

A Systems Analysis and Technology Roadmap for Autonomous Long-Haul Cargo Transport

by

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Abstract

The automotive industry is undergoing radical changes due to increased focus on electrification, automation, and ride sharing. Several OEMs and technology startups are making significant advances in autonomous technologies to enable driverless operations. Long haul trucking/ freight applications are expected to see the deployment of autonomous technologies before they are deployed in consumer cars given the deterministic operational design domain the trucks operate in. Most of the current R&D on driverless applications is focused on propulsion (i.e moving the vehicle from one point to another without the assistance of a human driver). To realize truly autonomous long-haul cargo transport, several other ancillary functions outside propulsion would have to be designed to be autonomous. This thesis attempts to take a top-down system thinking approach to explore such functions and propose architectures that would enable end-to-end autonomy and a roadmap towards achieving this over the next decade.

Use case analysis is performed to understand typical functions carried out during cargo transport. The technology readiness, societal readiness, and perceived return on investment of the technologies required is assessed. These high-level functions are then categorized into a set of architectural decisions and an architectural space is created by possible combinations of these decisions. The architectural space is represented as a technology readiness versus return on investment tradespace and architectural choices on the pareto frontier are analyzed. A technology roadmap of necessary is proposed. An analysis of possible off nominal scenarios is conducted, relative to the ability of the architectures to deal with them.

The main takeaway from this work suggest focusing on truck platooning as a near term goal towards partial autonomy which would realize immediate fuel saving benefits. Real time weight sensing, additional automation in performing activities like loading/ unloading cargo (for minimizing trip delays and increasing fleet throughput), pre-trip vehicle checks, automation in fault actions while en-route are also achievable within the next decade and would lead to significant cost savings and minimize operational losses for fleets. The analysis also indicates the need of onboard technologies to facilitate interactions with external human agents (a human machine interface) and increased reliance on faster data connectivity, transfer, and bigger data storage. The study of current state of art technological development suggests that the challenges in realizing autonomous long haul cargo transportation lie not only in the maturity of low TRL technologies, but also in the integration and tuning of existing technological solutions to suit the freight industry. Achieving full autonomy is not possible within next ten year timeframe due to the maturity of technologies required to address certain critical off nominal scenarios (e.g a truck

getting hijacked or vandalized, malicious actors filling incorrect fuel in the truck, cargo spilling out on the freeway while a driverless truck is enroute etc) and associated infrastructural frameworks (laws, insurance, ownerships). The study synthesizes these insights and presents the levels of autonomy that would be achievable within next decade and technological needs to achieve fully autonomous operations in longer run.

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List of Acronyms

ADAS	Advance driver assistance systems
AT	Autonomous truck
CAN	Controller area network
CPU	Central processing unit
DARPA	Defense advanced projects research agency
DOT	Department of transportation
DSRC	Dedicated short range communication
ELD	Electronic logging device
FMCA	Federal motor carrier safety administration
GPS	Global positioning system
HMI	Human machine interface
HVAC	Heater, Ventilation and Air Conditioning
IMU	Inertial measurement unit
IO	Input Output
LTE	Long term evolution
MIT	Massachusetts Institute of Technology
NHTSA	National highway transportation safety administration
NREL	National renewable energy laboratory
NVM	Nonvolatile memory
ODD	Operational design domain
OEM	Original equipment manufacturer
OPD	Object Process Diagram
ROI	Return on investment
SR	Societal readiness
TPMS	Tire pressure monitoring system
TR	Technology readiness
TRL	Technology readiness level
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
VIN	Vehicle identification number
VOIP	Voice over IP
USDOT	United States Department of Transportation

Chapter 1 - Introduction

1.1 – Background

With digitization and automation, several industries are undergoing radical changes. For the logistics and retail industry, automation in several steps of the supply chain is enabling companies to cater to increased demands, faster deliveries, and better customer experience. A big part of this industry is transporting cargo from production plants to warehouses or from warehouses to distribution locations around cities or destination locations. E-commerce has made these destination locations more heterogeneous, where the goods must be shipped not only to commercial establishments, but also to residential homes. Two thirds of all the goods shipped in the US are transported via roads, by trucks and trailers. In 2016, over 3.7 million heavy duty trucks were in operation and the industry has collectively had a revenue consistently above \$700B over last five years [1].

Increased e-commerce and the necessity of shipping goods as fast as possible, has led to increase in heavy vehicles on the road. Federal Motor Carrier Safety Administration (FMCA) estimates several thousand fatalities every year involving heavy duty vehicles [22]. It is also estimated that majority of such accidents are caused by driver error resulting from fatigue and on road stresses due to this increased volume of cargo transport. Adding driver assistance using autonomous (ADAS) technologies or even partial autonomy is expected to decrease the rate of on road fatalities.

Driver shortage and ageing driver population is also a serious problem faced within the fleet industry today. With increasing shipping needs, this shortage is only going to get worse in coming years. Varying levels of autonomies would assist in reducing the effects driver shortage. Autonomous functions in long haul cargo transport would also lead to increase savings in fleet operations. The overall system efficiency of delivering cargo from origin to destination depends of several factors including how the driver drives the vehicle. Adding autonomy to various functions, such as vehicle platooning, adaptive cruise control etc.. would lead to increasing overall efficiency.

Given the increasing reliance on faster, more efficient cargo shipping, driver shortage, increasing number of fatalities involving trucks and the need to improve overall fleet efficiency to minimize operational losses has necessitated the need of various levels of autonomies in today's long haul cargo transport. This study attempts to explore various avenues where partial or full autonomy can be incorporated in long haul trucking within next decade to alleviate some of the financial and safety concerns described above.

1.2 – Literature Review

1.2.1 Advances in autonomy

The airline industry has been the front runner of autonomous vehicles. Several of the aviation functions today are autonomous with a widespread social acceptance. Both technologies and infrastructure exist to allow airplanes navigate autonomously in cruise in varied weather conditions and air traffic situations with minimal interventions from the pilot. Most common automation systems in an aircraft are autopilots and auto throttles [31] which autonomously control the power to the engines in all situations. On board technologies and remote air traffic controllers assist pilots in making emergency decisions. The takeoff, landing and pre-flight checks still require human assistance, but proper processes and infrastructure exists today to assist the crew in performing these checks and maneuvers.

The three main areas of automation in airline industry are 1) Human Factors [62] (technologies such as autopilot, anti-skid braking systems, auto throttles etc. deployed to reduce human intervention), 2) Pilot and computer interfaces (automated warning systems and HMI to assist the pilot in monitoring and checking aircraft functions and ensuring proper configuration of the flight and 3) Flight management systems which automate most of the in-flight tasks of the pilot like determining flight position, managing sensors etc..

The auto industry can take several lessons from the airline industry to develop autonomous capabilities in the cars. Driving autonomously on the road with other traffic, pedestrians and roadside obstacles bring in more challenges to adopt full autonomy, but the basic themes from airline automation can be leveraged to develop technologies and interfaces that reduce driver's tasks and provide appropriate warnings where needed. There has been increased research and development in the fields of vehicle autonomy over the last decade [25]. DARPA challenges [26] pushed the boundaries further in the years 2004 through 2008 creating a self-driving cars community and spurred interest and innovation amongst industry and academia. Soon after, Google kicked off their self-driving car project [27]. Over the last decade, Google's self-driving car has accumulated over 20 million miles on public roads in around 25 major cities in the US [28], increasing the confidence in the technology maturation. Since Google's project started earlier last decade, we have seen several other automakers like Mercedes Benz, Tesla, Volvo, GM, Ford bring autonomous features in their brands or partner and acquire smaller startups like Cruise, Aurora, Agro for their technologies. Tesla's autopilot adds advanced driver assistance systems onto their vehicles that enhance safety and now the company is pushing the boundaries further by testing their full self-driving technology to achieve full automation [28].

This is a multi-faceted area of research involving engineers, manufacturers, law makers, policy makers, governments, and regulators. On a policy/ infrastructure front [56], cities and governments have started offering licenses to test and drive autonomous vehicles on their roads. Nevada was the first one to offer such licenses in 2012. Since then several cities and state have passed

legislations to allow testing of self-driving cars on their streets [29]. In 2014, NHTSA issued a draft of proposed rulemaking for autonomous driving. NHTSA also proposed five levels of autonomy [3] with decreasing reliance on human drivers. Regulations and standards [41], [42] around vehicle-to-infrastructure communication [61], cyber security [42] have also been drafted over the last five years.

1.2.2 - Autonomous Trucking

Compared to all the advances in passenger vehicle industry, the trucking industry has undergone very few major changes in last several decades. During WW1, the military was the first to use trucks to move ammunition. Usage of long-haul trucks for commercial transport saw an increase after WW2 and the construction of the interstate highway system. The Motor Carrier Act of 1980 [63] deregulated the trucking industry increasing the number of industries in operation while the Surface Transportation Assistance Act of 1982 [64] standardized the truck size and weight limits across the country. Since then there has been no major overhaul in the industry in the manner trucks are used and the types of trucks used to transport goods. The model of long-haul hub-to-hub transport coupled with last mile deliveries from distribution centers to destination points has largely been the same. In last few years truck OEMs have started installing driver assistance systems in an attempt to reduce accidents while only a couple years back the US government has mandated the use of ELDs [65] (Electronic Logging devices) to be installed on the trucks. Outside these, largely the way trucking industry operates, the routes, driver schedules, regulations have not been altered over last 50 years.

Recent advances in vehicle autonomy make up a good case for a potential disruption in this industry. World economic forum talks [33] talks about several advantages of autonomy in trucks in reducing labor costs, enhancing safety, increasing fuel efficiency, increased uptime etc.. Autonomous fleets would reduce resting times which would increase the shipping throughput thus bringing the shipping costs down while also reducing the delivery times making e-commerce more competitive [34]. The rate of accidents and fatalities due to driver fatigue is expected to go down, but on the other hand we may see intensifying insurance rates as insurance companies would have to deal with the risks of this emerging technology on a widespread scale. It could also result in redesign of distribution networks around towns where the truck needs to stop on a route (e.g for refueling) rather than places where driver must stop for rest. This may affect economies of certain towns which are built around a distribution hub and could also open avenues for entrants in the real estate market for new investments.

There are several startups backed by automotive OEMs that are working to improve the state of art of vehicle autonomy (hardware and software). Where companies like Optimus Ride, Motional or Cruise are focusing on geofenced applications in cities, companies like TuSimple or Ike Robotics are developing autonomy stack to be installed in long haul trucks. Waymo, a leader in vehicle autonomy, who has gotten permits to operate vehicles without a driver behind the wheel in the state of Arizona, has now entered the trucking segment as well.

From a technological standpoint, implementation of vehicle autonomy in trucking is considered to be a more deterministic problem with defined ODD (Operational Design Domain) which is restricted to highways; where generally lane markings are visible, lane width is consistent, route and speed limits are deterministic and there are very few off-normal incidents (pedestrians crossing on a red light, vehicles not yielding on a left turn etc.). On the other hand, it is also estimated that the truck driver shortage is expected to double over the next decade. Over 40% of total average marginal cost over last decade has been for spent on driver wages and benefits [4]. The driver shortage is leading to delayed deliveries and increased prices for goods. As e-commerce is on the rise, the shipping throughput is also expected to increase, thus worsening this situation. Driver shortage, changing driver demographic (ageing truck driver population) and rapidly increasing pay and benefits to retain drivers has led to increase in labor costs. Due to these, there is an increased interest in inserting vehicle autonomy in trucking applications.

According to the report [2], this adoption could happen over next 10 years. Futurebridge [36] talks about various technologies and expected adoption timelines for autonomous trucks from constrained platooning (deployed in parts today) through full autonomy by 2035. Peter Slowik and Ben Sharpe [37] perform an exhaustive analysis of various technologies currently commercially available and used to add autonomy in trucks. This adoption is likely to start with lowest levels of autonomy with constrained platooning; a technique to connect a convoy of manned trucks to a lead truck, allowing them to operate safely much closer together to realize fuel efficiencies benefits; and then progress towards more higher levels. NREL [5] estimates up to 65% of the miles driven can be driven under platooning which could realize up to 4% in fuel savings. As the technology progresses, the truck platoons (except the lead truck) could operate fully autonomously by following a lead truck (the one with the driver). The next technological milestone could be “constrained autonomy” where the entire platoon of trucks (along with the lead truck) could be operated without a driver. Drivers would take over at hubs on either ends to facilitate last mile deliveries.

