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Driver Intelligence Replacement in a Decision-Oriented Deployment Framework for Driving Automation

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Executive Summary

What some human drivers have done ***wrong*** has been blamed for much of the problem associated with the current highway systems. For example, driver inattention, fatigue and other human errors have often been cited as major sources of safety hazard on current highways and human capabilities as major limitations on current highway capacity. Such human deficiencies and the pervasive urban traffic congestion have motivated the concept of Automated Highway Systems (AHS). The fundamental objective of AHS is to achieve user and societal benefits through replacing human driving by automated machine driving. The first fundamental thesis of this paper is that safe replacement of human driving on highways by automation requires a rigorous examination into what most human drivers have been doing ***right*** on the current highway systems. Such an examination would provide much insight into the functional requirements for AHS, i.e., what machines must do to emulate or improve human driving. Furthermore, what human drivers tend to do poorly or well must be contrasted with what machines tend to do well or poorly. A complementary arrangement must be sought if the machines cannot safely or affordably replace driver intelligence for highway driving, either on a mature AHS or during intermediate stages toward it.

Driving tasks involved in any vehicle-roadway system depend on the driving environment. For example, city-street driving is different from driving on current highways and AHS driving may be drastically different from current highway driving. On an AHS, any human intelligence required by current highway driving must be replaced (emulated or improved) by machine intelligence or continues to be provided by the driver, if proven safe, unless the corresponding tasks are eliminated from AHS driving due to the environment change. Note that new driving environments may introduce new driving tasks. Since the driving environment during early deployment stages of AHS is likely identical to that of the current highways, most, if not all, of the current highway-driving tasks remain necessary. The second fundamental thesis of this paper is that current highway driving involves not only many routine chores, which machines tend to do well, but also much human intelligence, which machines tend to do poorly. Such intelligence is often required in subtle ways or is required only when unusual but normal events occur. We identify many such driving functions. If some of these required functions cannot be safely emulated by machines either in a mature end-state AHS or during intermediate stages toward the end state, then "driver-in-the-loop" must not be ruled out at the current research and development stage.

Since AHS is currently at the research and development stage and its successful implementation is subject to many exogenous events, deployment of AHS technologies should actually be regarded as planning of vehicle-highway automation features to ensure a high likelihood of evolution from the current highway system to a highway system with significant performance gains. At this stage, it should be viewed as the process of designing ***a sequence of products*** leading to a society with widespread acceptance and implementation of AHS. This is the third fundamental thesis of this paper.

Deployment of vehicle automation technologies requires various types of support, e.g., manufacturing of automation-equipped vehicles, infrastructure support, insurance underwriting, etc. Such

support involves major decisions on the part of the providers, each of which *rationalizes* its decisions for the benefit of its ***own*** organization. Users of **AHS** technologies are decision makers too, because they decide whether to purchase, maintain and use automation features. The fourth and final fundamental thesis of **this** paper is that all such decision making people or organizations must be identified and the vehicle-highway automation research and development community must devise deployment strategies (decisions), not just the target **AHS** system but also how to reach that target **AHS** system from the current vehicle/highway systems, that are so compelling from the *selfish* view-point of each of the decision-makers that the people and organizations make favorable decisions for **AHS** deployment.

1. Introduction

Due to the pervasive and fast worsening highway congestion problem and recent advances in intelligent vehicle technologies, the subject of vehiclehighway automation, particularly Automated Highway Systems (AHS), has received much attention lately. Most of these technologies are still being developed or tested in a test track or laboratory environment. Since deployment of these automation technologies in the ***real world*** is the ultimate goal, it actually dictates the technological requirements for vehicle/highway automation, as recently pointed out by Tsao [13]. Several recent papers [1,5,12,13] in the literature have pointed out many potential issues regarding deployment of full vehicle/highway automation, i.e. AHS. This paper proposes a framework for studying deployment of vehicle/highway automation technologies, including technologies for partial and full automation. Since full vehicle/highway automation encompasses its partial counterparts, this paper addresses explicitly the deployment of full automation. However, the framework can be easily specialized for partial automation. In this paper, full vehiclehighway automation is defined to be the degree of automation that allows hands-off and feet-off driving and an AHS is defined to be a vehicle-highway system that supports fully automated driving on dedicated lane(s). The concept of highway automation began decades ago. (See, for example, [10,3,8].) In a recent comprehensive treatment of conceptual AHS design, Stevens [9] discussed AHS deployment and operations goals, analyzed AHS characteristics and identified **37** alternative AHS concepts.

