The "systems architect" and "systems technical lead" roles will be well established as critical to success. These roles also support and integrate a broader range of socio-technical disciplines, technologies, and stakeholder concerns.

Span Global Disciplines and SoS Boundaries:
The system engineer will integrate concerns that span global and cultural boundaries as well as SoS boundaries. This role will encompass better understanding of emergent behaviors associated with system interdependence and human interactions.





All engineers will benefit from being systems thinkers. To this end, they should all have some education and training in systems and Automotive Systems Engineering. Formally designated systems engineers should be well-versed in a broad set of socio-technical and leadership skills beyond the technical, serving as a central, multi-disciplinary focal point for systems development. Systems engineers will continue to benefit from being "T-shaped" in that they possess deeper knowledge and experience in one or a couple domains but have a horizontal component that maintains credibility and fosters collaboration on a multi-disciplinary project.

3.4.3 Establish Essential Competencies

PRESENT:

Varied Competency Knowledge

Inconsistent Competency Definition:
The competency of today's automotive systems engineer vary significantly in the depth and breadth of their systems engineering knowledge.

Conventional Methods & Practices Applied:
Their competencies are often based on their do-main specific engineering background, an understanding of the specific practices that are employed at their organization, and the lessons learned from applying this approach on projects.

FUTURE:

Standardize System Competencies

Broadened & Consistent Competencies:
The expected competencies will be more consistently defined and broadened to support to the expanded role of systems engineers. The competencies will include leadership skills specifically tailored for working with diverse organizational, physical and cultural boundaries. They will also need accelerated project based learning opportunities to enable mastery of competencies.

Formal Methods Applied to Software/ Hardware:
Expected competencies will include regular use of formal methods for knowledge representation, decision analysis and complex system understanding. The future systems engineers will also need to be effective with software systems including software-based tools, "big-data" analytics and real-time hard controls.

The practitioner must have the leadership skills, coupled with deep system, socio-technical, and domain understanding to effectively support the evolving role. The need to understand and embrace the so-called soft skills necessary for leadership and the social sciences, which is required for a more complete understanding of the system's operation and impact, is a qualitative departure from what have tradition¬ally been a set of primarily technical competencies.

The accelerating rate of technology demands that future automotive engineers must have the ability to blend foundational automotive engineering competencies with emergent competencies required to manage consumer electronics, mobility, connectivity and service based applications. The innovations of 2025 will include the development and delivery of highly integrated customer solutions that take advantage of rich software feature sets. These software intensive feature sets will leverage "Big Data", they will dynamically analyze off-board data; determine value-added customer feedback and services and deliver these in a human friendly manner that does not undermine driving safety, security and integrity.

THE BREADTH OF AUTOMOTIVE SYSTEMS ENGINEERING COMPETENCIES

- **REQUIREMENT MANAGEMENT**
- **TECHNICAL SOLUTION**
- **QUANTITATIVE INNOVATION AND DEPLOYMENT**
- **REQUIREMENT DEVELOPMENT**
- **VERIFICATION**
- **INTEGRATED TEAMING**
- **CONFIGURATION MANAGEMENT**
- **DECISION ANALYSIS RESOLUTION**
- **PROCESS AND PRODUCT QUALITY ASSURANCE**
- **VALIDATION**
- **RISK MANAGEMENT**

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3.5 Education and Training

PRESENT:

Increased Workforce Demand

Increasing Education Demand:
The worldwide demand for systems engineers in all application domains is increasing the need for high quality education and training. A growing number of academic institutions are offering graduate-level programs.

Partial Curriculum & Training:
There are an increasing number of universities that teach systems engineering at the graduate level, although the total number is still small relative to other engineering disciplines. Many practicing engineers have not had formal education, but have learned "on the job".

FUTURE:

Building a Educated Workforce

Build Education Programs:
The worldwide demand for systems engineers is well understood and a life-long pipeline of educational, training, and mentoring is in-place to support it, building individuals and teams of the required size and multi-disciplinary capabilities.

Construct Core Curriculum Foundation:
Systems thinking is formally introduced in early education and is a part of every engineer's curriculum at the university level. Also, is grounded in the theoretical foundations that spans the hard sciences, engineering, mathematics, and human and social sciences. The Graduate Reference Curriculum (GRCSE) has recently been defined as part of an international

Develop Curriculum:
Educational and training programs will provide the systems engineers of 2025 with the socio-technical, leadership, and domain specific knowledge to engineer complex systems that span a broad range of application domains. Automotive systems engineering will be seen as a meaningful career, one which affects people broadly and has positive impact on addressing the most critical of society's challenges. As such, the automotive systems engineering curriculum will expand to include sociopolitical learning (e.g., economics, sociology, public policy, law).

Automotive systems engineering skills cannot be limited to a small number of systems engineers, but will be embraced by numerous discipline centric practitioners. As a result, automotive systems engineering education and training will be integrated into discipline specific engineering curriculums. Automotive systems engineering will be widely recognized as an important complement to domain specific education and taught for awareness in most other fields of engineering and social/economic/ policy educational areas.

For continuing relevance, automotive systems engineering education and training will stay abreast of the advancing processes, methods and tools while providing grounding in the theoretical foundations. This imposes requirements on the curriculum, instructional methods, and the instructor competencies. This field will be continually enriched by extensive theoretical elements from physics/engineering, sociology/anthropology and economics/political science. Educational and training programs will also become more pervasive to support the broadening applications of systems engineering, and the increased demands on the number of systems engineers.

Establish Lifelong Learning:
Education and training is a lifetime endeavor in which the systems engineers of the future will be actively engaged. This lifelong pursuit is necessary to build the initial foundations for automotive systems engineering, later to stay abreast of advances in technology and practices and to share their experiential knowledge with others that follow. Throughout this lifetime of education, systems training will leverage technology through knowledge representation, simulation, computation and visualization.
Systems thinking will be introduced early in education to complement learning in sciences, technology, engineering, and mathematics. Early education will also develop skills necessary for working together in teams to create solutions that satisfy stakeholder needs.

Formal Education:
Later formal education will teach basic automotive systems engineering concepts fundamental to sound engineering, as a part of all engineering instruction such as: soliciting and understanding stakeholder's needs, identifying and evaluating conceptual alternatives before arriving at a solution, considering full lifecycle impacts, and understanding and validating sources of data. Instruction will be practical, based on relevant real world experiences, to motivate students to acquire the requisite mathematical and scientific knowledge to support analyses and decision-making.

