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The U.S. Department of Energy’s (DOE) Energy Efficient Mobility Systems (EEMS) program envisions an affordable, efficient, safe, and accessible transportation future in which mobility is decoupled from energy consumption. The EEMS Program conducts early-stage research and development at the vehicle, traveler, and system levels, creating new knowledge, tools, insights, and technology solutions that increase mobility energy productivity for individuals and businesses.

The SMART Mobility Consortium (Consortium) is a multi-year, multi-laboratory collaborative dedicated to further understanding the energy implications and opportunities of advanced mobility solutions. The Consortium is the EEMS Program’s primary effort to create tools and generate knowledge about how future mobility systems may evolve and identify ways to reduce their energy intensity. It also identifies research and development gaps that the EEMS Program may address through its advanced research portfolio and generate insights that will be shared with mobility stakeholders.

This report was developed as part of the Consortium’s Connected and Automated Vehicles Pillar. The Consortium consists of five focused pillars of research that aim to:

- **Connected and Automated Vehicles (CAVs):** Understand the energy, technology, and usage implications of connected and autonomous technologies and identify efficient CAV solutions.
- **Mobility Decision Science:** Identify the transportation energy impacts of potential travel and lifestyle decisions and understand the human role in the mobility system.
- **Multi-Modal Transport:** Reduce modality interface barriers for passenger and freight movement and understand the interrelationships between various modes.
- **Urban Science:** Evaluate the intersection of transportation networks and the built environment in terms of energy opportunities.
- **Advanced Fueling Infrastructure:** Understand the costs, benefits, and requirements for fueling/charging infrastructure to support energy efficient future mobility systems.
This paper defines the range of CAV concepts that could be considered for analysis under the DOE SMART Mobility program. The CAV alternatives are very diverse and sometimes confusing to people who do not work with them regularly, so it is important to have clear descriptions to facilitate communication and understanding. It is also important to apply standard terminology so that people studying these concepts can understand each other clearly and avoid misunderstandings based on frequently-used but imprecise and misleading terminology (such as “driverless”, “self-driving” and “autonomous”). Finally, in a program as broad as SMART Mobility there is value in identifying a limited set of use cases that can serve as the bases for analyses in different laboratories and different pillars so that the results of the analyses can be compared on an “apples to apples” basis.

This paper has two parts. In the first part, the dimensions of the CAV space are defined to give an indication of the breadth of the alternatives and the potential for dimensional explosion if all combinations of alternatives were to be considered for serious study. In the second part, a limited set of representative use cases are defined and recommended to serve as the basis for subsequent analyses. These are provided to stimulate discussion that can hopefully lead to convergence on a common set of use cases that can unify the SMART Mobility analyses.

I. Dimensions of the CAV Space:

The CAV alternatives are described in terms of several dimensions that are coupled to varying degrees. Where the coupling is looser it is not as important to bundle the attributes into clusters, and some dimensions can be varied in the analyses without introducing distortions. In other cases, where the attributes are closely coupled in their influences on transportation system performance (such as the levels of automation and connectivity), it is important to clearly define how they are clustered. The relevant dimensions are:

- **Connected vehicles only (without automation of driving)** – several independent functionalities that can be analyzed separately

- **Automated vehicles**, characterized by:
  - Whether they are connected or unconnected (autonomous) [2]
  - Which of the SAE levels of automation they embody [6]
  - Their operational design domain (ODD) [∞]

- **Other attributes of the vehicles and their usage**:
  - Vehicle class (size and use for passengers or freight) [8]
  - Powertrain technology [8]
  - Business models to govern their operations [6]
An additional dimension to consider in evaluating the energy implications of CAV technologies is changes in the transportation infrastructure and external transportation policies that could interact with the CAV technologies. Examples are described after the CAV dimensions are presented.