The impact of such an operation could be significant [54], [55]. Autonomous trucks (ATs) will cut operation costs [53] and could alleviate industry’s capacity crunch. The total number of driving hours could rise from today’s maximum of 8hrs (to account for driver fatigue and safety) to almost 24 hrs. (where the truck can keep moving throughout the day). This will cut down on shipping times, consequently costs and fleets would be able to achieve higher throughput without increasing the fleet size. The American trucking association is estimating the current driver shortage to increase to almost 174,000 drivers needed by 2026 as younger generations are preferring alternate jobs. Adoption of ATs would alleviate this concern to some extent.

Most of the research and development in autonomous truck technologies has been focused on propulsion. It is seen from the airline industry parallel that it is imperative to give proper focus on non-propulsion related technologies and infrastructure required to be able to drive a truck from origin to destination without, or with minimal interventions from the driver. This may include some sort of vehicle management system (similar to a “flight management system”), a human-

machine interface (similar to cockpit displays and warning indicators in an airplane) and a traffic controller/ control room (similar to air traffic controller) to navigate the truck seamlessly through emergencies.

This thesis attempts to take a system thinking approach towards this problem. Leveraging architectural principles from [32] this work tries to understand high level functions required to be satisfied by the truck and then propose and perform a trade study for various technological concepts that would satisfy the functions. The work concludes by looking at the state of art and proposing a technology roadmap to achieve automation in long haul cargo transport.

1.3 - Research Objectives

All of the companies working towards achieving vehicle autonomy are solely focused on propulsion (i.e. driving from one point to another in an autonomous manner). While this is extremely important, it is not sufficient to realize a truly autonomous cargo transport. There are several functions that fleet managements perform today outside “driving the truck” which are critical for delivering cargo from origin to destination. The current fleet management function is responsible for routing the driver, emergency response, dispatch, alerting the drivers for impending weather conditions, maintenance and servicing of the vehicles and regulatory paperwork. Most of these functions involve interacting with the driver when the truck is enroute. With ATs, these functions may have to be re-designed and new functions may have to be added to eliminate failure modes that result in safety concerns, operational losses, or vehicle downtimes.

Disruptive innovation suggests that the new technology will be poor in executing existing functions while adding new functions. Many of the existing functions of fleet management that require interfacing with the driver to execute successfully, would have to be redesigned to interface with autonomy, while the autonomous systems on the vehicle should be designed to be capable of providing correct feedback needed to close the loop with the fleet management entities in absence of the driver.

The primary research objectives are

- 1) Evaluate existing fleet management functions and analyze how they would have to get modified to cater to vehicle autonomy
- 2) Evaluate off nominal scenarios and new failure modes that would arise due to autonomy
- 3) Perform targeted user study understand technology readiness, societal readiness and return on investment for critical functions that would be needed to be deployed to realize true autonomous cargo transport
- 4) Propose a technology roadmap for the next decade

The thesis looks at the next decade as a time horizon and attempts to provide a technology roadmap for technologies and processes needed (outside autonomous propulsion) to achieve higher levels

of autonomy in the trucking industry. Insurance, legal and policy constructs are outside the scope of this thesis.

1.4 - Thesis Outline

This thesis attempts to approach autonomous trucking from a systems perspective.

The study begins with stakeholder interviews. Insights from relevant stakeholders from academia and industry are summarized in Chapter 2. The chapter further investigates common operational scenarios that the drivers of a long-haul truck would experience while performing their duties. These operational scenarios form the basis of the study. Each operational scenario is analyzed further to understand common functions performed, by the system to navigate that scenario successfully. These functions and associated entities of forms satisfying the functions are discussed in this chapter.

Chapter 3 discusses the input-outputs and interfaces of the system and the proposes a conceptual architecture using these and the formal and functional decomposition of the system. The architecture is further refined into concepts of various subsystems needed to satisfy critical onboard functionality. Several architectural decisions are modeled for their technology readiness and return on investment which forms a basis of the analysis in following chapters

Chapter 4 and 5 discuss results from a study conducted to understand people's perception towards the proposed architectures in terms of their technology readiness, societal acceptance and perceived return on investment and ability to address certain off nominal scenarios. Several tensions between these figures of merit are discussed in these chapters along with architectures on the pareto frontier and how they satisfy the operational scenarios

The study concludes by taking all these insights and proposing a technology roadmap for next decade. This roadmap looks at today's technology trends, players in the market and their direction and attempts to recommend a path to achieve technology readiness for architectures on the pareto front.

The study considers the truck, a control room and interfaces between them as a system under study. External infrastructure required to support this system (roads, roadside sensors, satellites, dedicated pull over areas, maintenance depots etc.) is mentioned, but not in scope for this study. Furthermore, the analysis of organizational processes (partnerships between suppliers, insurance models, warranty models, legal and policy framework) required to deploy autonomous trucks in the US is also out of scope. The thesis primarily investigates technologies to be deployed within the system boundary to realize various levels of automation and proposes a roadmap for next decade and beyond.

Since most of the companies and tech startups are focused on perfecting autonomous propulsion, this study focusses on the functionality that would be required outside of autonomous propulsion to realize fully autonomous long-haul cargo deliveries in the US.

Chapter 2 - Concept of Operations

The previous chapter stated the increasing opportunity of autonomy in the trucking industry. The chapter also highlighted that autonomous propulsion, while extremely important and necessary, is not sufficient to realize a truly autonomous cargo transport. This chapter attempts to explore this claim further. The chapter analyzes current fleet management functions that are executed while delivering cargo from origin to destination.

The chapter explores typical use cases and operational scenarios first and then distills them into a list of common functions and interfaces needed for the said scenarios and formal entities that would support these functions. Having a clear understanding of various scenarios, functions needed in the system to enable proper operation across these scenarios and common entities of form supporting these functions, would provide necessary ingredients to design system requirements and conceptual architectures.

2.1 - Stakeholder Interviews

Several interviews were conducted to understand today's fleet management functions and how long-haul cargo transport is managed. The interviews spanned academia, fleet industry and OEMs. Two researchers from MIT were interviewed to understand the ongoing research in academia in the areas of urban transportation and vehicle autonomy. Interviews within the fleet management industry spanned across fleet manager and a truck driver.

Fleet manager interviews provided good insights on typical functions the fleet must carry out today to support delivering cargo from origin to destination and maintaining a fleet to enable these deliveries. Various aspects like – vehicle leasing and purchasing, maintenance, emergency response, regulatory requirements, insurance, and warranty frameworks were discussed in this interview. Two interviews with software engineers from OEMs developing autonomous and trucking technologies provided details on telemetry, data needs, data gathering and analysis technologies that the companies are currently working on.

An interview with a truck driver provided several insights on day to day driving operations, off nominal scenarios observed and typical driver responses to such unexpected conditions. The interview also provided information on different types of trucks and various controls and checks the driver must perform enroute to ensure safe deliveries. The interview also highlighted all the necessary functions a typical truck driver must do during their trip which provided inputs in designing concepts to enable these functions with varying degrees of autonomy.

2.2 - Operational Scenarios

These discussions with stakeholders provided details to design operational scenarios for autonomous cargo deliveries. Operational scenarios are typical conditions that the system entities (i.e truck, truck driver and fleet management) would observe during typical daily operations of cargo delivery and fleet management. Appendix A lists several such operational scenarios. Each scenario is further categorized into three modes – a) Normal operating conditions, b) Degraded operating conditions and c) Failure conditions. This section provides key takeaways from the scenarios. The scenarios provide details on

- 1) The actions a driver must take to satisfy certain conditions
- 2) The actions the fleet managers and ground crew must take to satisfy certain conditions.
- 3) The actions the truck's system must take to satisfy certain requirements.

Analysis of these scenarios provide guidance on typical functions the system would have to satisfy to be able to address the respective scenario. The next two sections distill all these scenarios into common functions that the system should be designed for and associated formal entities needed to satisfy those functions. These functionalities incorporated in the system would aid in addressing several of the common scenarios listed in Appendix A.

Category	Operational Scenario	Normal	Degraded	Failure
Interaction with human agents	Weigh station agent	Truck weighs itself on scales, produces a receipt and resumes trip when the receipt is verified by the agent. Truck mis-aligns on the weigh scales. Alignment of the truck on the weigh scales is performed according to DOT agents instructions	Alignment of the truck on weigh scales when DOT agent cannot take control and requires control room to remotely operate the truck	Truck is not able to weigh itself as the weigh scales are out of calibration
	Police	Truck gets pulled over by the police. The police checks registrations, permits and clears the truck for resuming the trip	Truck gets pulled over by the police. The police require the truck to produce paperwork, which the truck is unable to provide	Truck gets pulled over by the police for violating regulations. The truck is commanded to cancel its trip
	Border crossing agent	Trucks approaches state or national border, presents all the permits to the agent and resume the trip across the border	Truck approaches a state or national border but is unable to provide appropriate paperwork to cross the border	Truck takes a wrong turn and ends up at a border crossing without permits to cross the border
	Toll station agent	Truck arrives at the cash only toll station, interacts with the toll agent who charges the toll and then the truck resumes the trip	Truck arrives at the cash only toll station, but the toll agent is not able to deduct proper payment leading to trip delays	Truck arrives at an unmanned, but cash only toll station. The truck should have a way to not sit there indefinitely waiting for an agent
	Facility security	Truck reaches destination at regular hours. At the gate, the security agent scans the truck and allows it to enter the facility	Truck reaches destination at odd hours and the security agent does not allow the truck to enter the facility	Truck reaches the destination. The gate is locked and there is no security agent to summon next steps.
	Roadside assistance	Truck breaks down on a freeway, roadside assistance is scheduled. The roadside assistance crew arrive, fix the truck and truck is able to resume the trip	Truck breaks down on a freeway, roadside assistance arrives. They determine that the truck needs to be towed to a service station	Truck breaks down on a freeway and roadside assistance cannot be scheduled
	Agents at fuel stations	Truck enters a fuel station, an agent at the station fills the appropriate fuel and clears the truck to resume the trip	Truck arrives at a fuel station, but the fuel station is not manned	Truck enters a fuel station. The person at the fuel station fill diesel instead of gas and clears the truck to resume the trip
Pre/ Post trip activities	Loading/ Unloading cargo	The personnel loads the cargo, performs pre-trip checks and directs the truck to start its trip	The loading personnel loads the cargo but does not secure the straps properly	The loading personnel does not load the full cargo
	Pre/Post trip checks	The truck undergoes all the pre safety checks correctly and begins the trip	The truck performs all the pre trip checks, but flags a certain failure and does not begin the trip	Truck begins trip without doing pre trip checks
	Directing vehicle to depot	After unloading the cargo, the user directs the vehicle to the depot. The truck self drives to the depot and parks itself and schedules maintenance	The user directs the truck to the depot for parking, but parking space is not available	After unloading the cargo, a new user/ untrained incorrectly directs the truck to a wrong location.
	Directing vehicle to "truck wash"	The user directs the truck to a washing station. The truck aligns itself on the conveyor and transitions into an appropriate mode to enable wash	The user directs the truck to a washing station. The truck does not correctly align itself on the conveyor	The user directs the truck to a washing station. The cabin windows and cargo doors remain open and the interior gets damaged due to water and cleaning fluids
Off nominal breakdown response	Sensor failure	One/ Multiple sensors fail. The truck detects the failure and executes appropriate safety response	The sensor accuracy/ precision and resolution has changed over time and the sensed objects may be error. Dirt/ Dust/ Snow accumulation on the autonomy sensors. The truck looks for a range/tolerance in the sensed data and makes appropriate decisions	One/ Multiple sensors fail and the truck is not able to execute the safety response
	Vehicle failure in zero connectivity areas	Truck established connection and reports failure after recovering from connectivity loss	Truck should be able to establish request roadside assistance after experiencing failure in an area with no connectivity such that it has to come to stop	Truck experiences a failure and cannot establish connection at all
	Flat tire/ tire blow out	The truck detects a flat tire (or a blown tire) and executes the appropriate safety response	The truck detects a tire with low pressure (or a flat tire), but keeps driving as the presence of other tires would not lead to a catastrophic failure	Tire blows out on highway leading in uncontrolled propulsion
	Cargo door unlock/ cargo spill	Cargo door unlocks while the truck is in motion	Cargo door unlocks and cargo spills out. The truck detects the spillage and takes appropriate action	Cargo door unlocks and cargo spills out and leads to an accident
	Fuel leakage	Truck detects a fuel leak and takes appropriate action	Truck detects a fuel leak but get stranded as it cannot reach the nearest maintenance depot in time	Leakage sensor fails and truck is unable to detect a leak. The system should be able to get to safe stop in case fuel finishes without notice

Figure – 1 - Operational scenario – details

The operational scenarios are primarily divided into three categories and three conditions for each category. Figure 2 below shows the categories as rows and conditions as columns with total number of scenarios per category per condition as respective cell entries

	Normal Operation	Degraded Operation	Failure Condition	Total Scenarios
Interaction with Human Agents	7	7	7	21
Pre-Post Trip Activities	4	4	4	12
Off Nominal Response	6	6	6	18
Total Scenarios	17	17	17	51

Figure 2 - Operational scenario - summary

The three categories shown above are further described below

- 1) Interaction with human agents – There are several cases where a driver must interact with someone on the ground while hauling cargo. These interactions could come in the forms of – interactions with police, border crossing agents, destination facility security, roadside assistance services, weigh station DOT agents or agents at refueling stations to name a few. Today the driver performs unique activities during each such interaction. For instance, at border crossing, the driver would have to provide appropriate paperwork to clear the truck at the crossing. At a fuel station, the driver would have to either fill the fuel by themselves, or tell the agent which fuel (diesel, gas etc.) the truck needs and what quantity. The driver would also have to execute some sort of payment to complete the transaction. If the destination facility is gated, the driver would have to “sign in” at the gate security to be able to drive the truck to the loading docks. These interactions would still be required in autonomous driving scenarios where a human driver is not present. Hence, either some technology would have to be developed to facilitate such interactions, with the truck or a remote human entity, or proper infrastructure would have to be developed to eliminate such interactions all together. As an example, providing HMI (Human-Machine Interface) with displays for the truck to display necessary permits to border crossing agents is a technological concept to address one such interaction. The thesis explores such concepts and attempts to get user perception of their technology readiness, societal acceptance, and typical return on investment we would see if such concepts are to be deployed.