Workplace-based continuous learning programs will be individualized. In early to mid-career, training and education will provide the practitioner the opportunity to learn the latest systems capabilities and analytical techniques as well as specific institutional practices and standards.

Instruction will be practical, based on relevant real world experiences, to motivate students to acquire the requisite mathematical and scientific knowledge to support analyses and decision-making.
Greater in-depth analysis of domain-specific challenges and approaches will be provided for the professional practicing systems engineer or aspiring systems engineer to move from a discipline-specific or limited scope role into a broader automotive systems engineering role.

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SUMMARY

THE FUTURE STATE

PRESENT STATE

AUTOMOTIVE CHALLENGES → **PRESENT STATE IMPROVEMENTS** → **FUTURE STATE 2025 VISION**

- MANAGING COMPLEXITY
- COMPETENT WORKFORCE
- REDUCED LIFECYCLES
- DEVELOPING MODELING TOOLS
- KNOWLEDGE RETENTION
- COMPETITIVE ORG STRUCTURES
- COMPELLING CAREER PATHS

→

- ISOLATED SYSTEM DOMAIN
- LIMITED POLICY INFLUENCE
- INCREASING COMPLEXITY
- ENSURE FUNCTIONAL ROBUSTNESS
- LIMITED OFFICE-BASED TOOLS
- PROCESSES NOT WELL INTEGRATED
- LIMITED CONNECTED SYSTEMS
- LIMITED AD-HOC ARCHITECTING
- LIMITED FAULT RESISTANT ARCHITECTING
- ISOLATED LIMITED CYBERSECURITY
- INEFFECTIVE DECISION SUPPORT
- UNCOORDINATED MODELING
- WEAK THEORETICAL CONNECTION
- LIMITED DEPTH AND BREADTH
- VARIED COMPETENCY KNOWLEDGE
- INCREASED WORKFORCE DEMAND

→

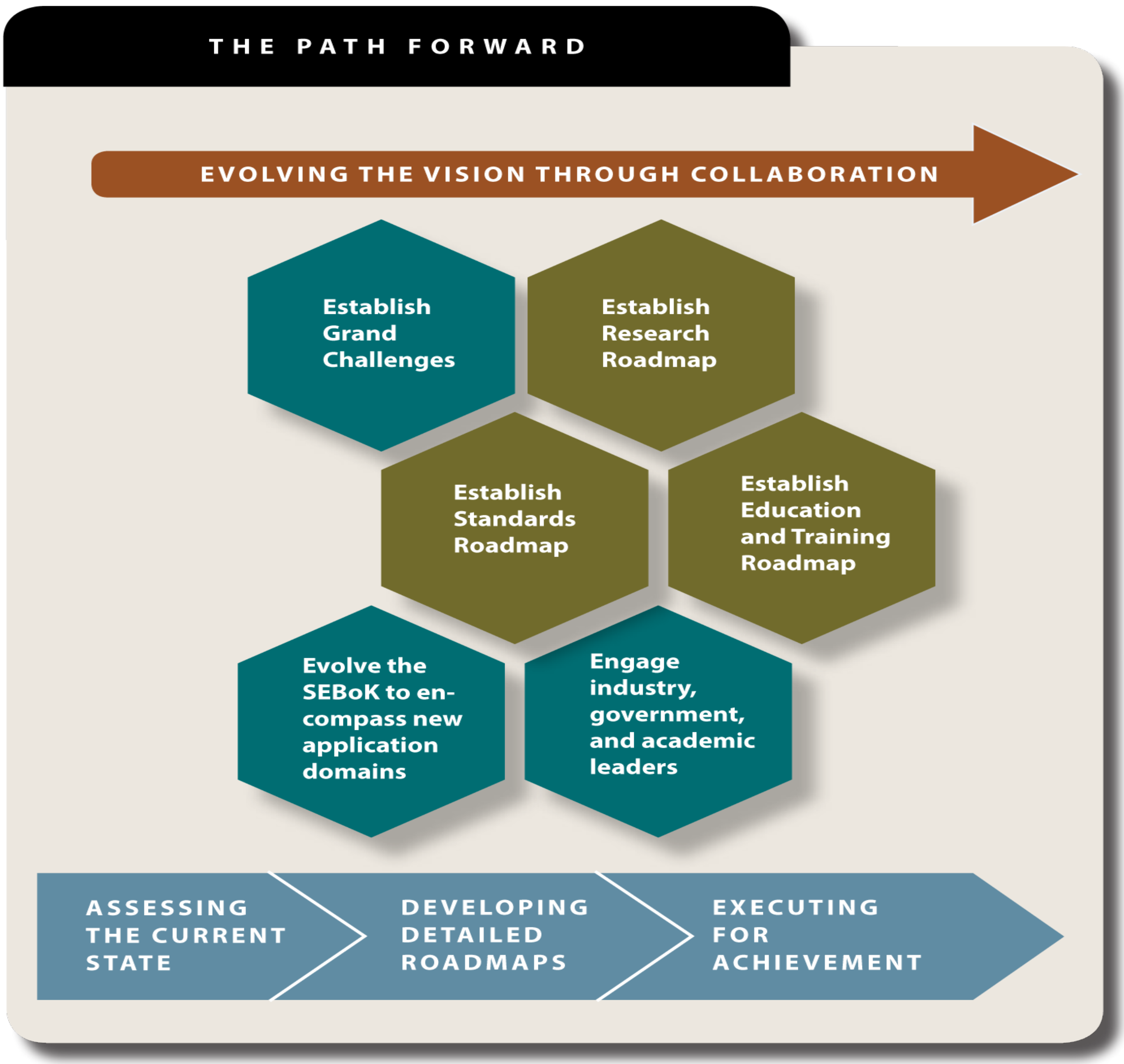
- COLLABORATIVE SYSTEM DOMAINS
- LEVERAGED FOR DIVERSE DECISIONS
- MANAGING COMPLEXITY GROWTH
- STANDARDIZE FUNCTIONAL SAFETY METHOD
- HIGH FIDELITY MULTI-LEVEL MODELS
- INTEGRATED COLLABORATIVE PROCESSES
- CONNECTED INTERNET OF THINGS (IOT)
- ARCHITECTING CROSS DISCIPLINES & STAKEHOLDERS
- EARLY FAULT RESISTANT ARCHITECTING
- EARLY CYBERSECURITY ANALYSIS & SIMULATION
- COMPREHENSIVE BROAD DETERMINISTIC MODELS
- COORDINATED SYSTEM MODELING
- STRONG SCIENTIFIC METHODS
- SPAN BROADER DISCIPLINES
- STANDARDIZE SYSTEM COMPETENCIES
- BUILDING A EDUCATED WORKFORCE