Much literature correctly pointed out human errors as major sources of safety hazard on the current highway systems [e.g., 7]. With what human drivers can do ***wrong*** in mind, many technologies are developed to enhance the safety of human driving, e.g., collision warning/avoidance systems. Most of these technologies are intended only to ***warn*** the human driver and some of them are contemplated to ***assist*** the driver by automated intervention. They are fundamentally different from those technologies intended to ***replace,*** partially or fully, human driving, e.g., ***AHS*** technologies. When contemplating replacement of human driving, one ***must*** also examine what human drivers can do and have been doing ***right.*** We observe that human driving involves not only many routine chores, such **as** lane keeping and headway keeping, but also much human intelligence and perhaps agility, especially when compared to machine intelligence and robots. Although such intelligence may not be needed all the time, they may be necessary during certain normal but unusual events. Therefore, research community for vehiclehighway automation, particularly AHS research, must develop a clear understanding and create a catalog of what human intelligence and practices are required for safe highway driving in the real world. Such understanding is also needed to examine the limitations of machines in performing such human functions and practices. Any deployable automation technology must be able to provide sufficient user service commensurate with or exceeding the cost. The user service may be in the form of warning, assisting or replacing the driver in performing some driving functions.

Deployment of vehicle automation technologies requires various types of support, e.g., manufacturing of automation-equipped vehicles, infrastructure support, insurance underwriting, etc. Such support involves major decisions on the part of the providers, each of which ***rationalizes*** its decisions for the benefit of their own organization. Users of AHS technologies are decision makers too, because they decide whether to purchase, maintain and use automation features. All such decision making people or organizations must be identified and the vehiclehighway automation research and development community must devise deployment strategies (decisions), not just the target AHS system but also how to reach that target AHS system from the current vehicle/highway systems, that are so compelling that the organizations and users make favorable decisions for AHS deployment according to their own organizational charter, policies, practices and capabilities.

The objective of this paper is to lay the foundation for AHS deployment research. Based on the two fundamental theses, this paper proposes a decision-oriented deployment framework for driving automation from a human driving intelligence replacement perspective. It is organized as follows. Section 2 defines the concept of AHS deployment. Section 3 addresses the intelligence and **skills** involved in human driving on conventional highways. Section 4 proposes the decision-oriented deployment framework. Concluding remarks and future research are given in Section ***5.***

2. Definition of Deployment

This section defines and clarifies the concept of deployment. We define AHS deployment as advancing from today's vehiclelhighway systems to wide-spread adoption of an AHS. It is needless to say that deployment refers to adoption in the ***real world.***

Successful AHS deployment requires actions by the AHS R&D community. Through these actions, certain events can be controlled or influenced by the community. However, there will be many external events which are beyond the control **or** influence of the community, e.g., society's environmental concern, non-AHS vehicle product innovations. Both such actions and external events play an important role in AHS deployment.

A concept similar to AHS deployment is that of ***AHS evolution.*** In fact, ***deployment*** and ***evolution*** are often used interchangeably. Evolution has a connotation leaning toward the involuntary manipulation by the exogenous events that are not controllable by the AHS community. In other words, it is often perceived as a passive and slow process. On the other hand, deployment is an active and faster process, which has a connotation leaning toward AHS community's taking those actions that help realize wide-spread adoption of the automation technologies.