- 2) Pre and Post Trip Activities – There are several safety-checks the drivers and ground crew has to perform before commencing their trip. These include activities like loading the cargo, strapping or securing the cargo, performing all the paperwork, linking the manifest to DOT servers, checking tire pressures, leaks, headlight/ indicator light status, brake pressure etc.. With autonomy in the mix, autonomous sensor conditioning and calibration would also be crucial to perform before beginning the trip. At the destination, the cargo must be unloaded and the truck has to be driven to its next destination. This could be a parking garage, another loading dock, a truck wash etc.. Usually all loading/unloading activities are performed by the ground crew, while the safety checks are carried out by the

driver. Hence, eliminating the human driver necessitates a way to carry out the necessary checks in an automated manner. Technological concepts (sensors and actuators) or a shift in responsibilities from “driver” to the ground crew performing loading/unloading could address these scenarios. With autonomous trucks, certain new failure modes would also surface (Appendix A) and the system would have to be designed to counter their effects.

- 3) Off Nominal Breakdown Response – There are several scenarios and failure modes that could manifest when the truck is enroute. Today, the driver can take proactive steps to mitigate these failure modes. As an example, if there is a flat or tire blowout, if the cargo door unlocks and unsecured cargo is at risk of spilling on the freeway, if there is a fuel leak or a headlamp goes out – in all such scenarios, the driver can at least pull over and request for roadside assistance. The absence of human driver poses a difficult technological challenge to mitigate the such breakdown effects. Today’s sensors can sense a failure, but now the system would have to be designed in such a way that the it is able to not only sense and report the impending failure but also take proactive steps to mitigate its effects. Appendix A lists such off nominal breakdown situations and typical response that the system should be designed for.

Scenarios from each category are then divided into three conditions that can be seen during operations.

- A) Normal Operation – These are expected actions stakeholders (driver, ground crew and fleet managers and the autonomous truck itself) will perform that does not result in a loss. Here the term “loss” considers financial losses, operational losses as well as safety concerns. The category involves all the cases the stakeholders face that result in successful hauling of the cargo.
- B) Degraded Operation - These are scenarios which are not expected in everyday operations and would result in an operational delay, but the system would have to be designed to have contingency plans to recover from such scenarios in order to minimize delays. These are the conditions which designers and engineers should think about while designing and deploying autonomous cargo delivery systems and have fall back plans in place to minimize losses. Such scenarios may include (but not limited to) conditions where the cargo is not strapped properly, tire air pressures are low, headlights or indicator lights are out, trucks registration is expired or there is coolant/ fuel leakage observed from the truck.
- C) Failure Conditions - These are unexpected scenarios which can result into not only operational delays and financial losses but can also be safety critical. The system should have emergency operations to minimize the impact of the scenario on losses. The later chapters of the thesis provide typical off nominal scenarios originating from deploying autonomous trucking systems and which could be safety critical. The thesis tries to get a perception of the importance to and today’s technology readiness for countering such scenarios.

The scenarios were further explored for the events leading up to the scenario, the actors involved in the scenario, conditions of the system before and after the scenario (pre, post conditions) and typical sensors and actuators (technological concepts) needed to address the said scenario.

The common system attributes that emerged from this exploratory study were –

- 1) The truck, human agents, control room and roadside assistance units are observed to be the common actors playing a role in all of the operational scenarios.
- 2) The system would need some way for a third party (outside of the manufacturer or the operator of the truck) to “communicate with the truck”. These can be formal entities like calling provisions, keypad inputs, touch screens, QR/ biometric scanners etc..
- 3) The system would need way to display data to external entities. Data could be in the form of relevant paperwork, permits, registrations, receipts that are required to be produced to a third-party agent during the trip or could be acknowledgements of a successful transactions that the truck performs either with external agents or with the control room. This could be achieved with formal entities like indicators, displays, digital communication media (email/ text) etc..
- 4) The system would need a manual override in situations where either the autonomous propulsion fails or is unsafe (due to sensor failures) or conditions where the truck is not able to execute certain functions/ transactions autonomously (e.g failure to perform pre-trip checks, failure to align itself on the weigh scales etc.) . Such manual override can be of the form of a human being able to drive the truck or tele-operate it remotely.
- 5) The system would require cellular connectivity to a remote-control room to send and store data (for further analysis) and receive commands (to execute certain transactions or be able to control the truck remotely in case of emergency situations). Proper contingencies would also have to be designed to address failures in data transmission in areas with low cellular signal strengths.

The above-mentioned attributes would have to be incorporated in the system design. The next sections describe the system boundary for this work and then explore common functions and entities of form needed to address these system attributes within the boundary.

2.3 – System Boundary

Figure 3 shows the system and its boundary and interfaces which are in scope for this study. The system under consideration consists of the truck and the control room. The system diagram also shows subsystems that would be required to address the critical functional interactions between the truck, the truck and human agents and the truck and remote-control room.

This thesis will focus on “truck + control room” as the system under consideration. Analysis of functions that the truck and the control room would have to perform along with the entities of form to be deployed on the truck and in the control room will be analyzed. As shown in the figure below various onboard subsystem like access control, cabin control, conditioning subsystems, HMI, their

associated interfaces to onboard hardware (various sensors and actuators on the truck), truck's software and interfaces facilitating bi-directional data transfer and storage are well within scope of this work.

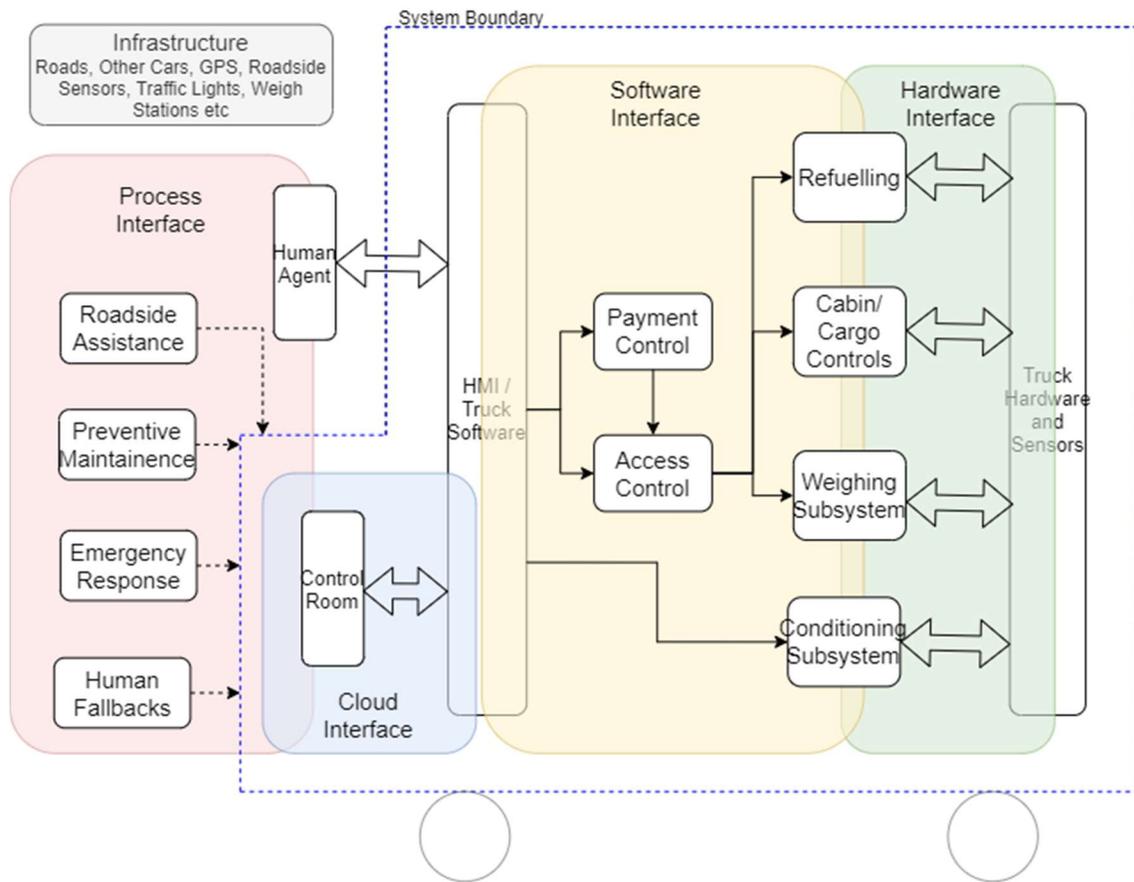


Figure 3 - System diagram

Off board technological infrastructure like roads, dedicated autonomous lanes, pull over areas, roadside sensors, GPS/ Satellite network, weigh stations (or their replacements) is critical successfully deploy autonomous trucks on the road, but will be out of scope for this thesis. Along with off board technologies, all the processes that would have to be put together to support autonomous cargo deliveries would be out of scope. This work will mention the importance of these technologies and processes but would not go into the details of designing architectures to support these.

2.4 - Function Decomposition

This section describes various functions that the system would have to perform to address the normal, degraded and failure modes listed in Appendix A across various categories. These functions are divided into following categories

1) Driving related functions

This category defines functions on the truck which would enable faultless driving from origin to destination. To name a few, these would include proper navigation (by avoiding non truck routes), real-time calibration and conditioning of sensors, detection and action on fault scenarios (like tire blowouts, leaks etc.), route optimizations which enable maximizing drive time while satisfying refueling constraints and trip delays due to road blocks and impending weather conditions.

2) Non-Propulsion related functions on the truck

This category defines functions which would be needed on the truck to enable several non-driving requirements that would originate from the scenarios for seamless cargo transport. These would include functions like the ability to connect to DOT servers, recording “black box” data, ability to detect unwanted, unsecured cargo, pre and post trip safety checking routines, navigation through weigh stations, detection and potential prevention of truck vandalization, detection and action on cargo spillage etc..

3) Interactions between the truck and a remote command center

A very critical aspect of autonomous long hauling would be the ability to remain connected to a central command station. Like the “air traffic controller” this command station would serve the purpose to guide the truck through any uncalled situations. This interaction would have to be bi-directional. Communication from truck to the command center would allow functions like transmitting desired data, transmitting failure conditions, requesting support from third parties and/or roadside assistance whereas communication from command center to the truck could be optimal route guidance, override commands, tele-operation (controlling the truck’s functions remotely)

4) Interactions between the truck and humans

This category would encompass all the functions performed by the driver today. Today’s human driver interacts with several human agents during a trip. These can be interactions enroute or at the origin and destination. Technology (and/or process) would have to be in place to execute all these interactions autonomously without the presence of the driver.

5) Interactions between humans

This category involves ancillary functions that would be required to facilitate autonomous cargo deliveries. By expanding the system boundary from the truck to the entire fleet management ecosystem, its observed that there are several processes that would have to be put in place to support autonomous long hauling. These processes would mainly involve

interactions with other humans/ organizations. Such include establishing partnerships with third party entities (like roadside assistance units, insurance companies, OEMs and software stack providers), maintenance processes and associated training that would be required to enable technicians to service these trucks. Analyzing architectures for these processes is out of scope for this thesis.