1. Connected vehicles only (without automation) – These can be treated as independent features that can be combined as desired, since they are not closely coupled with each other and their impacts on energy usage are largely decoupled from each other:

   (a) Cooperative collision warning systems (V2V, I2V) – These systems use wireless communication systems to enable vehicles to broadcast information about their motions to all other vehicles and vulnerable road users so that all are well informed about the movements of their peers. That trajectory information and other vital information about vehicle size and class can be used to predict potential collisions and to issue warnings to drivers to help them avoid the collisions. Since crashes are responsible for about a quarter of the congestion on U.S. roadways, reductions in crashes could help to reduce the frequency and severity of congestion, thereby saving some of the energy that is wasted on congestion today.

   (b) V2V cooperative driving/maneuvering enhancements – The main triggers of traffic congestion on freeways are lane changing maneuvers by drivers entering the freeway from on-ramps and deciding to switch to a different lane based on an expected travel time advantage or the need to get to the exit lane at a destination. The lane changing drivers and the drivers of the other vehicles in their immediate vicinity have primitive ways of communicating their intentions and preferences today (hand gestures or turn signals, which are all too rarely used), but with V2V communications those intentions can be displayed directly on the instrument panels of other drivers and it becomes possible to negotiate cooperative maneuvers earlier and more smoothly than today, reducing some of the congestion disturbances.

   (c) V2I/I2V route planning, parking information and reservations (eco-trip planning and routing) – Drivers currently choose their routes based on limited knowledge about the road network and the traffic conditions between their origin and destination. More complete information about real-time traffic congestion, traffic signal phase and timing and availability of parking can be provided using I2V communications so that drivers will be better able to avoid the worst traffic conditions, minimize their stops and idle times at red traffic signals, and find available parking spaces without excessive search time. With the addition of V2I communications, they can also request a reservation for a
parking space based on a real-time anticipated arrival time, to further reduce VMT waste in the search for parking spaces.

(d) Local SPaT information to support eco-driving decisions by drivers (eco-signal control) – Traffic signals that broadcast their real-time signal phase and timing (SPaT) information can help drivers save energy that would otherwise be wasted in an excessive frequency and severity of stop-start cycles. The broadcasted SPaT data can be used by in-vehicle systems to display recommended speed changes allowing drivers to get through a stale green signal before it turns red or to coast down to a slower speed approaching a red signal without stopping if that signal will be turning green soon enough. The V2I communications in the opposite direction can be used to generate signal priority requests or simply to inform the signal controller of the arrival of a vehicle that is waiting for a green phase (which could be provided with a minimum delay if other vehicles are not making a conflicting movement).

2. Automated vehicles – These attributes are not generally independent because of their close coupling with each other, which makes it difficult to limit the dimensions of the alternatives that need to be considered. When several coupled variables influence the energy saving potential of an automated vehicle concept it can be difficult to determine how much of that energy saving is attributable to each variable. The primary relevant attributes of automated vehicles that need to be considered are:

(a) Connected or unconnected (autonomous) implementation (2):
This is one of the most important classification attributes for considering the energy impacts of any AV system because the unconnected version of an AV could produce significant negative impacts while the connected version of the same AV could produce significant positive impacts. The use of data communicated from other vehicles makes it possible to damp out traffic flow disturbances and drive AVs closer together, with smoother speed profiles and reduced aerodynamic drag. Without that connected vehicle data, the gaps between AVs will have to be larger than now, reducing roadway capacity, the disturbances will be amplified, and energy will be wasted in excess acceleration and braking cycles.

(b) SAE Levels of automation, Levels 0 – 4 (5 levels)
The dominant characteristic used to distinguish among different automation systems is the level of automation, as defined by SAE in their J3016 Recommended Practice document (2016). These levels specify the functionality that is implemented by the driving automation system and the functionality that is retained by the driver, regardless of the specific technological implementations that different manufacturers may choose (such as types of sensors or actuators). The SAE classification scheme includes six levels, but Level 5 is not discussed here because this could only become
feasible beyond the planning horizon for the organizations developing CAV systems – Level 5 CAV systems would have to be able to perform all dynamic driving tasks under the full range of roadway, traffic, weather and environmental conditions in which humans are able to drive. Widespread use of that capability is outside the planning horizon of the SMART Mobility program.