It is important to point out that deployment issues are not confined to only deployment stages but actually dictate the technological requirements. We now briefly illustrate that deployment could introduce many challenging R&D issues, both technological and non-technological. Consider an urban AHS where vehicle movements and maneuvers, and even the roadway, are under tight AHS monitoring and control without driver intervention. Through communication and sensing, uncertainty about vehicle movements is minimized and safety can be achieved, at least in theory. However, if (i) automated vehicles will need to be inter-mixed with manually driven vehicles, either in the same lane **or** in adjacent but non-physically-separated lanes, in any of the intermediate deployment stages and (ii) their drivers cannot be expected to stay alert and react safely to any possible mishaps during automated driving, then safety during any such stage may require more sophisticated and yet reliable technologies than otherwise. Therefore, in this case, it is deployment, rather than the target mature AHS, that actually dictates the technological requirements of AHS.

Since the end-state AHS is currently being researched and debated and the end-state design should be able to be evolved from the current highway system, deployment should be interpreted as design of evolutionary paths from the current highway systems to any automated highway systems (hands-off and feet-off driving on dedicated lanes) with significant performance gains. In this sense, deployment actually encompasses the design ***of*** the end-state AHS. In short, deployment can be viewed as design of a sequence of automation products. In the opinion of the authors, deployment, if not properly treated at the ***outset*** of AHS R&D, could become a potential "showstopper". Therefore, we invite intense research into deployment as an ***integral*** part of AHS system definition and specification. Elias **[4]** and Bonderson [2] recently called for effort in devising an evolutionary implementation plan for AHS. Ward [16] and Tsao [13] studied evolutionary scenarios for AHS.

3. Human Driving Intelligence/Skills and Advances in Automation Functions

In this section, we first provide a list of example human driving functions, many of which involve human intelligence and **skills,** and then give several examples illustrating the potential difficulties **for** replacing such intelligence. We close this section with a list of extra functions provided by vehicle-highway automation.

Human driving functions can be put into two categories: normal driving functions and emergency handling functions. This paper focuses on the former. The latter will be reported separately. Note that current human emergency handling functions may not be as relevant to AHS design as their normal counterparts because AHS may have very different failure events and emergency situations than its manual counterpart. **For** more details on possible AHS failure events, the reader is referred to Tsao et al. [15].

Normal human driving functions include:

(F1) infrastructure recognition

- highway configuration:
  - boundary
  - number of lanes
  - use restriction (e.g. **HOV,** light-duty vehicle lane)
  - grade
  - physical barriers
  - terrain **off** the lanes
- lane characteristics:
  - boundary
  - curve
  - pavement condition
- merge geometry (including on-ramps and other lane-drop locations)
- diverge (split) geometry (including off-ramps and other lane-addition locations)
- lane-changing restriction areas
  - physical barriers
  - solid painted lines

(F2) sign recognition

- speed limit
- lane-use instructions
  - exit information (e.g. at the exit or prior to it)
  - exit only
  - exit destination (direction of city street or crossing highway)
  - lane closure
- merge
- diverge (split)
- yield
- weight limit
- vertical clearance
- use restrictions, e.g. no-truck lane or "trucks use right lane"
- narrow bridge
- tire-pavement friction (ice, slippery)
- visibility, e.g. fog, lighting
- wind gust
- detour
- changeable message signs

(F3) obstructiodnon-obstruction recognition

- vehicles cutting in ahead
- slower vehicle ahead
- failed, stressed or stopped vehicle

- humans or animals ahead, moving or still
- safety-impacting debris ahead, moving or still
- recognition of non-obstruction
- occurrence of accidents in the front or on the side
- safety impacting incidents

(F4) obstructiodnon-obstruction prediction
- all seven categories above

(F5) obstruction avoidance
- all seven categories above

(F6) safe speed determination
- visibility
- tire-pavement friction
- wind gust
- traffic condition (e.g. in neighboring lanes)

(F7) vehicle following

(F8) lane cruising

(F9) lane keeping

(F10) lane changing

(F11) merging

(F12) de-merging
(F13) sensing state **of** vehicle (e.g. possible current or pending vehicle failures)
(F14) vehicle failure response
(F15) emergency maneuvering

The above list is not exhaustive. There are other possible human driving functions and skills, particularly, those functions, intelligence and skills that are required for driving trucks, including single-unit trucks, tractor trailers, articulated trucks, and buses. Furthermore, these functions and the required intelligence and skills should be identified for a wide variety of driving conditions and environment, e.g. weather conditions, incident conditions, and presence of reckless, aggressive, or drunk drivers, etc.