- RELEVANT TO A BROAD RANGE OF APPLICATION DOMAINS, WELL BEYOND ITS TRADITIONAL ROOTS TO MEET SOCIETY'S GROWING QUEST FOR SUSTAINABLE SYSTEM SOLUTIONS TO PROVIDING GLOBAL FUNDAMENTAL NEEDS.
- APPLIED MORE WIDELY TO ASSESSMENTS OF SOCIO-PHYSICAL SYSTEMS IN SUPPORT OF POLICY DECISIONS AND OTHER FORMS OF REMEDIATION.
- COMPREHENSIVELY INTEGRATED INTO, AND REPRESENTING MULTIPLE MARKETS, SOCIAL SYSTEMS AND ENVIRONMENTAL CONSIDERATIONS.
- FULLY ENGAGING AND DELIVERING TO MULTIPLE, COMPETING STAKEHOLDER DEMANDS ACROSS THE ENTIRE "END-TO END" PRODUCT LIFECYCLE INCLUDING LONG-TERM ENDS-OF-LIFE RISKS.
- SUPPORTED BY A MORE ENCOMPASSING FOUNDATION OF THEORY AND SOPHISTICATED MODEL-BASED METHODS AND TOOLS ALLOWING A BETTER UNDERSTANDING OF INCREASINGLY COMPLEX SYSTEMS AND DECISIONS IN THE FACE OF UNCERTAINTY.
- ENHANCED BY AN EDUCATIONAL INFRASTRUCTURE THAT STRESSES SYSTEMS THINKING AND SYSTEMS ANALYSIS AT ALL LEARNING PHASES.
- PRACTICED BY PROFESSIONALS WITH THE NEXT GENERATION OF TOOLS AND METHODS NECESSARY FOR THE EVERY GROWING COMPLEX SYSTEMS AND INTEGRATION CHALLENGES.
- A KEY INTEGRATING ROLE TO SUPPORT COLLABORATION THAT SPANS DIVERSE ORGANIZATIONAL AND REGIONAL BOUNDARIES, AND A BROAD RANGE OF DISCIPLINES.

4 Realizing the Vision

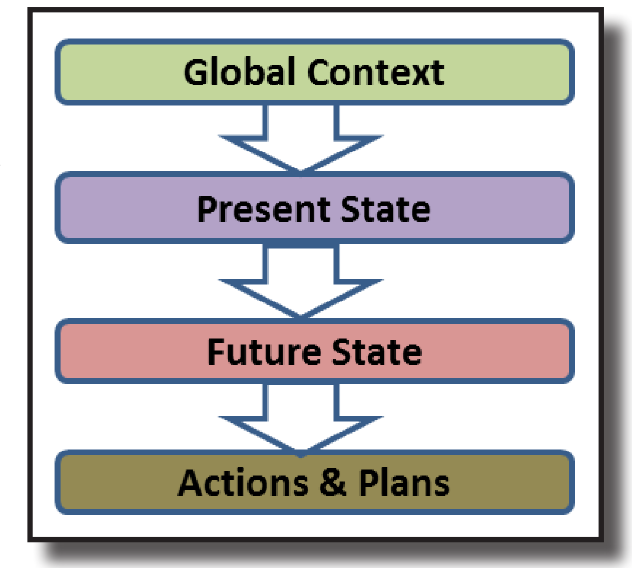
This vision for automotive systems engineering is not intended to simply be a prediction of the future, but rather a prescription for the evolution of automotive systems engineering to meet the needs and challenges of our evolving global environment.

The vision is intended to inspire and guide the direction of automotive systems engineering to meet these needs and challenges, and it requires broad participation from the automotive systems engineering community at-large to develop and execute the path forward to realize the vision.



4.1 Outline: Realizing the Vision

4.2 Recap and the Path Forward



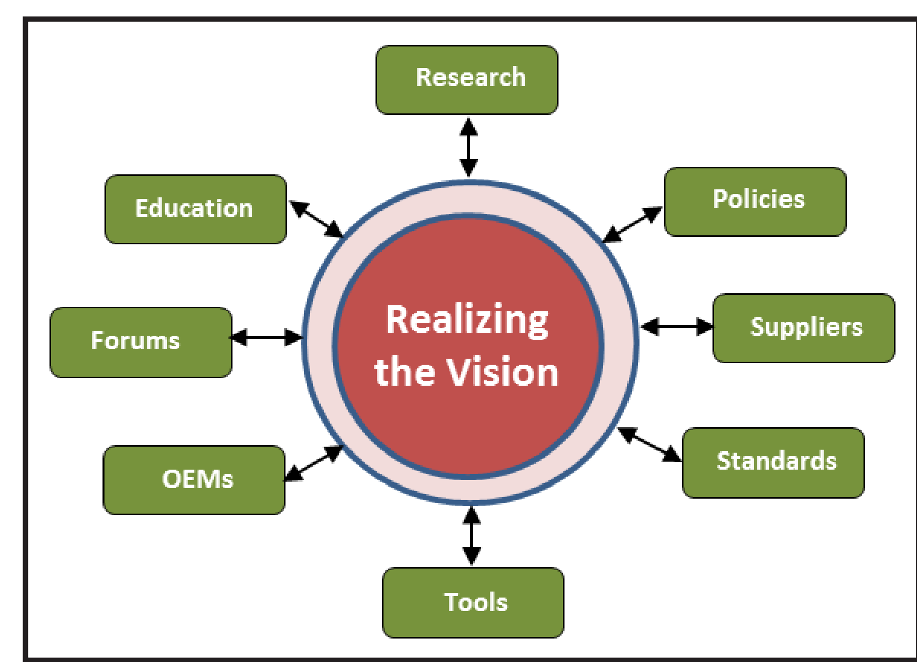
Section #1's "Global Context" provided an analysis of the global trends that are and will continue to impact automotive systems engineering in 2025. Megatrends included urbanization, growth of the middle class, demand for increased mobility, and hyper-connectedness.