Figure 4 shows various functional interactions between different stakeholders. Appendix B lists all the relevant functions that would be required to address the operational scenarios listed in the above sections. This list does not include all the autonomy software requirements for perception, localization, planning and control of the vehicle since all the autonomous vehicle companies are already actively working on perfecting these. The list includes additional functions, outside of autonomous propulsion, that would be needed for seamless cargo transport.

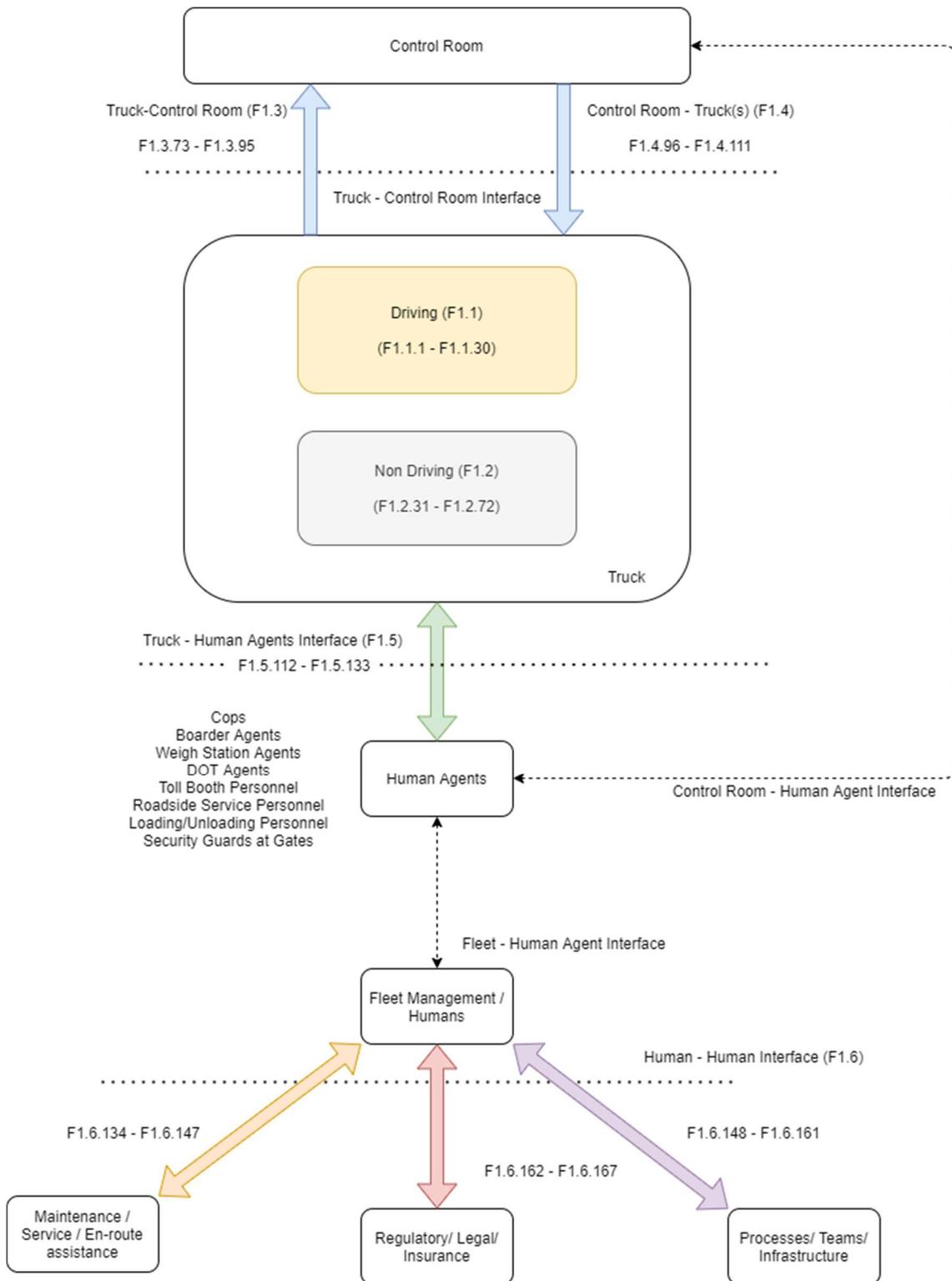


Figure 4 - Functional decomposition

2.5 - Formal Decomposition

The operational scenarios call out sensors/actuators needed and typical inputs and outputs of the system satisfying each scenario. This chapter explores formal decomposition of the entities of form that would be needed to satisfy the functions listed in Appendix B. A L-2 decomposition of common formal entities is shown in Figure 6. This type of decomposition was selected so that it is easy to map the functions to corresponding entities of form and hence facilitate modularization of the system as shown in the figure 5 below. The modularization would aid in resource mapping and allocation during system development. This type of decomposition is just one proposed way of decomposing and modularizing formal and functional entities and could vary based on the approach adopted by system architects. The scope of this thesis limits this decomposition to “truck + control room” as a system. Formal and functional entities outside this system boundary will be considered out of scope for this study.

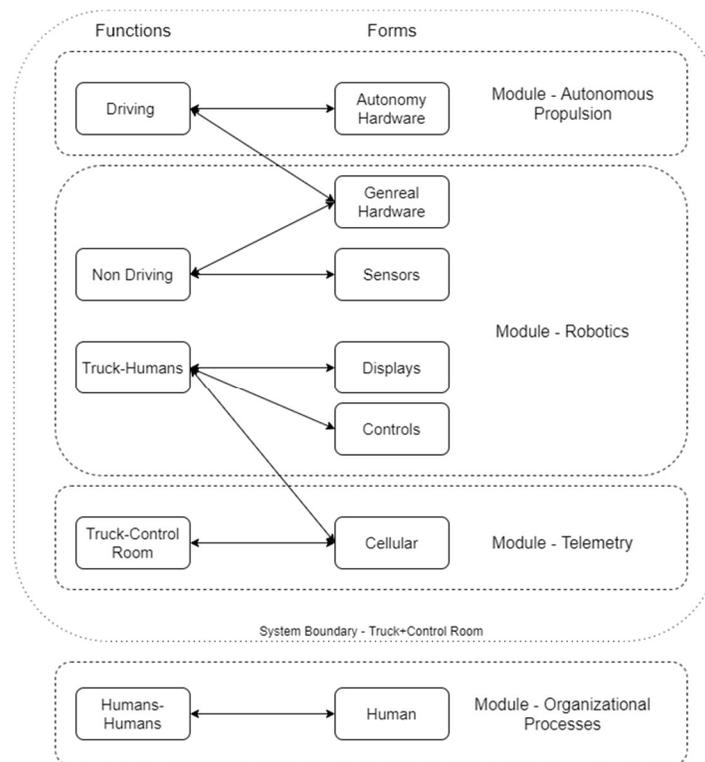


Figure 5 - System modularization

These formal entities are grouped into seven main categories. The controls and displays category would facilitate “truck-human” interactions. The formal entities under “Sensors” and “General Hardware” category would play a role in satisfying non-propulsion related functions where as “Autonomy Hardware” would be used for propulsion functions. The bi-directional communication between the truck and command center would be facilitated by the “Cellular” category whereas

the various entities of form under the “Human” category would play a role in designing for interactions between humans.

The formal decomposition and categorization maps back to the functional decomposition, which in turn maps to the common scenarios that would be observed in autonomous cargo deliveries. This mapping would set the stage for conceptual architecture of a long-haul autonomous trucking system.

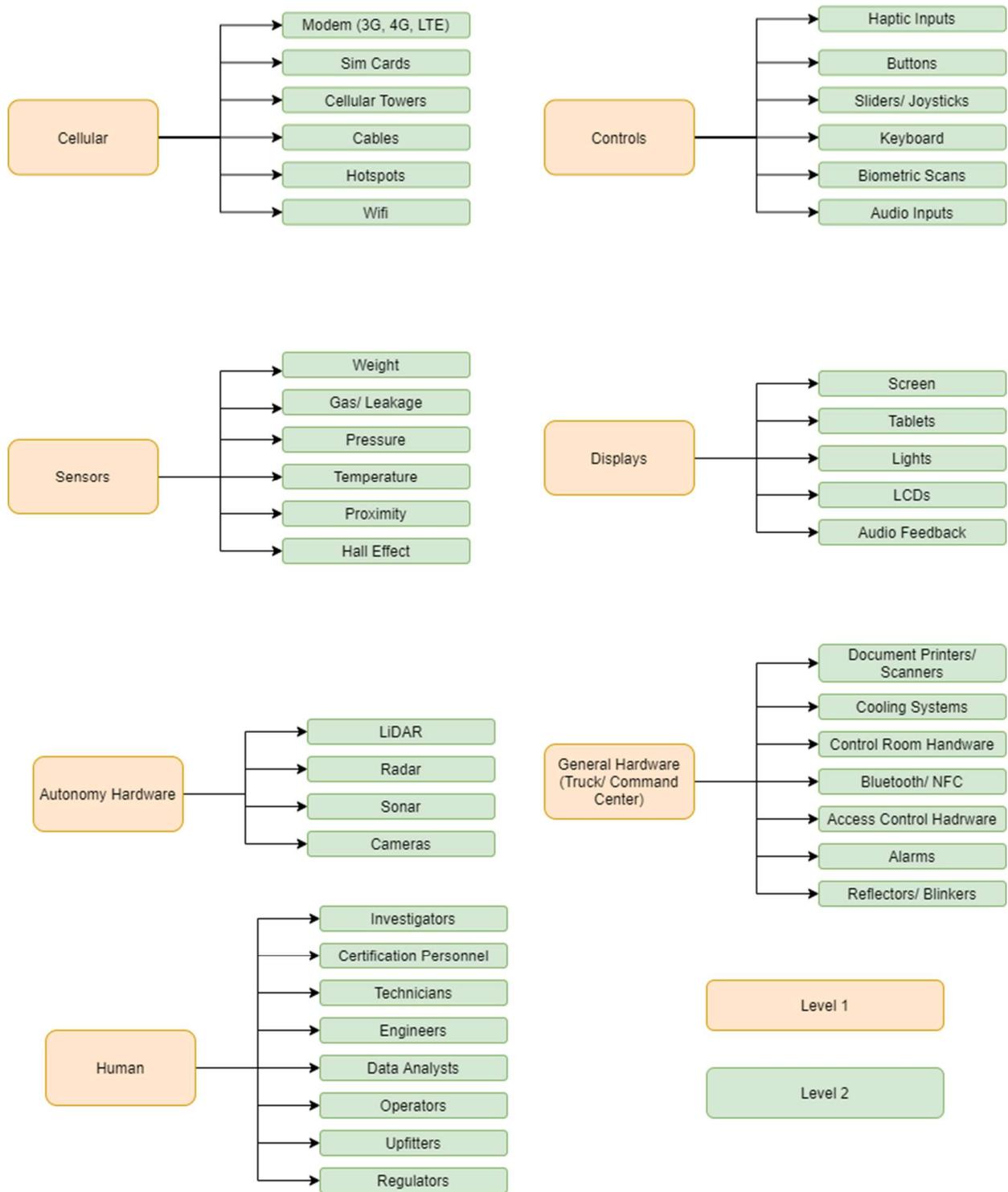


Figure 6 - Formal decompositions

Chapter 3 - Development of System Architecture

This chapter explores various architectural decisions needed to address functions that originate from normal, degraded and failure mode scenarios described in previous chapter.