We note that in a mature **AHS** the driving environment may be controlled ***so*** that not all these functions will be required. However, we also note that, although it may be ***so,*** the driving environment during some intermediate deployment stages, if any, may not be as much controlled as the mature **AHS.**

Some of these human driving functions may be not only replaced by automation but also improved by it. For example, the vehicle-following function may be improved by elimination of driver inattention and by shorter actuation delays. However, some other driver functions may be difficult to replace, particularly those requiring high levels of human intelligence, and their automated counterparts may not perform as well. Consider the function of obstructiodnon-obstruction recognition.

The obstructiodnon-obstruction function identifies those safety impacting objects or debris ahead, in the lane and even in adjacent lanes, and ignores those that are not safety impacting. This function requires a high level of human intelligence - detection of still or moving objects, object recognition, prediction of trajectory of an moving object, threat assessment (including possibility and consequence of impact), and avoidance maneuvering. The function of object identification determines if there is actually an object or debris ahead in the lane. This function may be a difficult one to implement. It **is** well-known that radar technology may not be able to identify an object like a brick with satisfactory reliability. If a vision-based system **is** used to perform object identification and recognition, then the system must be taught so that it ignores many images commonly found on current highways and likely found on future AHS. Examples abound. They include pavement patches, cracks, tire marks, water puddles, water marks, shades of adjacent trees, sign posts and vehicles, etc.

Prediction of obstacle trajectory and threat assessment could even be harder. Example abound. When human drivers have spotted deers on the side of the highway, they would drive cautiously or even slow down in anticipation of possible entry to the highway by the deers. Note that they would do that even if the deers are standing still and show no sign of movement. To emulate this human intelligence and behavior, the vehicle needs to be taught to recognize such animals and the potential threat off the roadways (not just the pavement areas alone). Otherwise, if the deers jump into the roadway and create a collision and if the vehicle is expected to perform brain-off driving, then the liability is likely on the vehicle manufacturer.

Debris may fall from vehicles, especially from trucks - pick-up or other trucks. If the vehicle is expected to detect the fallen debris, determine the threat and perform avoidance maneuvers, then the vehicle must not only be cognizant of the fact that there is a vehicle in front of it but also what the vehicle is carrying and what is dropping from the vehicle. When the vehicle in front carries objects like bicycles at the back of vehicle, to emulate the human intelligence and behavior, the vehicle needs to recognize them and leave extra spacing for safety.

When a vehicle breaks down, the driver and even passengers will get out of the vehicle to inspect, push, or repair the vehicles **or** to seek assistance. People will be present on the highway, including children. To emulate human drivers, the vehicle needs to be able to detect the presence of people, especially children, and react to their presence safely.

Note that machine intelligence may eventually be able to perform these functions. However, these considerations certainly impose requirements on the concept of **AHS.** The cost and the time till technological maturation may be negatively impacted. Perhaps the most important point of all is that driving on highways requires a high degree of human intelligence and emulation or improvement of such intelligence is required if the vehicle is to support brain-off driving in the current uncontrolled (though limited access) highway driving environment. Note that such an emulation task requires much advanced technology and is closely related to the once popular discipline of artificial intelligence.