The formal definitions in SAE J3016 are rather complex and depend on use of a variety of carefully defined supporting terms. In the interest of brevity, simplified versions of the definitions are used here, but the full set of definitions, which is well worth studying, is available at: [http://standards.sae.org/j3016_201609/](http://standards.sae.org/j3016_201609/)

a. Level 0 – No Driving Automation – safety warning or intermittent control intervention systems could be implemented at this level, since they do not change the driver’s role in any meaningful way.

b. Level 1 – Driver Assistance – automation of either lateral or longitudinal control of the vehicle under some conditions (within a specified Operational Design Domain or ODD), while the driver performs the other control function and continuously monitors the driving environment for hazards. (Example: adaptive cruise control)

c. Level 2 – Partial Automation – automation of both lateral and longitudinal control of the vehicle within a specified ODD, while the driver continuously monitors the driving environment for hazards. (Examples: current freeway driving systems offered by Tesla, Mercedes, Volvo, BMW, Infiniti and others)

d. Level 3 – Conditional Automation – automation of both lateral and longitudinal control of the vehicle within a specified ODD without continuous driver monitoring, but depending on the driver to provide a “fallback” intervention on short notice to maintain safety when the system requests help to manage a hazardous situation that it cannot handle itself. (No examples currently exist, and many developers have decided to avoid developing systems of this type because of doubts about the feasibility of the driver fallback intervention)

e. Level 4 – High Automation – automation of the complete dynamic driving task within a specified ODD, with enough fallback capability engineered into the system that it can guarantee transitioning the vehicle to a minimal risk condition regardless of the hazard encountered. (Examples: automated people movers on segregated guideways, prototype driverless low-speed shuttle vehicles, heavy trucks in fenced-off mines, and many developers attempting to develop vehicles to provide driverless taxi-like services within highly constrained ODDs)

Note that the definitions of automation levels focus on the role of the driver, but the developers of the more highly automated systems are also defining roles for remote supervisors or
dispatcher who could intervene to assist some Level 4 vehicles without drivers when they get in trouble.

Both technical and general-interest discourse about driving automation systems has been seriously hampered by imprecise and misleading terms that have commonly been used to refer to automation. In some cases, this has been imprecision on the part of journalists writing for non-specialist readers that do not discern nuanced distinctions in meaning. In other cases, industry representatives have used language that is susceptible to multiple interpretations. Both cases are damaging because they lead to misunderstandings by the general public and their political leaders, which can produce unfortunate legislative and public policy decisions.

SAE J3016 includes detailed explanations about why terms such as “driverless”, “self-driving” and “autonomous” should generally be avoided because of the confusion that they create when they are applied indiscriminately to wide ranges of driving automation systems. Most of these systems are indeed NOT “driverless,” but they change the role of the driver. There is one limited class of vehicle, referred to as “ADS-dedicated vehicles”, that is designed to operate without any in-vehicle driver controls, and those are the only ones that should be considered “driverless”. The problems with “autonomous” and “autonomy” are even more severe and widespread because these terms have been used by many people as synonyms for “automated” and “automation” respectively, especially when considering the higher levels of automation, but their meanings are in fact very different. “Automation” refers to the substitution of electronic and/or mechanical systems for human labor, which is indeed the central concept most of the time. “Autonomy” refers to independence and self-sufficiency rather than replacing humans, so “autonomous” is a modifier that should be applied only to the limited subset of automation systems that are designed to operate self-sufficiently, without benefit of vehicle-vehicle or vehicle-infrastructure communication or cooperation. Unfortunately it has been so widely misused that it is rarely clear what it is intended to mean when it is used.