Section #1 then went on to identify and discuss some key automotive challenges of complexity, safety, and security that will result from the trends and the required technological and system solutions.

With this in-frame, Section #2 proceded to lay out the present state of automotive systems engineering.

Finally, Section #3 shared a view of the envisioned future state which compared and contrasted the key systems engineering activities, competencies and technologies; making reference to where the state of the art is today and what it needs to become.

Collaborative Effort:
A successful path forward must have the active engagement of industry, academia, and government. This engagement will be structured as a collaboration between representatives from both traditional and non-traditional automotive systems engineering application domains, providing the opportunity to synergize investment and other resources across domains, while focusing on the unique needs of each domain. The collaboration will incrementally evolve the vision through the involvement and focus of professional societies such as INCOSE, IEEE, SAE, and others, as well as researchers, educators, and tool vendors.



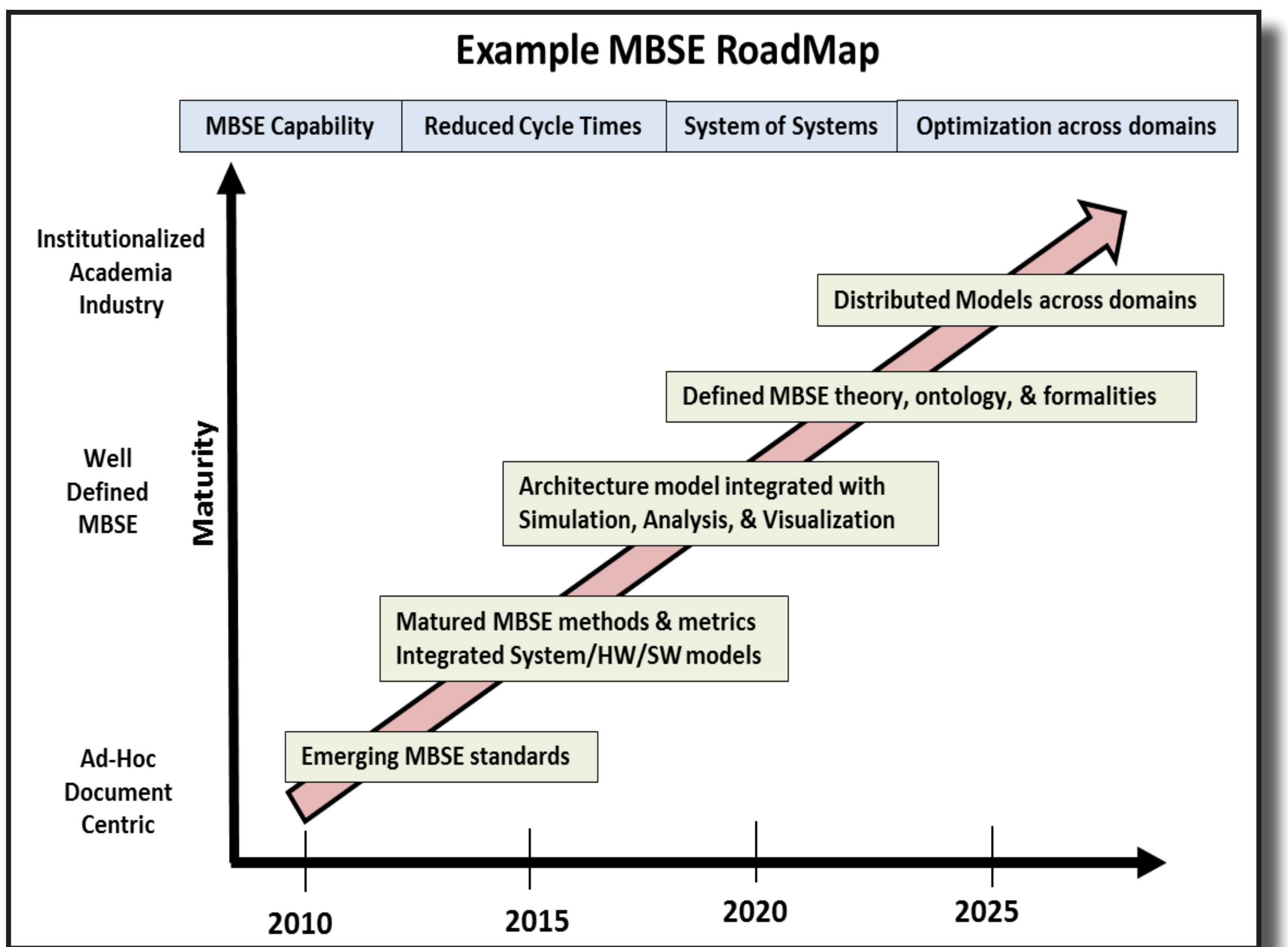
4.3 Establishing Roadmaps

With the prescribed future state in-mind, it will be important to chart a course for the community of practice by establishing roadmaps for research, education, and standards. Issuing grand challenges could then be used to energize the community, create focus, and gauge progress towards the vision.

MBSE Research Roadmap:
The research roadmap will mature the theoretical foundations as a basis for advanced automotive systems engineering methods and tools. Less focus will be placed on discipline-specific modeling, but rather how a managed, curated, diverse, and integratable set of models can drive key decision making - from technical concept evaluation to business decisions.

Education Curriculum Roadmap:
The education roadmap will help build the competencies for the workforce of 2025 and include both curriculum and instructional methods starting in early education.

Standards and Practices Roadmap:
A third roadmap will identify, develop, and evolve standards for codifying the practice, which can contribute to the body of knowledge. This includes standards that consider the automotive domain boundary as being much broader than even today in the context of transportation services, mobility systems, and IoT.



4.4 Identifying the Key Actions

Key Process and Capability:
This section lays out a methodology for analyzing key systems engineering process and capability areas to close the gap beteen the current state presented in Section 2 and desired future state in the previous section.

This methodology with leverage the Analytical Hierarchy Process (AHP) to develop the ranked alternatives to pursue in order of impact and importance. The data that follows is a prototype evaluation leveraging this methodology.