In the backdrop of technological emulation of some forms of human intelligence, some complications related to emulating human agility arise. For example, when "driving into the sun" on a highway at dusk, human driver could squint for better vision. If the AHS uses a vision-based sensing system, then the system needs to be able to adjust quickly to the particular lighting condition. When human drivers detect particular situations that deserve attention, they can quickly focus on the situation. If the AHS uses a vision-based sensing system, then the system needs to be able to detect the suspicious situations and quickly focus on them. These may very well be doable but requires additional features on the vision-based system. Another example would be the merging process at an on-ramp or highway-to-highway interchange in which a human driver easily recognizes the geometry by turning his or her head. If the AHS uses a vision-based sensing system for such geometry, then the camera(s) and the imaging processing system needs to be able to determine where to focus the camera(s) and may need to turn the camera(s) accordingly. If the merging process is not coordinated among the vehicles approaching the merge point, then the vision-based system needs to be able to discern traffic conditions precisely and accurately for safe merging, which may require turning the camera(s). Again, this may be doable but requires additional features on the vision-based system.

There are things that drivers of the current highways would do but are generally not considered as driving functions. Automobile drivers tend to avoid driving near heavy vehicles for safety reasons.

They also seem to avoid driving parallel to other automobiles. They would change lanes for higher speeds and yield to traffic entering the highway from on-ramps, particularly trucks, and to vehicles attempting to make lane changes. These need to be considered during **AHS** design too.

In responding to the technological difficulties of obstacle detection, object trajectory prediction, threat assessment and obstacle avoidance, the concept of obstacle exclusion has been contemplated. This concept may be implemented with physical barriers separating the automated lanes from the automated lanes and with high fences on top of barriers or even nets covering the top of the lane. This can prevent objects being thrown into the automated lanes but cannot prevent them from being thrown from vehicles using the automated lane. Vehicles with open loads can be disallowed into the automated lanes and vehicles with loads need to lock their cargo doors securely. However, enforcement may require visual inspection at the entrance. This is possible at the dedicated on-ramps but is likely quite difficult to be enforced on the fly at the entrance locations on the transition lane. The fences and nets can prevent animal entry but not from entry/exit ramps areas or from the opening on the transition lane. Without nets on top of the lane(s), objects can be thrown in from adjacent area via some mischievous or sabotage acts.

This concept will be very difficult to implement in the rural areas. Furthermore, even if obstacle exclusion turns out to be a viable engineering concept, how the driving public perceives this is quite uncertain. It is well-known that for any public works projects, safety itself may not suffice and perceived safety is also important.

When deploying a particular automation technology, the driving functions to be automated and the limitations of such automation must be clearly identified and the degree of safety must be rigorously assessed. Any deployable automation technology must be able to provide sufficient user service, particularly safety, commensurate with or exceeding the cost. If replacement of any of the normal operation functions in an **AHS** is not technologically or economically feasible, then human role must be considered as an integral part of the *normal* operation of such an AHS. Nelson **[6]**, Elias **[4]** and Bonderson [2] all recommended study of driver role in *malfunction* management.

Vehicle/highway automation can provide many functions beyond those that human drivers can. We provide a list of functions in addition to those human functions listed above that automation may employ. We emphasize those functions intended to facilitate vehicle maneuvering. Detailed functions intended to optimize system performance, especially system throughput, can be found in Tsao [11,121.

(F16) communication

- recognition of which vehicles, the ID, to communicate to
- establishing dedicated communication channels for communication
- exchanging messages to ensure the safety and efficiency of maneuvers

(F17) maneuver coordination

- vehicle movement/maneuver planning
- coordinator/participants identification/designation
- maneuver execution
    - safety conditions verification (initiation, continuation, abort)
    - protocols

(F18) system functions

- check-in
- check-out
- traffic monitoring
- entry metering

- flow optimization

These functions have received some attention in the AHS R&D community. But, the important point is to study these functions in detailed context of real-world situations, not in abstraction. Technological emulation of some of those driving functions needed for driving on current highways listed above has been treated in the context of intelligent vehicles. But, again the important point is to study them under concrete driving situations.