3.1 – System IO

The operational scenarios were examined to analyze common inputs and outputs needed to achieve the critical functions for autonomous cargo transport. These exclude the inputs and outputs for autonomous propulsion as the focus of this thesis is to study non-propulsion related design decisions required to achieve autonomous cargo transport. The figure below shows the list of common inputs and outputs required for satisfying functional requirements from Appendix B

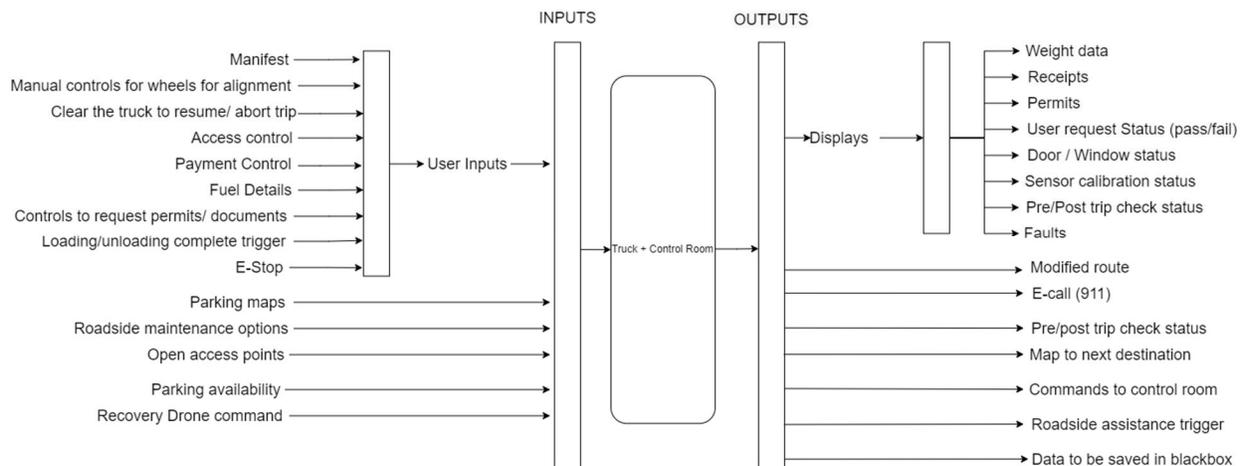


Figure 7 - System IO

The architecture chosen should satisfy each of the said operational scenarios in their normal, degraded and failure modes. This means, every subsystem should have contingencies planned in cases of system failure or undesired emergence. This chapter will also explore these contingencies and places where pure technological solution may not be sufficient in addressing failure mode.

3.2 – Interfaces

The system diagram in Chapter 2 shows four types of interfaces namely software, hardware, cloud, and process interfaces with are within the system boundary. This section describes the need for these interfaces and gives an overview or design requirements for these. The next sections describe certain critical subsystems that would satisfy functions across these interface boundaries.

The software, hardware and cloud interfaces can be considered as technological interfaces where technological concepts would aid in designing these interfaces. The process interface are the interactions required with external organizations to satisfy certain functional requirements called out in Appendix B.

3.2.1 - Software Interface

This interface would include the software necessary to perform all the functions outside autonomous propulsion. Software interface would provide design choices for the following functions

- Ability to authorize access to the user to interact with the truck
- Ability to allow user to charge payment for operations like truck wash, refueling, toll charges, on-road violations etc.
- Functionality to display relevant data on the trucks infotainment system (manifest, permits, activity status indicators etc.)
- Support for manual override operation
- Functionality to sense data from various non-autonomy sensors and instruct the propulsion system for safe operation. Software functionality to perform sensor calibrations, check pressures, temperatures, leakages,
- Functionality to establish connectivity with a central database to share data (manifest, meta data for any human/truck interactions etc.) and with control room to send data and receive instructions
- Ability to schedule roadside assistance with authorized third-party providers
- Advanced rerouting functionality

3.2.2 - Cloud Interface

Cloud Interface can be considered as a subset of software interface. This serves a functionality of maintaining connectivity with the truck as well as with third party entities (like first responders, roadside assistance etc.). This interface between the control room and the truck would be essentially used for sending/ sharing data, accepting remote commands from the control room, remote fault monitoring, initiating emergency calls, remote rerouting assistance, route optimizations under bad weather conditions, roadblocks etc..

The cloud interface also serves the need for an interface between the control room and third-party entities. These would be entities like roadside assistance crew, maintenance crew, first responders, other autonomous vehicles in the fleet. Fleets would have to establish certain partnerships with such entities (more described in the process interface) and have a universal way of establishing connection to these.

3.2.3. - Hardware Interface

Hardware interface is between the subsystems and individual sensors. Various sensors and actuators would have to be mounted and routed on the truck (apart from the usual autonomy sensors) to achieve a failsafe autonomous operation. These would come with their own harnesses and mechanical (packaging constraints, reliability) and electrical (noise susceptibility, SN ratio)

design constraints. The system would have to be designed taking these into consideration. Formal entities listed below would be used in designing concepts for this interface.

- HMI sensors and actuators (haptic, capacitive, biometric, voice, buttons, dials, joysticks)
- Sensors for cabin control (proximity, magnetic, capacitive)
- Conditioning (weight, pressure, temperature, leakage, strap tension)
- Actuators for cabin control and conditioning (linear motors, solenoids, electromagnets)

3.2.4 - Process Interface and Organizational Structure

To deploy autonomous trucks in near future, certain organization and process infrastructure needs to exist. It is apparent from the operational scenarios and failure mode analysis that just technology won't be sufficient to realize autonomous trucking in a cost-effective manner within next decade. This thesis assumes that human interactions are necessary to realize the vision of autonomous long-haul deliveries. This sections briefly describes the kind of interactions that would be needed but a full analysis of these interactions and process additions is out of scope for this thesis:

- Manual Overrides – We anticipate every autonomous truck would have a manual override mode and all the functionality for a human to drive the truck from one location to another. This means that the trucks would retain steering wheels, accelerator, brake pedals and all the cabin controls including HVAC. The truck could have enhanced access control features to only allow authorized users to access the truck and be able to drive it.
- End Point Activities – As mentioned above, we envision the end point activities would involve humans in immediate future. We anticipate humans would still own the following activities
 - a. Loading, unloading the cargo
 - b. Securing the cargo and checking whether it is secured
 - c. Filling in the manifest and linking it to DOT servers
 - d. Performing pre trip checks for functionality outside autonomous propulsion.
 - e. Driving vehicles to parking areas, truck washes, maintenance stations
- User Management and Access Control - Since user authorization may be critical for accessing truck's functions and overrides, the fleet management would require having certain back end operations for granting appropriate access levels to users and tagging them with trucking assets. This may warrant formation of an entity within the fleet to manage user authentication and associated hardware (database, servers etc.) to securely store this data.
- Refueling infrastructure – Refueling the truck fully autonomously is an extremely complex technological challenge. Soon, we envision fuel stations would be manned. Proper precautions should be taken to minimize the possibilities of filling in the wrong fuel (gas v/s diesel) and hence accountability of refueling personnel would be very critical in such scenarios. We envision this to be a third-party entity providing refueling resources at the fuel stations. The meta-data collected during refueling process (ID of the truck/ fleet, ID of user, amount of fuel filled, other service performed (filling air, cleaning sensors etc.)) could be used in the business model of such entities in the way they would charge the fleets.

- Roadside Assistance and Emergency Response Infrastructure – The operational scenarios listed in Appendix A illustrate several degraded and failure modes, some of which can be mitigated using technology on board, but some of which would require human assistance. Roadside assistance units are envisioned to provide such an assistance for breakdowns and off-nominal failure modes. In the near future we anticipate fleet management to carry out this function. The fleet management can deploy roadside assistance units themselves or can partner with third party entities for such a service. The upside of having it inhouse is to have full control over the service, but it would come with significant upfront investment in hardware, real estate, personnel, and training to be able to do it in house. Third party units would have this infrastructure and fleet can minimize the overhead by outsourcing service to third parties.
- Maintenance - We envision three types of maintenance programs that would have to be offered by the fleet management – a) roadside/emergency maintenance, predictive maintenance, and periodic maintenance.

Roadside Emergency Maintenance - Several aspects should be considered while designing such an infrastructure like-

- Managing of this entity
- Technician authorization and skills training
- Data analysis and troubleshooting
- Infrastructure to schedule and perform emergency assistance
- Real estate for deployment of roadside assistance units.

We anticipate a third-party service entity managing these to minimize the overhead on fleets. This third party could be a subsidiary of the OEM. Skill training programs would help in upskilling service technicians with the latest technology. Software provider companies would also be an important stakeholder as we envision, they would have data engineering capabilities to scrape the data coming from autonomous propulsion systems.

Predictive Maintenance – Predictive maintenance would become a significant part of fleet management to maximize the uptime of fleets. With advances in connectivity and data science, huge amounts of data can be continuously analyzed to look for patterns and deviations. Data from all sources (pre/post trip check data, periodic maintenance data, realtime on-road data, data when vehicle is parked etc.) would feed into the data science algorithms. Several insights (like some of them mentioned below) could be generated from such data analysis and maintenance activities can be scheduled in the trucks downtime.

Periodic Maintenance – Every fleet has periodic maintenance plans and infrastructure. This infrastructure would get updated and the technicians would get trained to perform maintenance on the autonomous propulsion system as well. The technicians would have to be reskilled in sensor calibrations and cleanup. Universal standards would have to be developed to understand which sensor/system is “out of tolerance”. Without a standardized architecture, servicing autonomous

propulsion system would be extremely difficult and subjective to the knowledge of the technician. Proper manuals would have to be made and delivered with the truck explaining the autonomous propulsion system and the location of all the hardware. A parts warranty system would have to be designed for autonomy hardware. Since technically this hardware (and associated software) would come from suppliers to OEM, the existing supplier warranty architecture can be leveraged to extend warranty programs to these additional subsystems.

3.3 - Conceptual Architecture

Figure 8 shows an OPD (Object Process Diagram) of autonomous cargo delivery systems. The operational concept begins at loading the truck with cargo. The truck performs all the pre-trip checks before commencing the trip. Various sensors can be used to perform these checks (like checking tire pressures, cargo straps, door locks, brake function etc.). If the prechecks pass, the truck starts driving to destination, else it shall abort the trip and contact relevant authorities. Enroute, the truck can experience various scenarios like – crossing a border where the truck should interact with border patrol, driving through a car wash, where truck would have to ensure all the windows are rolled up or off nominal scenarios like detecting a flat tire and needing to pull over. Several sensors can be used to detect these off nominal conditions and certain displays/ controls would be needed to interact with external entities (like border crossing agents). The system should be designed with contingencies if any of the automation fails. As a contingency, a manual override shall be present for a human to take over the functions of the system. There shall be a way to schedule roadside assistance as well in case of emergencies. The truck would finish the trip at its pre decided destination. At the destination, the truck would align itself to the unloading dock where either machines or humans can unload the cargo. The OPD shows entities of form needed to satisfy these functions that the system would have to execute in this operational concept.

Several subsystems would have to be designed to satisfy the functions shown in the architectural diagram. The next section illustrates some common subsystems outside of autonomous propulsion that would be needed to successfully carry out the critical functions.