It is recommended that each Automotive OEM perform this analysis individually and then combine the results with those of other OEMs for an industry-wide assesement.

Key Process Area:
A Key Process Area is a grouping of related activities and tasks that deliver a set of analysis and work products, such as requirements engineering.

Key Capability Area:
A Key Capability Area is a grouping of engineering competencies and skills sets that are collectively used to develop an analysis or technical work product.

Gap Analysis:
The table provided is a generic set of KPAs and KCAs that help focus on the industry wide needs and provides a framework for generating a gap analysis.

Key Actions:
This final analysis in the INCOSE Automotive Vision 2025 serves as a call to action for cross industry collaboration around some specific, high leverage, non-competitive systems engineering KPAs and KCAs. The "Systems Engineering Enablers" table captures a proposed, ranked set of high leverage KPAs and KCAs that have been identified and discussed within the vision document.

These are a starting point and serve as a framework for a planned cross automotive industry engagement. These KPAs and KCAs might change during deliberations with other OEMs, Tier1s, and tool vendors.

The resulting discussion will define the agreed KPA/KCA list and an associated gap analysis. This will then support the next steps which will be to engage and collaborate to implement actions that will close the systems engineering gaps and prepare the industry of the future challenges outlined in this paper.

System Engineering Enablers	Relative Importance Target Score
Standard TMM (Competency)	10
(MBSE) Tools	10
Virtual Analysis and Validation PMTi	10
Architecture Analysis & Design PMTi	10
Science and Research	10
Project Management Processes	9
Positions staffed	9
Recognition	9
University Curriculums	9
Defined and standardized Roles	8
Organization Structure	10
Career Path established (Development)	8
Professional Body engagement encouraged	8
Policy Engagement Process	8
High Schools Projects	8

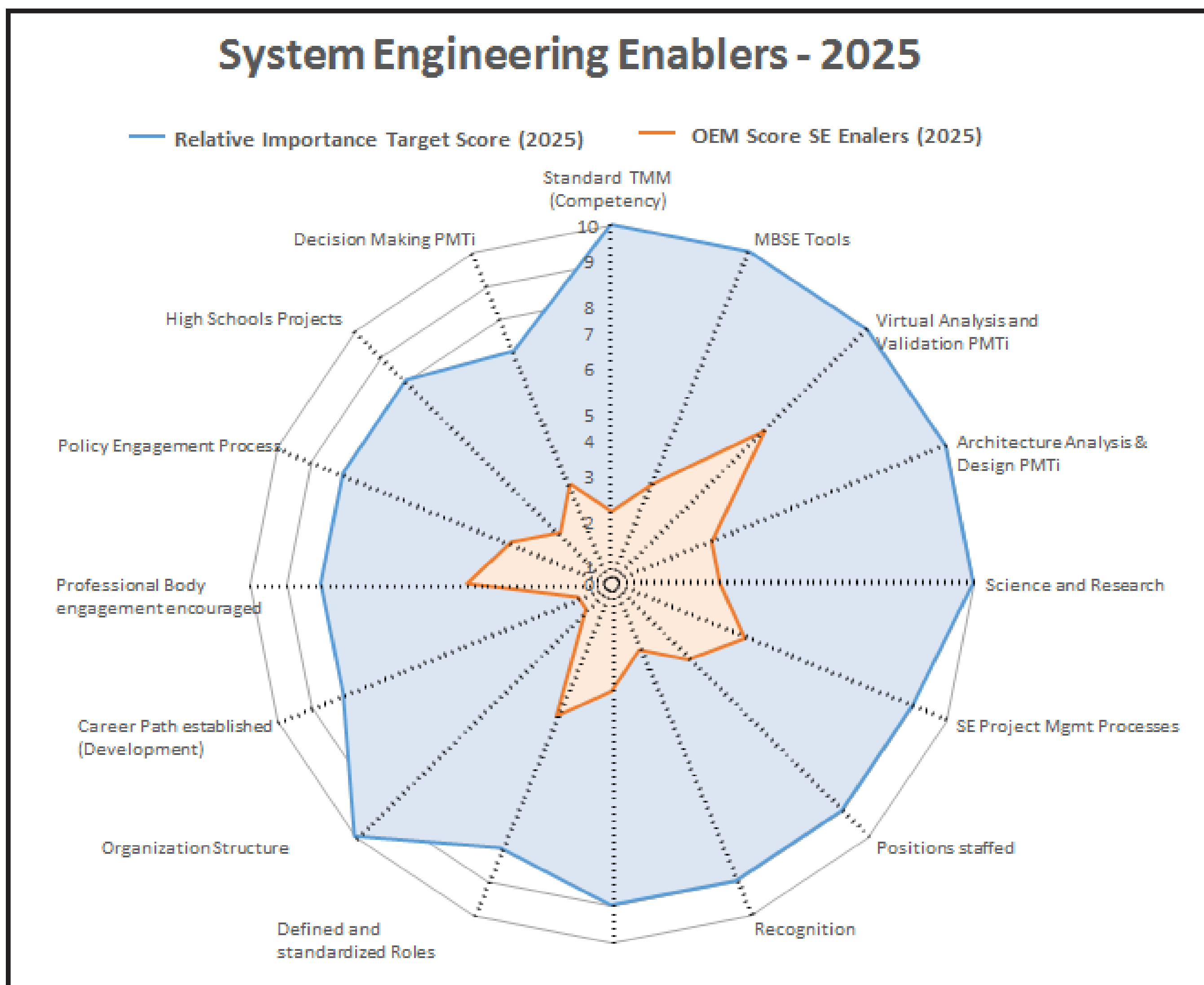
4.5 Determining Enablers

The associated spider or radar chart presents the non-scientific analytical results of a KPA, KCA weighting and scoring process.

KPA/KCA Weighting:
Each of the fundamental KPA/KCAs were given a relative importance weighting between 1- 10 (10 being highest weighting). This importance weighting provides an industry (and individual Company) capability target. The KPA/KCAs were then individually assessed for the current industry capability against target.

The radar charts provide both the relative KPA/KCA importance and target level and current industry capability. It clearly identifies where the industry needs focus its energy to develop both internal Company and cross industry capability.