4. A Decision-Oriented AHS Deployment Framework

A major group of decisions to be made by the AHS research and development community associated with deploying AHS technologies are to assemble the technologies in packages and to ”sell” them in steps that lead to the eventual implementation of AHS. Users of AHS technologies are decision makers in that they decide whether to purchase, maintain and use automation features. There are many other decision-making bodies that will jointly realize the deployment **of** automation technologies. Deployment of vehicle automation technologies requires various types of support, e.g. manufacturing of automation-equipped vehicles, infrastructure support, insurance underwriting, etc. Such support involves major decisions on the part of the providers, each of which ***rationalizes*** its decisions for the benefit of its own organization. AHS deployment requires the support by the general public too, a portion of which may not choose to use AHS at all. The importance **of** these decisions motivated our decision-oriented deployment framework.

The decision-oriented deployment framework consists of the following five major steps.

(S1) Identify all relevant decision variables and decision makers.

(S2) Group such decision variables into two categories: exogenous variables and endogenous variables.

The exogenous variables are those that can influence the future of AHS but cannot be controlled or influenced by AHS community. The endogenous variables are those that are controlled or can be influenced by AHS community.

(S3) Further partition the endogenous variables into independent variables and dependent variables.

The independent variables are those that are directly controlled by AHS community. Dependent variables are those that are not directly controllable by AHS community but can be influenced by the decisions and actions taken by the AHS community. Major independent decision variables include automation technologies, **AHS** operating strategies, and the deployment strategies. Example dependent variables include driver (user) acceptance, public acceptance, and vehicle manufacturer attitude, etc.

(S4) Given the exogenous variables and using the driving intelligence replacement perspective discussed in Section **3,** AHS community properly determines the independent decision variables to influence the decision makers of the dependent variables in the attempt to bring about the successful deployment of AHS.

(S5) **Assess** the likelihood of external events as well as that of the outcome of the dependent decision variables; develop contingency plans for AHS deployment accordingly.

AHS deployment will be subject to the influence of unfavorable exogenous events, e.g. general public’s environmental concerns. AHS R&D involves primarily integrating various technologies for the implementation of the automation concept and does not pioneer any particular technology. For example, AHS R&D community seeks ***to*** adopt sensing (e.g. radar and vision/image process), communication, computing and actuation technologies but does not in general spearheads R&D into these particular technologies. Therefore, important exogenous events include the maturity of the these technologies as a function of time.

AHS community can leverage upon favorable **non-AHS** events related to vehicle-highway systems. Such events include acceptance of vehicle technology innovations, e.g. collision avoidance and adaptive cruise control. Such favorable events also include need for mobility, just-in-time manufacturing, transit, and defense conversion, etc. Due to the existence of these potentially volatile external events, ***contingency plans*** for AHS deployment is required.

A major group of the independent decision variables is about packaging automation technologies for replacement/enhancement of some or all human driving functions. Implicit in these decisions are the uses of the automation technologies (including which driving population can use them and what driver functions are replaced, i.e. emulated or improved, and how to use the technologies.) Another major group of independent decision variables is about sequencing and timing of introduction of the technology packages. These two groups are the ultimate independent decision variables that ***drive*** the whole AHS deployment process. In short, the AHS community should provide a deployment "roadmap" or "blueprint" so convincing that the rest of the relevant decision makers would follow the roadmap to the complete realization of AHS.

There will be many dependent decision variables involved. Some of the corresponding decision makers have also been called stakeholders. Such decision makers include:

(1) People
  - users: automobile drivers and passengers, transit users
  - local communities
  - interest groups: environmental groups, safety advocates
  - general public, including critics

(2) Government/Agency
  - metropolitan planning organizations (MPOs) and regional and transportation planning organizations
  - state and local government
  - federal government

(3) Industry
  - auto makers and related design/manufacturing industries
  - insurance industry
  - transit service providers (possibly government agencies)
  - trucking firms

Each of these entities examines AHS attributes, including those of the target AHS as well as those related to the associated deployment strategy, of its interest and evaluates AHS and its deployment according to its goals, objectives, policies and practices. Note that these entities rationalize their decisions according to their goals and objectives. The AHS community needs to understand the goals, objectives and needs of these decision makers and then influence their decisions.