(c) Operational design domain (ODD) is a term defined in SAE J3016 as the specific conditions under which a given driving automation system is designed to function, including driving modes. An ODD may include geographic, roadway, environmental, traffic, speed and/or temporal limitations. The driving modes could include fully access-controlled freeways in either low-speed or high-speed driving conditions, or low-speed urban driving in sites that are protected from intrusions by most other vehicles. There is an infinite number of possible ODDs, considering the diversity of conditions that could limit the operations of driving automation systems, but these are critical aspects of the descriptions of the capabilities of any driving automation system. It is essential for the designer of the system (and the assessor of its impacts) to precisely specify the ODD. Representative examples of the attributes that could specify the technological limitations of a specific system are shown here, but there is no expectation that all of these would be modeled explicitly. Rather, they can be used to support estimates of the percentage of all driving that could be done by any specific driving automation system to be studied.
a. Roadway type (freeway, rural highway, suburban arterials, urban streets, suburban residential streets, pedestrian zones, bicycle paths, segregated paths, etc.)

b. Traffic conditions/speed range (freeway at free flow, congested freeway, high-speed arterial, medium speed arterial, low-speed city streets, low-speed residential streets, walking/running speed with pedestrians, low-speed in parking lots, ...)

c. Geographical boundaries (city neighborhood, college campus, office park, retirement community, resort community, public park, ...)

d. Weather and lighting constraints (rain, snow, fog, dust, wind, low sun angles, nighttime darkness, ...)

e. Ability to cope with anomalies (work zones, emergency responders, erratic other drivers, animals, road debris, ...)

f. Reliance on supporting infrastructure (pavement markings, signage, street lighting, physical segregation by curbs or barriers, cooperative traffic signal control, ...)

3. Other Relevant Descriptors of Vehicle Operations

These descriptors of vehicle operations are largely decoupled from the previous descriptors of connectivity and automation. This means that the different levels of connectivity and automation can be applied to vehicles characterized by the attributes below with relatively limited consideration of coupling effects.

(a) Classes of vehicle (8 basic categories)

a. Passenger, ultralight duty (1-2 people) – These would be a new class of vehicles especially designed for highly automated driving to provide personal mobility to individuals, especially to those who may not be able to drive themselves

b. Passenger, light duty (3-9 people) – This includes automobiles and vans that are driven by people who have ordinary driving licenses, as well as conventional taxi, limousine and TNC vehicles and their future counterparts that have driving automation systems.

c. Passenger, medium duty (10 - 20- person shuttles) – This includes larger vans and small buses that require a special class of driving license if they are manually driven, as well as new specially built automated low-speed shuttle vehicles.

d. Passenger, heavy duty (Full-size bus, over 20 passengers) – This could also include buses or other large transit vehicles operating on dedicated guideways or tracks.

e. Freight, ultralight duty (few kg capacity) – This refers to a new generation of small robot vehicles that are designed to carry small packages or specialized
cargoes at low speeds and for short ranges (operating on sidewalks or other spaces that are segregated from normal road vehicles)
f. Freight, light duty (Class 1-3 trucks) – up to 14,000 lbs. (6,350 kg) gross vehicle weight rating (GVWR)
g. Freight, medium duty (Class 4-6 trucks) – between 14,001 and 26,000 lbs. (11,793 kg) GVWR
h. Freight, heavy duty (Class 7-8 trucks) – over 26,000 lbs. GVWR