Call to Action Gaps:
The gaps to target are used to identify in the next section the "Call-to-Action" and proposed plan that will move automotive systems engineering to the next level; required to deliver exciting, outstanding quality, robust, safe, and secure products in the years to come.



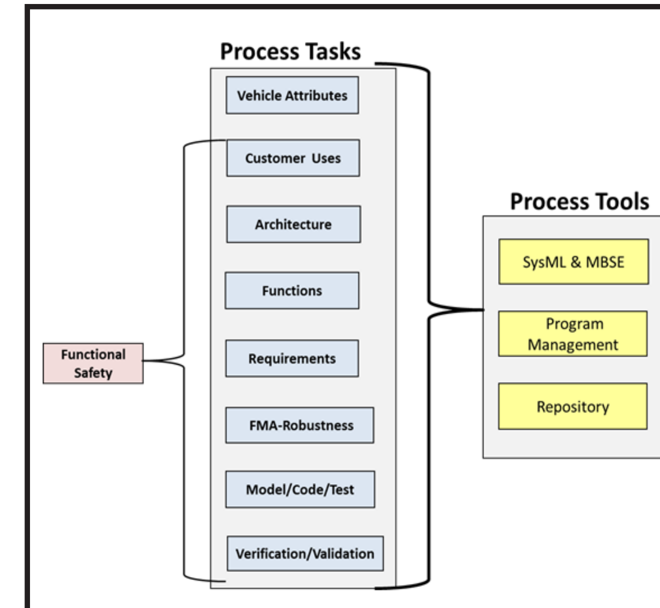
4.6 Creating the Action Plan

In reviewing the systems engineering key process area and key capability area gaps it becomes apparent that there are two distinct categories of work required.

One category is primarily within the ownership and control of the individual companies wishing to build their systems engineering capacity and capability.

The second category includes activities that require the collaboration and alignment across industry partners to define, agree, and deliver the needed process, capability, or standards.

The Gap analysis radar chart on the next page provides some insight into the relative urgency of action within the respective areas.



Competency Maturity Model:
The System engineering Technical Competency Maturity Model: has scored this highest in the relative importance --current capability gap assessment. The need to develop a cross industry and internal company set of gore competencies against which our engineering workforce can assess themselves, and plan training, mentoring and project experiences against is fundamental. The TMM ideally would be industry aligned to support the dynamic nature of the 2025 workforce.

The engineers will be highly motivated to improve their core competencies and skills in the knowledge that these skills are recognized and needed across the global automotive industry. In addition, if this TMM content is also aligned with non-automotive systems engineering models, then the entire engineering workforce and associated industries will benefit.

With equal gap weighting is the need for a well-structured and enabled systems engineering organization within the automotive companies.

System Engineering:
The systems engineering organization provides the umbrella within which to develop roles and responsibilities, rewards and recognition, corporate wide systems engineering TMM models, and the initiatives to drive required internal investments for tool functionality and system engineering analysis based design enhancements.

Without this organizational authority and control, a matrix approach manifests itself that ultimately will focus on the product timing and deliverables at the expense of the up-front systems engineering needs.

There are many different organizational approaches that could be adopted to enable the capability and effectiveness within a business, indeed many companies undergo a dynamic learning and restructuring throughout the organizations existence directly responding to the external technological and societal demands. The most important action is to establish an systems engineering organization and then adapt it as required to meet the changing demands over time.

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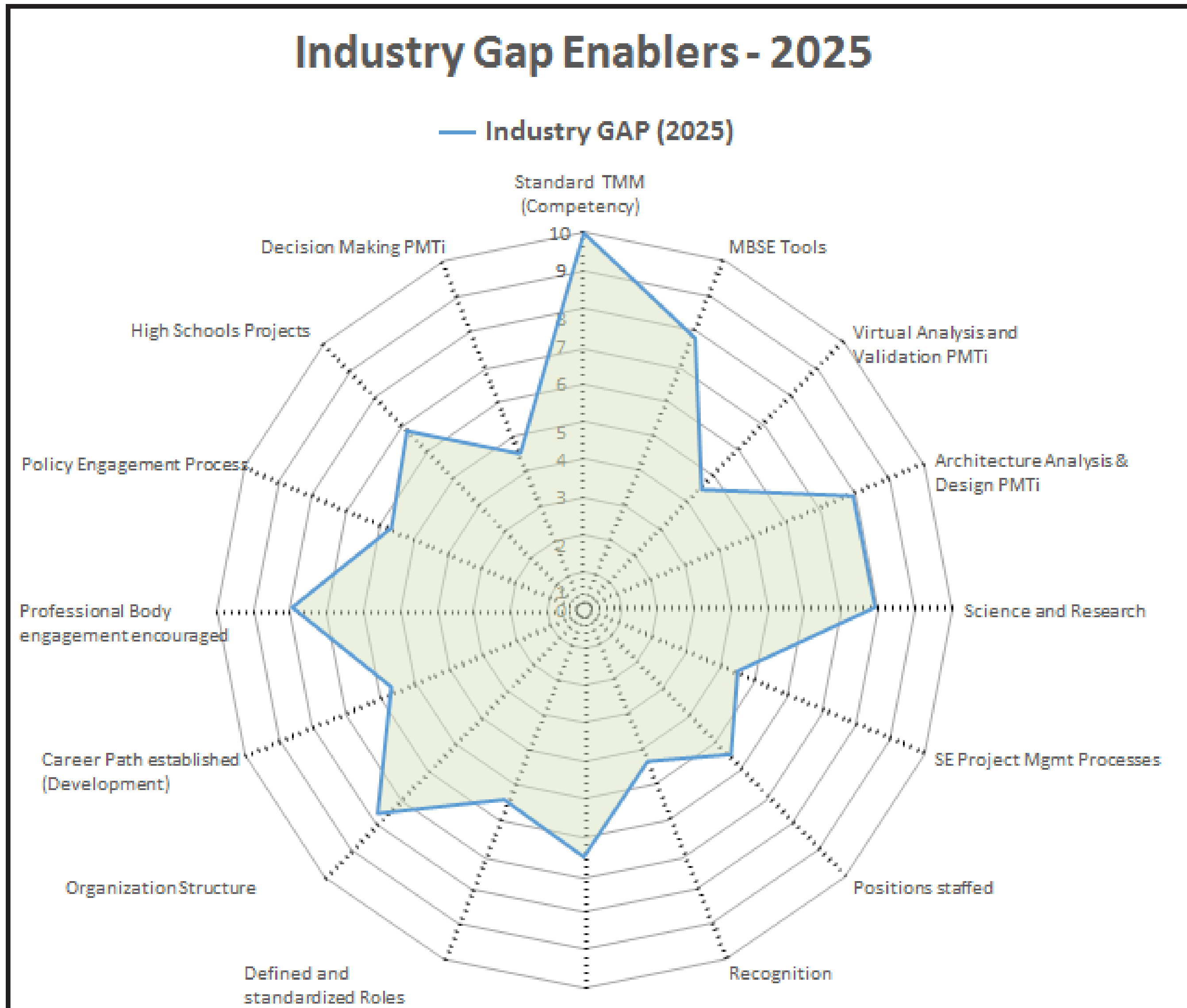
4.7 Determining Gaps