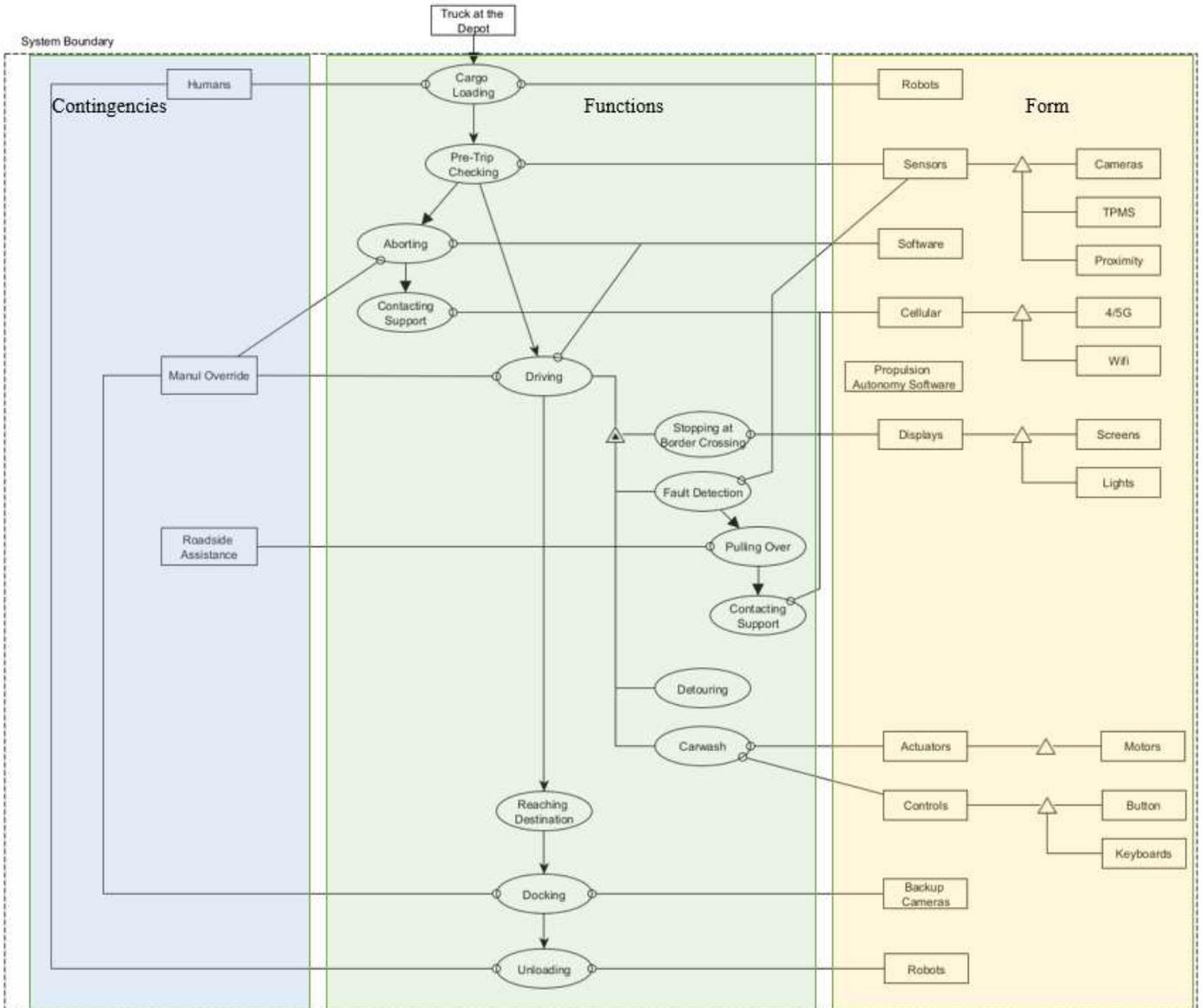


Figure 8 - System architecture

3.4 - Subsystems

Operational scenarios have provided a way to understand critical functional requirements, formal entities, inputs/outputs, and interfaces needed to design for the normal, degraded and failure mode conditions to achieve autonomous cargo deliveries. This section explores concepts of certain subsystems that would play a role in achieving the critical functionality needed for autonomous trucking. These subsystems are conceptualized to satisfy common critical functions listed in Appendix B. The design is intended to be solution neutral and does not recommend any specific entity of form to satisfy the function of the subsystem in discussion. Further trade space analysis of cost v/s utility would be required to refine the solution neutral subsystem space into a solution specific choice.

3.4.1 - Access Control Subsystem

The primary function of this subsystem would be to ensure proper access only to the users who are authorized to interact with the truck. This set of users would include – fleet management personnel, loading/unloading crew, personnel interacting with the truck from control room remotely, agents enroute which may include, but not limited to – DOT agents, police, roadside assistance personnel etc..

Proper access control is necessary to avoid unauthorized people getting access to the truck controls which may lead to truck vandalization, operational and financial losses and in certain cases safety hazards. Access control would protect against scenarios like random people entering the truck cabin, thrashing the seats, stealing cargo (leading to operational and financial losses) or even changing cabin control settings (which could lead to safety hazards).

To enable proper access control, each truck should be connected to a database of authorized users. The HMI on the truck should allow the user to scan their identification which then would be verified against a database to grant access. To allow for access control to work properly even in low connectivity areas, this database should be made available offline (on the truck). The database can be updated periodically when the truck is in a good connectivity area (e.g. a depot). The HMI should also enable some indicators for the user to know whether the access was granted.

The other side to this “on-truck technological solution” is to have all authorized users provided with access devices. These identification devices (cards, chip, barcodes etc.) should be linked to the central database and updated periodically to allow users access to required trucking assets. There needs to be a centralized agency (preferably a joint commission of all fleets and DOT) which issues and manages these identification cards to all authorized users. Users should be vetted before they are granted access. The access parameters can be user id, truck VIN, access period (24x7, only weekdays, only certain shifts per day etc.), access level (cabin control, refueling, manual override, remote navigation etc.) and every access attempt should be timestamped and logged within the DOT/ fleet management system.

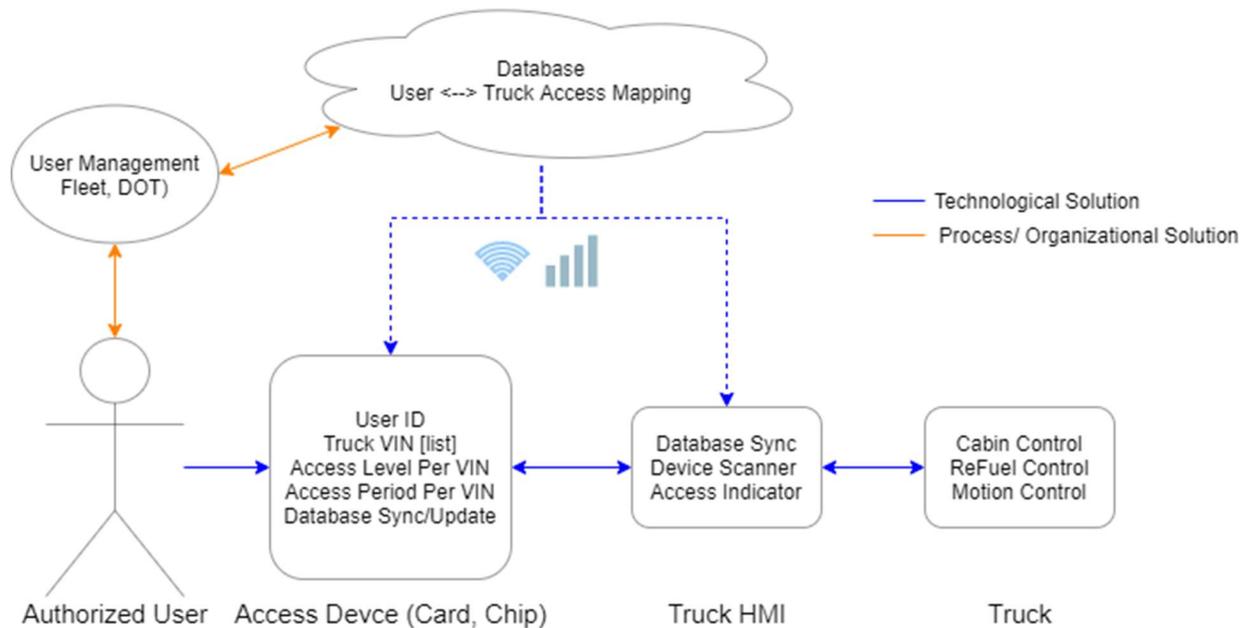


Figure 9 - Subsystem – Access Control

Access control still has failure modes which cannot be mitigated using current technological solutions. Situations like stolen access devices, smashed windows to gain access to interiors are always possible even with today's technology. In such cases, a process can be instituted to recover from such conditions, but the recovery processes themselves (internal investigation, lodging an FIR, police investigation, insurance investigation) would have their own costs associated with them. New technologies can be developed (advanced smash-proof window material, but that would come with added costs as well. Near term solutions can be installation of cameras on the truck to detect unauthorized access and raise a complaint against potential vandalization to recover from the damaged caused.

Thus, Access Control subsystem is necessary to grant and track proper access and prevent unauthorized users from accessing the truck. This can be achieved by a combination of on-truck technologies and fleet management processes, but it won't prevent all instances of unauthorized access (at least for the foreseeable future)

3.4.2 - Payment Control Subsystem

The payment control subsystem would be used to deduct any charges necessary during the truck's daily operation. When driver is replaced by autonomous technologies, all the instances where the driver must make a payment would have to be automated as well. Few of such instances would be a) Payment at a refueling stop, b) a truck wash center, c) if the truck gets ticketed due to violation.

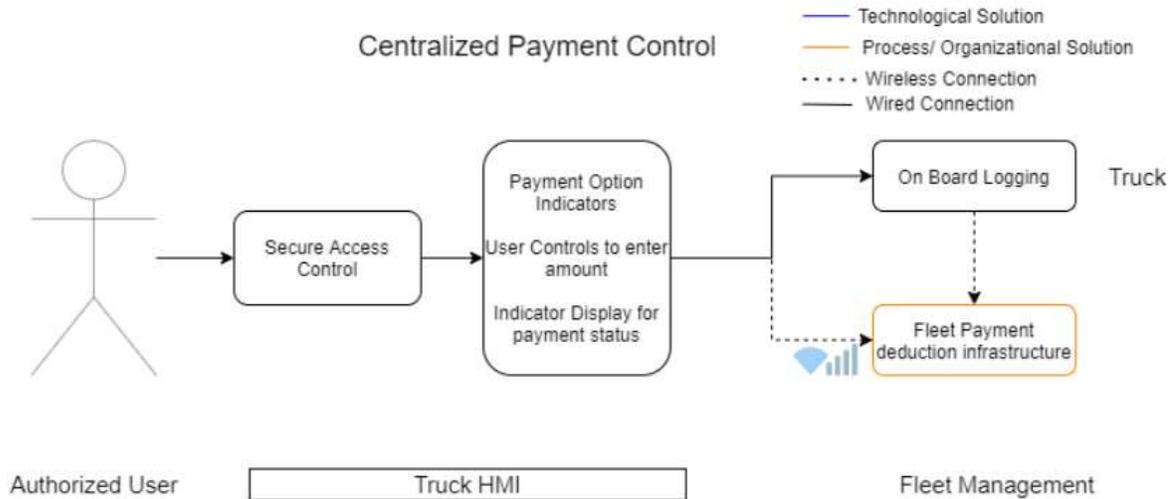


Figure 10 - Subsystem – Centralized Payment Control

The payment system can be built in a centralized or a distributed format. As shown in figure 10, in a centralized system, a payment portal can be on every truck secured by access control. Once the authorized user is identified, the user can enter the amount to be deducted for the operation using the truck’s HMI (This interface can take a form of a touch screen, press buttons or a keyboard along with an indicator display). The HMI could further be designed to give the user pre-selected options to avoid incorrect payment entries. In cases where none of the displayed options are viable, the truck can give a way for the user to enter custom amount provided that this request is verified before the payment is processed. An onboard storage of payment request may be needed to be able to process payment in low/ zero connectivity areas. In such cases, the truck’s HMI should display relevant tracking information to the agents as the payment requests would get executed later. The advantage of such a system is that the onboard units can be directly linked with the fleet management servers and there won’t be any new infrastructure needed outside of the truck’s payment control system to manage these payments. The downside of this approach is additional cost of hardware needed to be installed on the truck to enable this. This hardware is rather a duplication of hardware which is usually present at all such locations where some sort of payment is needed. And hence the distributed system is also evaluated in this section.

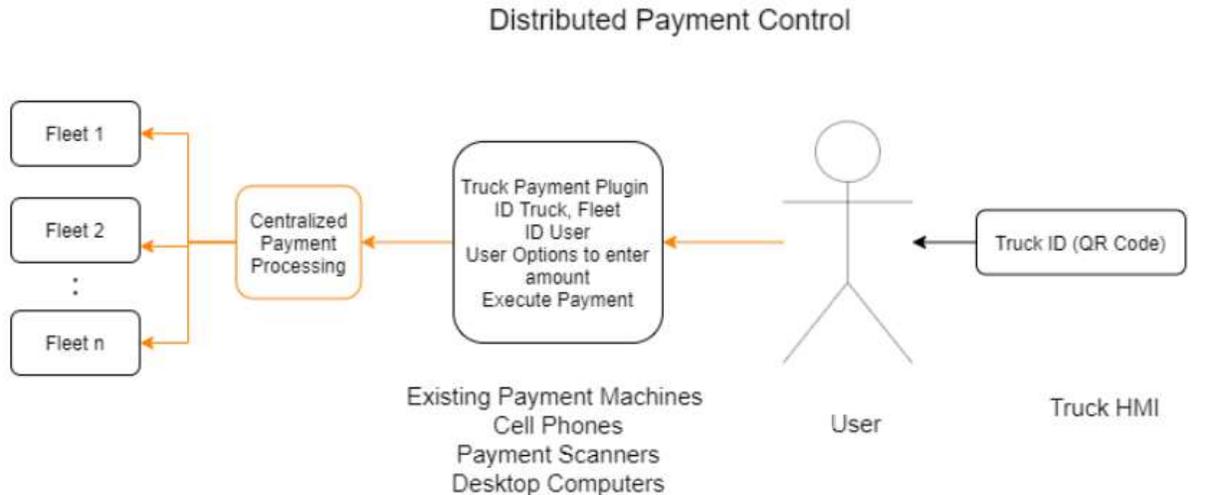


Figure 11 - Subsystem – Distributed Payment Control

In a distributed system as shown in figure 11, the payment control can reside with the agents requesting payments. The agents should be able to scan the truck for some sort of identification, which, along with their own identification, would then be used on their handheld devices (cell phones, payment machines) or desktop computers to deduct payment. The advantage of such a system is that such distributed payment hardware infrastructure already exists at such locations (fuel stations, wash centers) and can be updated with custom software allowing these agents to “charge” the truck. The downside of this approach is that there needs to be a whole new infrastructure to connect these payment devices to individual fleets who own the truck. If hundreds of fleets leverage such a system, then an independent off-board entity’s existence would be needed to manage the payments. This would require an organizational infrastructure to design and manage such third-party payment entities working with the fleets. These entities can employ personnel at such stations to deduct correct payments from autonomous trucks.