(b) Powertrain technology (8)
a. Conventional gasoline internal combustion engine: most light-duty passenger vehicles on the road today use this technology.
c. Natural gas: A small fraction of on-road vehicles use this technology today, but it is a candidate future technology especially for heavier-duty vehicles because it emits fewer greenhouse gases than petroleum-based fuels.
d. Hybrid gasoline or diesel: This technology combines a conventional gasoline or diesel engine with an electric motor, regenerative braking and battery to provide enhanced fuel efficiency. Depending on the design, the coupling to the wheels could be mechanical or electrical.
e. Plug-in hybrid: Similar to a hybrid as described above, this type of technology has a larger battery and relies less on fuel combustion to provide power. There are currently 21 light-duty vehicle models in the U.S. market, with all-electric driving ranges from 12 to 53 miles (http://www.plugincars.com/cars).
f. Battery electric: This technology eliminates fuel combustion altogether in an “all electric” design consisting of a large battery, electric motor and regenerative braking. Currently there are 15 all-electric light-duty vehicle models in the U.S. market, with driving ranges from 58 to 315 miles (http://www.plugincars.com/cars).
g. Hydrogen fuel cell: This technology requires a source of high-purity hydrogen stored on-board at high pressure. Rather than combusting the fuel directly, it is fed to a high-efficiency fuel cell, providing electricity to drive an electric motor, similar to battery electric vehicles. There are currently three hydrogen fuel cell vehicle models available in the U.S. market (Toyota Mirai, Hyundai ix35 Fuel Cell, and Honda Clarity).
h. Externally-supplied electricity (catenary or inductive): These systems are electric or hybrid vehicles with very small batteries; the electricity is supplied externally via overhead conducting wires (catenary) or through electromagnetic coupling from transmitters in the road surface (inductive). Catenary-based vehicles have been used for decades in some bus, train and trolley systems, and Siemens is demonstrating the technology as an “add-on” for
heavy-duty freight vehicles to reduce urban air pollution in Sweden and California. Inductive systems are currently limited to stationary charging but are in principle able to supply power to moving vehicles.

(c) Business models (may affect class of vehicle chosen)
   a. Private use: Conventional, privately-owned and operated vehicles.
   b. Short-term rental / car-share (Zipcar, Getaround, Car2Go, GiG, etc.): This vehicle business model allows drivers to access vehicles a short distance from their home or office for limited-duration trips. Unlike traditional car rental companies that charge by the day and typically require substantial transaction time, these approaches are designed for rapid, seamless access with use times as little as a few minutes. One-way car-sharing adds flexibility by freeing drivers from having to return cars to the same location; a variant on this idea is free-floating car-sharing whereby vehicles can be left in any legal parking space anywhere within a defined region.
   c. Transportation network company (TNC = Uber, Lyft, conventional taxi, etc.): Unlike car-sharing, TNCs provide drivers and can offer door-to-door service. Recent innovation has allowed anyone with a smartphone app to hail a ride and anyone with a vehicle to become a driver; the ride-matching process has become an automated process facilitated by advances in routing technology. Shared-ride TNC trips are also becoming a popular way to save consumers money while enhancing vehicle utilization, and is possible because of sophisticated routing algorithms.
   d. Public transit-like (fixed or semi-fixed route & timetable, possibly with first/last-mile capability): Traditional public transit operates fleets of dedicated large-capacity vehicles, sometimes in dedicated corridors (e.g., bus lanes, rails) according to a predefined schedule. Combining this type of service with TNC approaches could allow for synchronization of first- and last-mile transport with transit corridors, either with the same or different vehicles. Schedule flexibility may also become possible if the transit service can coordinate the itineraries of all riders, so that vehicles leave right after customers arrive, rather than at predefined times.
   e. Private goods delivery: This concept consists of on-demand transport of goods, much like the transport of people using TNCs. These are to be distinguished from technology designed to operate exclusively on sidewalks, which falls outside of the scope of SMART. In addition to traditional take-out food delivery services, TNCs such as Uber are now embracing this business model, along with others (GrubHub, Munchery, Amazon and others), and are also expanding delivery to other items (UberRUSH), competing with established courier delivery services such as Pedal Express and FTD. Brick-and-mortar (especially grocery) stores as well as online retailers such as Amazon now offer delivery of any item in stock within a few hours, and
Amazon is exploring non-traditional vehicles (e.g., aerial drones) to enhance efficiency.

f. Common carrier goods delivery: Traditional and express mail delivery (US Postal Service, UPS, FedEx, etc.) is now being complemented by new entrants offering faster, more flexible services, perhaps most visibly led by Amazon. The line between private and common carrier goods delivery is blurring, with more companies offering rapid delivery services as commerce moves online.