Stimulate Effort:
It is hoped that the result of this automotive systems engineering vision paper will be to stimulate a larger effort of systems engineering leadership across the automotive industry. Specifically, individual projects would be created with focused engineering teams to develop strategies, plans and undertake aligned activities to advance the science and capability of Automotive Systems Engineering. The next phase of this INCOSE led automotive systems engineering vision effort will be to identify and engage with industry OEMs and Tier 1s; to establish these working groups and pursue these goals.



4.8 Collaboration Benefits

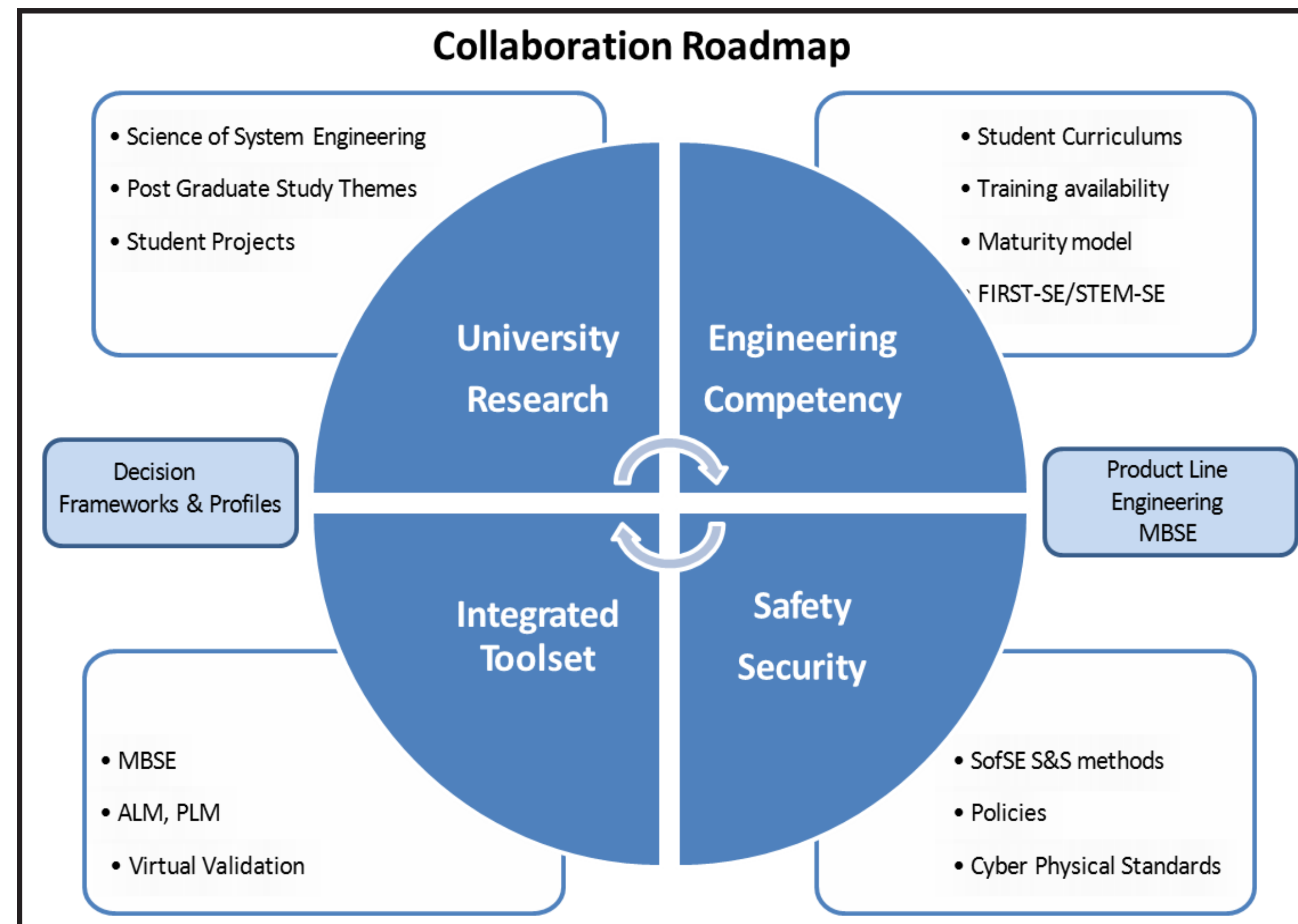
Systems Engineering Science and Research, Architecture analysis tools, and Professional engagement is ranked as the next highest gap. These areas would require three distant activities to be undertaken to close the gaps;

1. A broad OEM engagement with INCOSE to drive auto- motive agendas within the INCOSE organization and to encourage each OEMs workforce to participate and define the competencies, best practices, and grand challenges of the future.
2. An aligned effort between OEMs and Suppliers to drive University research into the science.
3. The creation of an aligned set of tool functionality definitions that drive global tool vendors in the creation of the next generation of (MBSE) and System Architecture analysis tools.

The diagram below captures the areas where cross-OEM and Tier 1 collaboration could be most beneficial to drive systems engineering disciplines, capabilities and competencies throughout the automotive industry.

They are grouped into four major categories:

1. University research
2. Support tools functionality and requirements
3. Engineering competency development
4. Standards, specifically for safety and security.