To leverage such a system in immediate future, the truck’s ID can encode fleets information and payment deduction methods which can be scanned at such stations. In this manner, no new organizational or technological infrastructure would be needed to allow payment processing. Although this opens several security challenges that the system designers would have to account for to prevent unauthorized deduction of payments. Access controls system on the truck can be used to add an additional layer of security to only allow authorized users access fleet information.

3.4.3 - Cabin Cargo Controls Subsystem

Cabin controls subsystem should be designed to control the cabin and cargo area functionality. This would include controlling doors and window movements, locking mechanism, fuel port access and providing options for cabin climate control and infotainment under manual override conditions.

Door and Window status sensors and actuators would play a significant role in this subsystem. In a regular non autonomous truck, the driver is capable of taking appropriate action (aka actuators)

on conditions where cargo door is ajar or cracks open, or a window remains open when it is supposed to be closed (e.g. when the truck is undergoing a wash). In such instances, either the driver's presence of mind, or an indication from someone on the road (honking, shouting at the driver) serves as indicators (aka sensors) to raise awareness towards such situations.

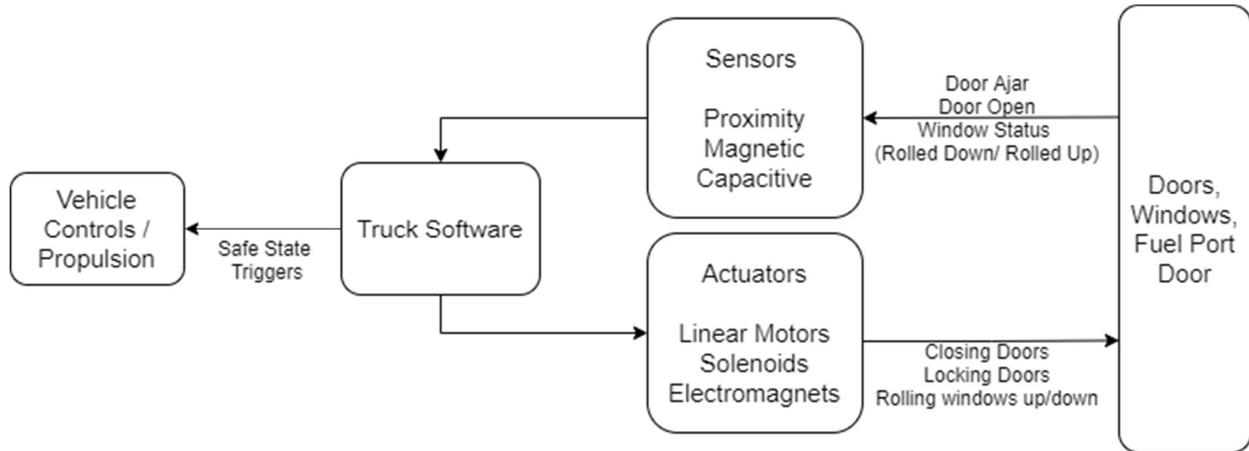


Figure 12 - Subsystem – Cabin Control

Due to the absence of driver in autonomous trucking, such instances would have to be detected using technology. Door ajar, Door/window open sensors would have to be mounted at each of the doors and windows. Proximity sensors, magnetic/ capacitive sensors can serve this purpose. Doors of several higher end vehicles and charge port doors of electric vehicles today already have such sensing mechanism, so this technology exists in the market. The difference is, today, these sensors just sense the status of the door and provide a user telltale on the dashboard. Due to the absence of the driver, several actuators would have to be mounted on the doors and windows to forcibly close them (roll them up) and lock them. Linear motors, solenoids, electromagnets are some of the actuators that can be used for this purpose.

The truck software should also have some sort of a safe state reaction if cargo door opens during a trip as there could be a safety hazard of cargo spilling out on the freeway. The truck could go into a mode of reduced speed (limp home) and pull over until the actuators are able to close the doors and lock them.

This adds cost to the system, but the all the technology exists today to implement such a subsystem in immediate future. Further, there are failure modes where these actuators could wear out and fail over time. One way to ensure safety is to check for secured doors and windows during the pre-trip conditioning checks that the truck would execute right before commencing a trip.

Cabin controls also include climate control (AC/ Heat) and infotainment (radio, music). In a fully autonomous operation, where driver is absent, there would be no need of controlling the cabin climate. The AC or cabin heater can be turned off in this mode to save fuel. Climate control and infotainment should be only allowed when the truck is running in a manual override mode. In near future it is unlikely to have a fully autonomous truck with no human intervention and hence

eliminating HVAC and infotainment in its entirety seems unlikely, even though they would bring some significant cost savings per truck.

3.4.4 - Conditioning Subsystem

The primary intention of this subsystem would be to certify the truck for commencing the trip. In regular non autonomous trucking operations, the driver executes a range of checks before starting to drive. These checks include checking the tire pressures, checking tires for flats, inspecting whether the cargo is secured correctly, verifying operations of any lift gates if present, checking brakes, lights, wipers etc. The driver also performs periodic checks after every few hundred miles to make sure the truck is still good to keep driving. The absence of driver necessitates the need of performing these checks in an autonomous fashion at least to some extent.

This subsystem would involve a range of sensors and actuators to perform certain checks after loading is finished and before the truck starts the trip. These checks can be divided into two categories, a) checks for making sure the autonomous propulsion hardware is within spec and b) checks to verify if all other truck systems are functioning properly. The truck HMI would provide diagnostic indicators to let proper stakeholders know if the truck has passed all the checks. The truck HMI and the software should also facilitate scheduling of assistance services to address the problems found in the conditioning checks.

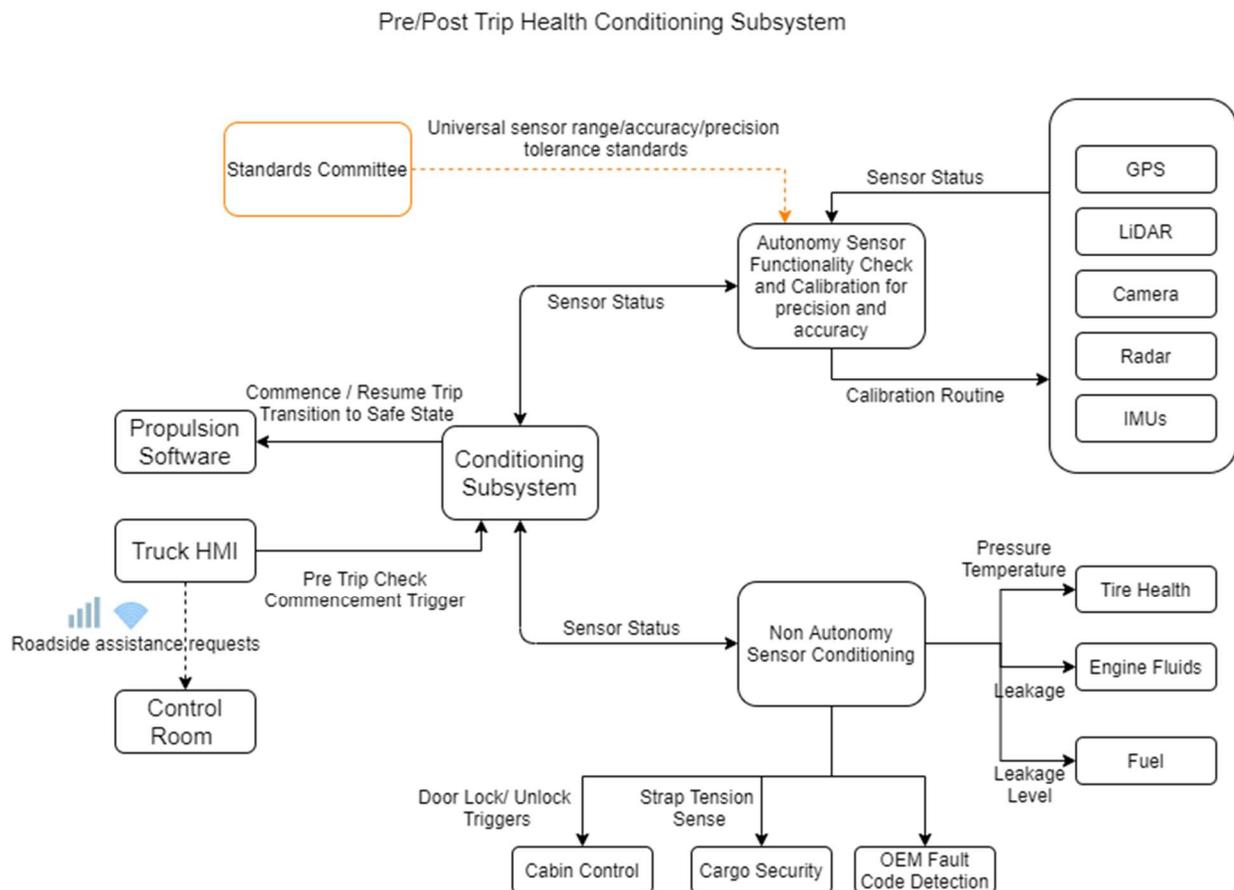


Figure 13 - Subsystem – Conditioning

3.4.4.1 - Checks for autonomous propulsion system

Autonomous propulsion sensor functionality is extremely important to enhance on-road safety. The truck should check for functionality and not start the trip if a certain sensor is deemed to be non-functional. Autonomous sensor calibration would also be an important aspect of this subsystem. All the LiDARs, Radar, Cameras, IMUs and GPS sensors should be checked for precision and accuracy. If the sensor readings are out of spec, then a self-calibration routine should be performed by the truck to align the sensors with published autonomous vehicle standards.

This necessitates the need for an entity which would publish expected tolerances for such autonomous vehicle sensors. We could expect this entity to be a joint group between OEMs, government, and the academia. Without proper guidance from a published standard, it would be difficult to universalize the calibration requirements, which in turn may result in sensor variances across OEMs potentially leading to on road safety hazards.

3.4.4.2 - Checks for non-autonomy related functionality

This subsystem would also be designed for checking tire pressures and temperatures, engine fluid or fuel leaks, gas leaks in case of hazmat trucks. Pressure, temperature, and leakage sensors would be useful in satisfying these needs. The subsystem would also check whether the cargo has been secured correctly. Sensors to measure the tension in the cargo straps may come useful in designing such a feature. The truck software should also look at any active fault codes which would lead to setting a check engine light on the truck. The software should prevent starting the trip if any of such conditions are true.

One can argue that many of these non-autonomy checks can still be performed by a human. This is true when the truck is still at the loading dock. We estimate that in near future, the cargo would still be loaded and unloaded by a human. Hence this person can also be trained to do these checks which are usually done by the driver. This would reduce some complexity in the system and could bring in the deployment timelines. There would have to be personnel training programs to train humans to perform all these checks, but existing driver training programs can be modified to suit autonomous trucking.

The tricky part comes when these checks must be performed enroute. Technology can come to assist in such scenarios. If any of the above-mentioned checks fail, the truck can transition into an appropriate safe state and report its status to the control room. Either the control room or the truck itself, can initiate a call to roadside assistance unit to schedule service on the truck. This necessitates the need of such an organizational infrastructure where trained technicians are available for roadside assistance and can be scheduled by the truck or by the control room. The next chapter on maintenance would go into more details on this.

Adding all the sensors (pressure, temperature, leakage, tension) and associate software adds complexity to the system and additional failure modes. To be able to deploy autonomous trucking in immediate future, the fleets can leverage refueling stops on the route to perform these checks manually. A trained person can be deployed at such refueling stops where such on-road checks can be performed. This would still not be as effective as a driver doing periodic checks because the driver can always get informed “real time” between the check periods by other drivers if

something on the truck is failing. Hence, we estimate periodic checks at truck stops to be only a stop gap solution until a cost-effective technological way of doing real time checks is deployed. Real time checks would mitigate the probability of on-road accidents and incidents, but would come with added complexity, cost, and longer deployment timelines

3.4.5 - Refueling subsystem

In regular non autonomous vehicles, driver is responsible for refueling the truck. The driver uses their best judgement to decide when to pull over, reroutes the truck to the nearest gas station and fill the correct fuel at that gas station. All these steps – a) decision to refuel, b) re-routing to nearest gas station and c) filling the correct fuel would have to be performed in absence of the driver in a truly autonomous operation.