4. External Influences (Infrastructure and Transportation Policies)

The CAV systems do not operate in isolation, but they rely on roadway infrastructure as their running way and their usage is governed by transportation policies created at the local, state, or federal level. These external factors can have significant influence on how the CAV systems operate and on their contributions toward transportation energy consumption (or savings).

Examples of roadway infrastructure changes that could influence CAV usage include:

- Construction of new roadway infrastructure in established corridors or as a way of stimulating development in new corridors.
- Segregation of roadway infrastructure for connected vs. unconnected or automated vs. manually driven or freight vs. passenger vehicles, simplifying the operating environment for CAV systems
- Widespread implementation of I2V and V2I communication systems throughout the roadway infrastructure, supporting CAV applications
- Upgrades to roadway infrastructure signage, markings and geometry to make it friendlier for automated vehicle operations and enabling higher levels of automation to be deployed earlier.

Examples of transportation policy changes that could interact with CAV system usage include:

- Roadway usage pricing based on measures other than fuel consumption, such as mileage-based fees or peak-period congestion charges
- Changes in the gasoline tax at federal and/or state levels
- Pricing or traffic priority policies to encourage shared vehicle occupancy
- Restrictions on availability of parking or pricing mechanisms that influence parking location
- Insurance pricing regulations that consider technologies such as collision warning and avoidance or automated driving systems
- Federal Motor Vehicle Safety Standards (FMVSS) or other regulations specific to higher levels of automation in new vehicles
- Incorporation of CAV features into fuel economy standards
• Land use policies that impact transportation systems and the use thereof

II. Example Concepts:

A limited number of “representative” systems are suggested here as candidates for deep-dive modeling in the SMART Mobility program. These systems use automation at different levels, and virtually all of them should be connected, although we could consider unconnected versions of some of them as well to show the contrast (illustrating the importance of connectivity). These systems or use cases are clustered by general application area so that their relative deployment phasing can be visualized more clearly (lower technology systems peaking earlier, and then superseded by higher technology systems with more comprehensive capabilities):

Eco-driving systems (smoothing speed profiles)

(1) I2V cooperative eco-driving support for Level 0 manually driven vehicles, including eco-routing, parking information systems, eco-signal advisories and eco-signal adjustments to signal cycles to minimize energy usage. These could be analyzed individually and combined in different combinations to yield impact estimates since their effects are not tightly coupled with each other.

(2) Urban eco-signal control with I2V communication to vehicles that adjust their speed profiles using Level 1 longitudinal control to minimize stops and energy consumption along signalized arterials.

Urban mass transport systems

(3) Laterally guided bus on busway: Level 1 automatic steering control of heavy-duty transit bus operating on a fixed route mainline service in high-density urban and suburban environments, under all weather and lighting conditions.

(4) Highly automated bus on busway: Level 4 automation of heavy-duty transit bus operating on a dedicated busway in a protected right of way in high density urban and suburban environments, under light supervision by a dispatch center, and under most weather and lighting conditions.

(5) Semi-fixed route automated shuttle: Level 4, medium duty passenger vehicle, ODD limited to prescribed route + small drop-off/pick-up region around it, public transit-like business model for short distance first mile/last mile access to mainline transit or activity center circulation, closely supervised by dispatch center.
Automated taxi services

(6) First-generation low-speed automated urban taxi: Level 4, ultralight to light duty passenger vehicle, ODD constrained to urban/suburban streets within limited neighborhoods (e.g., Automated Mobility Districts) at speeds up to 25 mph, fair weather only, TNC business model, with safety closely supervised by dispatch center.

(7) Advanced automated taxi: Level 4, passenger ultralight to light duty, ODD limited to metropolitan region, otherwise mostly unconstrained except for edge cases (unusual weather, hazards, etc.), TNC business model loosely supervised by dispatch center.