Consider the following example. Primary government roles in supporting transportation service include the provision of highways, its safe and efficient operations and basic ride quality. However, they do not seem to include provision of driver comfort, especially that enabled by automated driving. Therefore, it may be undesirable if AHS deployment calls for extensive infrastructure before performance of the highway system, particularly safety and throughput, is improved. Possible automation technologies available for early deployment include automated lane cruising (i.e. automated lane keeping coupled with adaptive cruise control), which is expected to provide much driver comfort but not much, if at all, system throughput and safety improvements. Due to the institutional objective of the governments, it is desirable for the deployment of this technology not to require significant amount **of** infrastructure modification and investment.

It is up to the AHS research and development community to identify all the relevant decision variables and decision makers and identify all possible issues and difficulties involved in ensuring decisions in favor of AHS deployment, ranging from technological issues to institutional issues. Getting these decision-making people or organizations involved early in the AHS system definition and development process will most certainly benefit AHS deployment. Tsao [12] identified many issues for initial AHS deployment and proposed a shuttle van service for AHS debut, i.e. the first user service involving hands-off and feet-off driving. Tsao [13] also identified many general deployment difficulties and illustrated them with an evolutionary AHS deployment scenario.

Finally, it may be worth pointing out that AHS community can also try to influence the occurrence and direction of external events. For example, it can influence the evolution of vehicle technology, e.g. product innovations, compatibility to AHS, and AHS-ready products. It can also influence the direction and rate of infrastructure modification. For example, it can try to delay the exhaustion of right-of-way for conventional use so that the remaining right-of-way can be used at a later time for building AHS lanes (to avoid lane conversion, which could encounter considerable resistance similar to that experienced by highway authorities for HOV lane conversion).

5. Conclusion

Driving on current highway systems requires much driver intelligence and agility. Many driving tasks requiring such intelligence and agility have been identified. In an AHS, they must be emulated or improved by machine driving, if the driving environment remains the same. Feasibility and cost of technology to replace driver completely needs to be rigorously examined. Vehicle cost consideration should not be focused only on mass-product cost. High vehicle cost during introductory stages must be born by some people or organizations who can afford it and can benefit from it sufficiently to justify the cost. At the current stage, driver-in-the-loop should not be ruled out as part of the end-state AHS, not to mention the intermediate states, because complete replacement of driver intelligence and agility appears difficult. Furthermore, unless the system can detect and respond safely to each and every of its failure and emergency conditions, driver-in-the-loop should be considered also for abnormal AHS operations.

A decision-oriented deployment framework has been proposed. Many decision-making people and organizations affecting AHS deployment have been identified. AHS community needs to partition the corresponding decision variables into exogenous, dependent and independent decision variables and then identify the deployment difficulties according to the goals and objectives of the decision makers. This decision perspective accentuates the importance of AHS community's decisions, i.e. the independent decision variables, regarding (a) packaging technologies for driving automation (e.g. automated lane cruising only, but no debris/obstacle detection and avoidance), (b) the uses of technologies (driving population, e.g. bus/truck/auto drivers, and how to use the technologies, e.g. dry surface only with driver sensing and backup), and (c) deployment strategies (i.e. sequencing and timing of the incremental introduction of automation technologies and their uses). Subject to the external events, these decisions collectively determine the success likelihood **of** AHS realization.

Future research work includes the development of (i) a complete catalog of human driving functions, especially those requiring driver intelligence and skills, (ii) an exhaustive list of relevant decision-making people and organizations, and (iii) a complete collection of deployment issues and difficulties. Finally, there is a need for a comprehensive list of possible external events that are out of the control of the AHS community. Based on these, realistic deployment plans can be devised and contingency plans developed.

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