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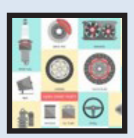
4.9 Future Vision Actions

VISION IMPROVEMENT AREAS:

- COLLABORATIVE SYSTEM DOMAINS
- LEVERAGED FOR DIVERSE DECISIONS
- MANAGING COMPLEXITY GROWTH
- STANDARDIZE FUNCTIONAL SAFETY METHOD
- HIGH FIDELITY MULTI-LEVEL MODELS
- INTEGRATED COLLABORATIVE PROCESSES
- CONNECTED INTERNET OF THINGS (IOT)
- ARCHITECTING CROSS DISCIPLINES & STAKEHOLDERS

- EARLY FAULT RESISTANT ARCHITECTING
- EARLY CYBERSECURITY ANALYSIS & SIMULATION
- COMPREHENSIVE BROAD DETERMINISTIC MODELS
- COORDINATED SYSTEM MODELING
- STRONG SCIENTIFIC METHODS
- SPAN BROADER DISCIPLINES
- STANDARDIZE SYSTEM COMPETENCIES
- BUILDING A EDUCATED WORKFORCE

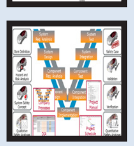
AUTOMOTIVE VISION (FUTURE ACTIONS)



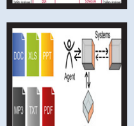
ACTION: Expand Across Automotive Domains
Actions for collaborative standardization of system practices both within the automotive organizations and across adjacent and supplier industries supports the full mobility of the global coordinated workforce.

ACTION: Improve Decisions for Stakeholder Needs
Actions for generating characterizations and visualizations for complex policy issues are improved and are approachable by policy makers and other stakeholders.

ACTION: Manage Complex Systems
Actions to identify unanticipated behaviors and integrated modeled software interactions will be established and methods for tracking and handling and mitigating complex system behaviors will be common place.



ACTION: Ensure Functional Safety Robustness
Actions to standardize functional safety using system-theoretic accident models combined with hazard based risk assessment techniques that leverage traditional reliability tools.

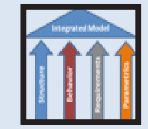


ACTION: Leverage Enhanced Tools
Actions for tools to integrate EE, SW, and Controls, CAD/CAE/PLM environments, project management and off-vehicle service systems into use of multi-level, multi domain, and dataset -enabled engineering and simulation.

ACTION: Integrate Multi-discipline Processes
Actions to integrated team & organization workflows for multi-disciplinary to support agile program planning, execution, and monitoring with efficient collaborative change process throughout all phases.

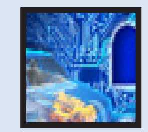
AUTOMOTIVE VISION AREAS (FUTURE ACTIONS)

ACTION: Enhance Connected Systems
Actions for inter-connected computers and users, to include systems and devices that monitor & control everything from household appliances to automobiles to provide information leveraging from the pieces.

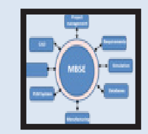


ACTION: Improve Architecting
Actions integrated across disciplines, domains and lifecycle phases to provide a single, consistent, unambiguous, system representation to address broad range of concerns.

ACTION: Expand Fault Resistant Architecting
Actions for autonomous vehicles will leverage architectural safety and security design principles that build on aerospace and military best practices and extend these with system-theoretic accident models and processes.

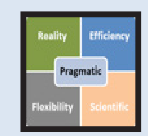


ACTION: Reduce Isolated Cybersecurity
Actions to fully integrate simulation toolsets to enable probabilistic attack scenarios to be based evaluated using different product-infrastructure design strategies.

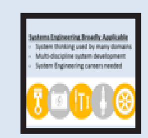


ACTION: Support Design Decisions
Actions for visualization tools will enable interactive analysis from many different stakeholder-specific viewpoints, allowing decision makers to gain new insights, perform what-if analyses, and make decisions with confidence.

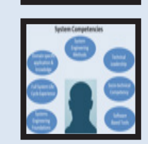
ACTION: Coordinate MBSE Modeling
Actions to make use of internet-driven knowledge representation in a virtual environment that span the full lifecycle from concept through development, manufacturing, operations, and support.



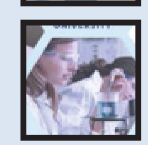
ACTION: Connect Scientific Based Methods
Actions for probability theory, decision theory, and game theory to ensure methods that lead to the selection of a system design that maximizes value under uncertainty.



ACTION: Broaden the System Engineering Roles
Actions will address concerns such as security, economic viability, and sustainability that span broader disciplines, applications and technical domains to increase broader range.



ACTION: Establish Knowledge Competencies
Actions of software intensive feature sets to leverage "Big Data", they will dynamically analyze off-board data; determine value-added customer feedback and services and deliver these in a human friendly manner.



ACTION: Build the Workforce
Action of education, systems training will leverage technology through knowledge representation, simulation, computation and visualization -- Workplace-based continuous learning programs .

GRAND AUTOMOTIVE CHALLENGES FOR SYSTEMS ENGINEERING

1. **Research:** Establish University led research projects into the science of systems engineering, product line engineering, decision making, cascaded feature/function composition analysis.

2. **Competencies:** Develop a core set of automotive systems engineering competencies, recognized and implemented industry wide.

3. **Education:** Establish a core University curriculum for systems engineering that includes an integrated set of technology driven projects. Systems thinking is taught at all levels of education.

4. **MBSE:** Develop and implement a standardized model-based systems engineering tools with full product lifecycle management and software systems engineering toolset interoperability.

5. **Policy Analysis:** Establish automotive systems engineering as an indispensable discipline for policy analysis of autonomous vehicle technologies.

6. **Systems Architecture:** Develop systems engineering architectural frameworks that support model based analysis and design of for analysis simulation tools for designing and predicting the behavior for trusted, robust and resilient systems.

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CONTRIBUTING TEAM

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- Initially developed at Ford Motor Company and later taken up as a multi-OEM project under the AWG for a shared automotive vision document, there have been many participants and we regret if we have missed any names herein.
- To the best of our abilities the key content contributors for the Automotive World In Motion - Systems Engineering Vision 2025 include:

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REVIEW & SUPPORT TEAM

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Roger Burkhart	J. Robert Wirthlin	Gary Rushton
Isuzu:		
Koichi Shibuya	Takashi Akagi	Toshi Shibata

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