Automated goods movement services

(8) Basic truck platooning: Level 1 longitudinal control only for heavy-duty trucks operating on intercity freeways, under all weather and lighting conditions, by common carrier or private operator.

(9) Advanced truck platooning: Level 1 leader, with Level 3 or 4 followers, in dedicated truck lane in freeway right of way, both urban and intercity, under most weather and lighting conditions, by common carrier or private operator.

(10) Low speed urban goods distribution robot: Level 4 automation of ultra-light goods movement vehicles at very low speed in urban pedestrian environment (sidewalks rather than roads) under benign weather and lighting conditions, crossing roads with pedestrians but not generally sharing the road with other vehicles, deployed from local fixed distribution hub or larger freight vehicle.

Automated private personal vehicle systems

(11) Cooperative ACC or platooning for light-duty passenger cars: Level 1 longitudinal control only, operating on urban and intercity freeways, rural highways and major arterials, under all weather and lighting conditions.

(12) Urban freeway automated driving system: Level 4 automation in mixed traffic on urban freeways under benign weather and lighting conditions, but with human driving in all other environments, applicable to cars, buses and trucks.

(13) Intercity freeway automated driving system: Level 4 automation in mixed traffic on intercity freeways under benign weather and lighting conditions, but with human driving in all other environments, applicable to cars, buses and trucks.
Automated highway system: Level 4 automation in dedicated, segregated lanes on urban and intercity freeways, under all weather and lighting conditions, applicable to cars, buses and trucks – but they must transition to lower automation when they leave the segregated lanes.

The above systems are examples that could be reasonably expected to reach deployment within the planning horizon for the SMART Mobility program (up to 2050). Interest has been expressed in exploring some speculative high risk/high reward “moon shot” possibilities as well, based on the notion that unexpected technological advances could accelerate progress in some specific dimensions during the coming decades. A few examples of CAV-related “moon shots” that could have larger energy impacts if they were to become technologically feasible include:

- Ultra-light freight delivery robots take over the majority of small-package deliveries in urban and suburban areas.
- Unpiloted aerial vehicle (UAV) drones take over the majority of small-package deliveries in rural areas.
- Level-4 automation of truck platoons dominates long-haul goods movement, eliminating driving jobs in the following trucks and reducing operating costs substantially.
- Virtual reality becomes so compelling that it eliminates the need or desire for a substantial portion of person trips.
- Automation technology advances rapidly enough that most urban and suburban trips can be made safely in private personal vehicles without drivers, freeing up the driving time for other activities and enabling the vehicles to be shared sequentially or parked remotely.
- The dreams of shared automated urban mobility are realized, such that large fractions of person trips in urban regions are taken in shared-ride taxi or van services operated without drivers.

Timing of Availability:

For analyses of energy impacts to be done at base years 2030, 2040 and 2050, those impact estimates will be very sensitive to the assumptions that are made about the extent of usage of each system. This is a subject of great uncertainty, since the market impact/timing will be influenced by the pace of technology development/maturation, the degree to which it is included on new vehicles (together with the rate of retirement of old vehicles), and the degree to which individuals choose to use the technology when it is available. Past experience with vehicle technologies (in contrast to mobile phone technologies) indicates that even after the first availability of a new technology on premium vehicles, it takes one or two decades for that technology to become standard on most new vehicles. The lag for vehicle fleet turnover adds at least another decade for the technology to be present on most vehicles on the road, and even when the technology is on the vehicles, consumers do not necessarily choose to use it during all of their traveling. Some of this market adoption and consumer choice work is being done in the Mobility Decision Science pillar of SMART Mobility, but the predictions based on technological
feasibility are developed here within the CAVs pillar, where there is more attention to the technological challenges that must be met to implement the systems.

The graphs below show initial estimates of the ranges of market penetration that could be expected for each of the example systems in the target years, with deliberately cloudy lines on the plots to emphasize the uncertainties. The primary point of this exercise is to show the wide range of uncertainty that applies, and to recognize that regardless of the degree of optimism that may be applied to the estimates there is a significant inertia in the large and capital-intensive transportation system that limits the rate at which it can implement major changes. Connected and automated vehicle technology adoption rates are difficult to predict due to the uncertainties associated with the development and integration of complicated emerging technologies. To introduce the vehicles into public service they will have to demonstrate safety levels that are at least equal to existing human-driven vehicles. Based on extensive prior experience in the development of automated vehicles, we have integrated the following considerations to predict future adoption rates:

- estimates of technology development times for each CAV application to perform safely in the least challenging operating conditions,
- estimates of additional technology development time for operation in a broader range of more challenging operating conditions covering more the country,
- the historical market penetration growth of new technologies in newly-purchased vehicles
- estimates of future vehicle fleet turnover rates.

Although it would be comforting to be able to rely on a mathematical model to derive estimates of the rate of growth in usage of each of the CAV systems, development of a realistic model of these processes would be a complicated, costly endeavor. The outputs of simpler models would be driven by the simplified assumptions embedded in the model formulation and in the selection of the input values, so in the end the results would not necessarily be as realistic as the estimates suggested here, which provide a range of potential outcomes suitable for analysis within SMART Mobility.

The optimistic (high) estimates displayed here assume that the advancements of the technology proceed without significant setbacks or disappointments, that the current high level of industry investment in development of the technologies continues to grow, and that the public reactions to automation are very enthusiastic. The pessimistic (low) estimates are based on more conservative but realistic assessments of the time and level of effort that will be needed to achieve demonstrably safe driving automation for each application and of the level of public enthusiasm that could be expected. These account for the extra time and effort that would be needed to solve unanticipated technical problems and to provide the systems with the capabilities to operate in increasingly challenging and complicated environments.
The percentages on the vertical scales of the plots refer to the fraction of the total VMT that are likely to be traveled within the U.S. within the vehicle usage segment being described. This does not account for potential changes in the amount of travel in each segment, so large changes that shift travel from one class of vehicle or service to another are not represented here. In the earliest period (2030) these estimates are dominated by consideration of technological feasibility and challenges of ramping up the number of equipped vehicles in the overall vehicle population, but by the latest period (2050) some of the less advanced systems are likely to see their percentages decline as they are superseded by more advanced counterparts becoming feasible.

The example systems are clustered in groups that provide comparable services so that the evolution of market percentages can be more clearly seen, with early growth of the first-generation systems saturating when superseded by second-generation counterparts with greater capabilities.

The eco-driving systems are shown separately here, Concepts 1 and 2 from Section II of this report. Because these are at lower levels of automation, they can be expected to reach an appreciable market penetration in 2030 but they are likely to decline in the later period when they are superseded by more highly automated systems.

The development of three kinds of urban mass transport automation systems (Concepts 3-5 from Section II) is depicted in the next set of graphs, with the simple lateral guidance systems having the highest usage at the early stage of development, but declining at the later stage when they would be superseded by the more highly automated buses on busways.
The Level 4 urban taxi service (Concepts 6-7 from Section II) development is depicted in the next graphs, with the simpler low-speed-only taxi services developing earlier and then superseded by the more advanced services that can operate under a wider range of conditions.

The development of the CAV systems for goods movement is depicted in the next set of graphs, representing two generations of truck platooning systems for inter-city movements (Concepts 8 and 9 from Section II), beginning with the basic truck platooning that could be in widespread use.
by 2030. This is likely to be superseded by the more advanced form of truck platooning with higher automation in the later years.

The implementation of CAV systems for private personal vehicles is depicted in the final set of plots, covering Concepts 11, 12 and 14 from Section II. This shows the importance of the simpler Level 1 CACC and platooning systems at the earlier stage, only to be superseded by the more highly automated systems in the later years.