The current autonomous propulsion technology state of art is developed to execute the first two requirements seamlessly. The preloaded maps in the truck software and real time “remaining mileage” computation algorithms would provide a way to decide when and where the truck should pull over for filling up. The last step of filling the correct fuel would add significant complexity to the system.

For the truck to get filled in a truly autonomous system, the following should happen

- a) Truck should align itself at a gas station
- b) The fuel port should get unlocked and open to allow the nozzle to be inserted
- c) The fuel nozzle should “self-present” and get aligned with the fuel port and then be able to retract back once the fuel is filled
- d) The station should “somehow” select appropriate fuel (gas v/s diesel) and be autonomous to start and stop filling fuel
- e) The system should be capable of charging the truck appropriately for the fuel filled
- f) The system (fuel station + truck) should be somehow linked to a central database to allow seamless execution of payments
- g) The fuel station should be connected to a central system to allow scheduling fuel refills at the station.

To automate all of this would add significant complexity to the system and would involve multiple stakeholders along with low TRL technologies. This thesis aims to explore system designs to allow deployment of autonomous trucking in immediate future. Hence for this qualitative analysis, we are considering that the fuel station to be manned and a human would fill fuel in the truck.

Interaction at a manned fuel station

Even a manned fuel station brings in technological challenges as illustrated below. But present day technologies and some process additions would allow mitigate some of the failure modes explored in the operational scenarios.

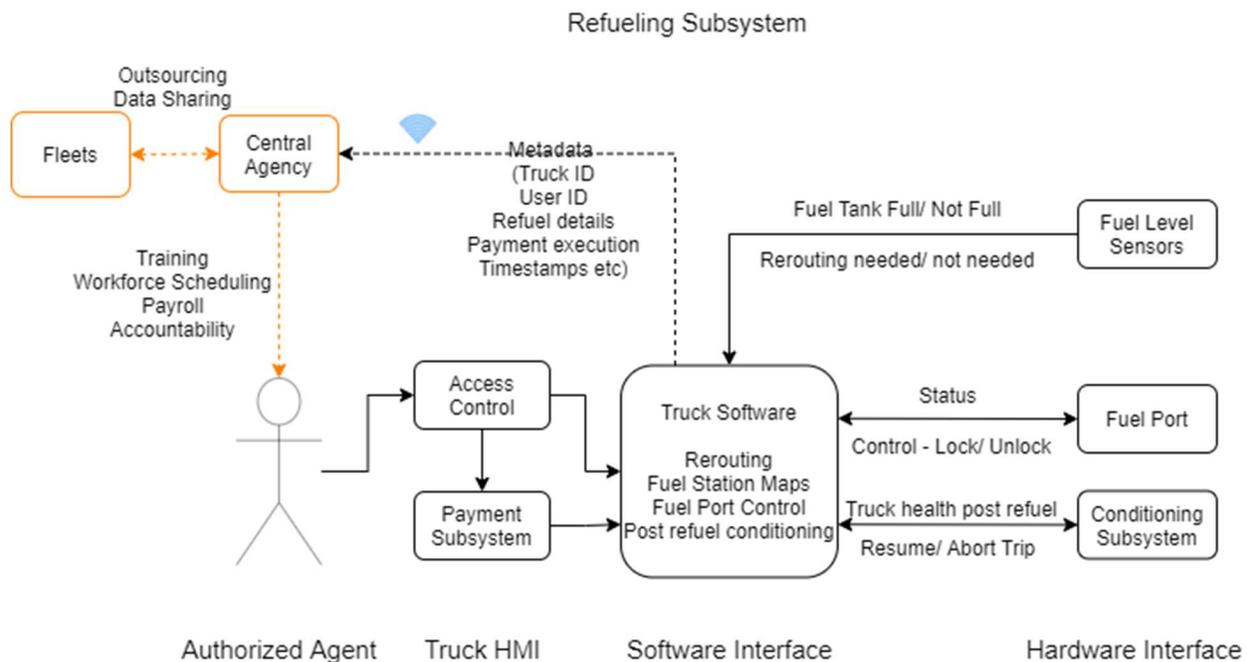


Figure 14 - Subsystem – Refueling

A refueling subsystem would be connected to the access control subsystem. The authorized user would only be able to fill gas after getting authorized. Fuel port door (secured with a lock) should open only after authorization is complete. The refueling subsystem should also be connected to the payment subsystem to allow the human agent to charge the truck for fuel filled. The conditioning subsystem should sense fuel level and the status of the fuel port and be able to close the port and lock it after refueling is complete.

The complexity comes in when the system must be designed to prevent intentional or unintentional filling of wrong fuel by malicious actors or untrained users. Addressing this failure mode purely with technology would add significant implementation challenges. Technologies would have to be developed to sense the user movements (which button the users press / which nozzle user inserts in the fuel port) and somehow disable the fuel entry passage on the truck using actuators mount on the fuel port. Exploring technologies to enable this is out of scope for this thesis.

For deployment of autonomous trucks in immediate future, we suggest adding training programs and accountability processes to mitigate such malicious acts. Only trained personnel affiliated to a centralized agency should be allowed to man the fuel stops. The person refueling the truck should be IDed and the user ID, truck ID along with the refueling metadata should be stored in the fleet data base. On board cameras can be used to capture images of the person filling up the truck for accountability (similar to cameras under Tesla vehicles mirrors to identify vandals). The conditioning system should also be designed to do a post fill up check to make sure correct fuel is filled. This can be performed by starting the engine for a short moment and measuring emissions out of the tailpipe. If deemed out of spec, the truck should be able to schedule roadside assistance and report the incidence to appropriate authorities.

3.4.6 - Weighing Subsystem

The truck needs to get weighed periodically in its route. The period and the allowable weight thresholds are determined by the DOT by analyzing the manifest that is entered in the system before the truck starts its trip. The road infrastructure in the US provides scanners which identify the truck and provide an indication to the driver whether they should take the weigh station exit. Upon entering the weigh station, the driver guides the truck on to the scales and a DOT agent executes a weight check. The agent clears the truck to resume trip if the weight is within limits, else fines are imposed on the fleet and the driver has to abort the trip.

This thesis aims to explore how the current infrastructure be used to allow autonomous trucks perform weight checks. The truck software should be designed to sense the road signals and decide whether the truck has to get rerouted to a weigh station. At the weigh station, the software should be able to guide the truck autonomously on the weigh scales. After the DOT agent performs weight checks, the truck's access control subsystem should allow the agent to "clear" the truck to resume or abort trip. This can be some sort of a user input from the agent. The truck should resume trip if cleared. If the trip is aborted, the truck should pull over to a safe location at the weigh station and connect to proper authorities and initiate an inquiry with appropriate metadata.

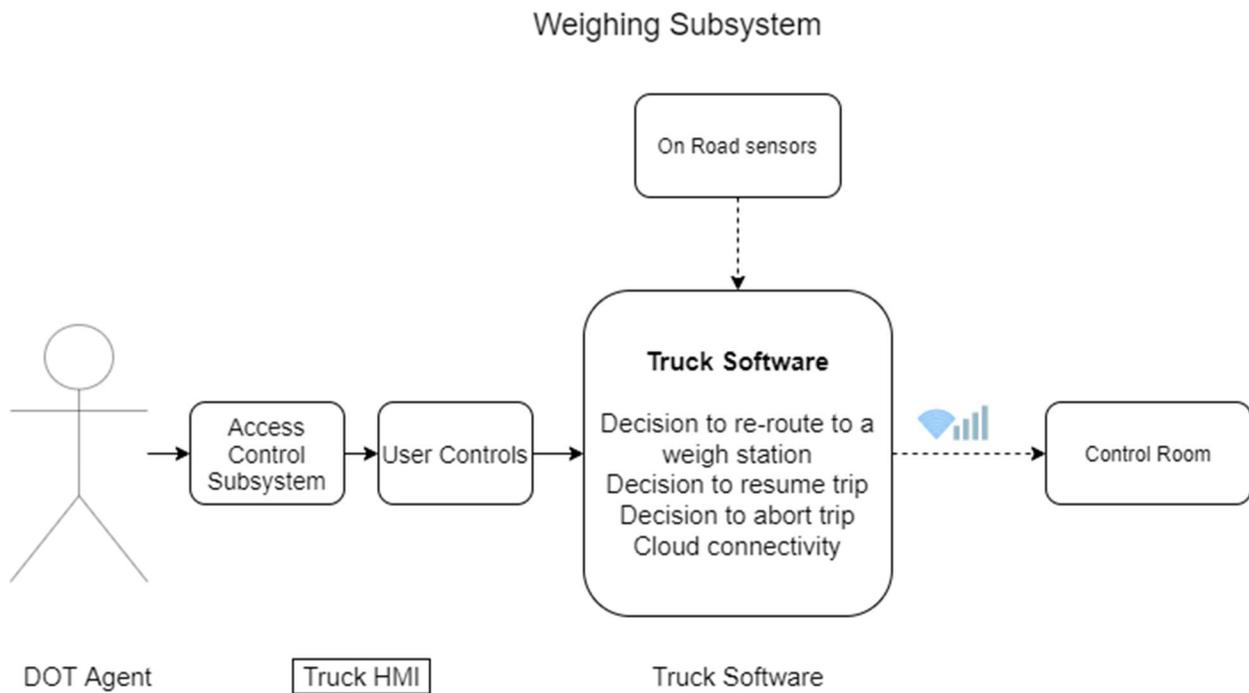


Figure 15 - Subsystem – Realtime Weighing

The following section describes common architectural decisions that would have to be modeled to design these subsystems, which satisfy the critical functions in the conceptual architecture.

3.5 - Architectural Decisions

The conceptual architecture described in previous section and the subsystems needed to be designed for critical functions and interfaces suggest following architectural decisions that would be important to explore. This section describes various architectural decisions and architectural choices for autonomous cargo delivery system. The following chapters will explore the technology readiness, societal readiness to accept such architectures and return on investments within next decade if deployed.

The critical architectural decisions are listed in the table below

ID	Architectural Decisions	Option 1	Option 2	Option 3
D1	Truck-Human Interaction	Truck HMI	Manual Calls to Fleet Management	
D2	Refueling	Fully autonomous	Manned	
D3	Pre-Post Trip Checks	Fully autonomous (performed by truck)	Manual (performed by humans)	Semi autonomous (propulsion system checks performed by truck, rest by human)
D4	Last Mile Drive (from unloading dock to parking garage, or truck wash etc.)	Fully autonomous (truck waypoints are fully programmed, and no interaction is needed)	User enters destination points using truck HMI	Manual (someone drives the truck)
D5	Loading / Unloading	Autonomous	Manual	
D6	Weight Checks	Using realtime weight sensors	Manual at a weigh station, done by an agent	
D7	Payment Subsystem	On-truck / Truck HMI	Off board	
D8	Access control	None	Authorized access control to selected users	
D9	Manual Override	Yes	No	
D10	Roadside assistance scheduling	Manual	Automated, truck initiates a call	
D11	Non-Autonomy vehicle fault handling	Fully autonomous	Manual	Remote
D12	Remote Control	Full Propulsion control (includes fault response and remote take over)	Route Guidance	None

D13	Data storage	On board	Cloud	Both
D14	Cabin controls (door locks, strap tensions etc.)	Only sense and report/set faults)	Sense and Actuate	
D15	Platooning	Yes	No	

Figure 16 - Architectural decisions

3.7 - Unique Architectures

These architectural decisions create a space of 248,832 unique architectural choices. These unique choices are categorized into four main categories

- a) Baseline Architectures
- b) Fully Autonomous Architectures
- c) Hybrid Architectures
- d) Platoons

Baseline architectures comprise of today’s state of art technology seen in a long-haul truck. Kenworth T880, Peterbilt 379, Freightliner Columbia [23] are some of the famous products in the market that could be considered as baselines. These architectures require a human driver and support system to perform all the critical functions necessary for delivering cargo. These would have some levels of ADAS on board to assist the driver for lane keeping and cruise control. These architectural choices are considered as baseline when comparing against choices of varying levels of autonomy for their technology readiness and return on investment.

Architectural Decisions		Truck - Human Interaction	Refueling	Pre-Post Trip Checks	Last Mile/ Destination Drive	Loading/ Unloading	Weight Checks	Payment	Access Control	Manul Override	Roadside assistance scheduling	Data Storage	Cabin Controls	Non Autonomy fault handling	Remote Control	Platoon Modes	Connectivity
Baseline	B1	No	Manual	Manual	Manual	Manual	Manual	Off Board	No	No	Manual	No	Sense	Manual	No	No	No
	B2	No	Manual	Manual	Manual	Manual	Manual	No	No	No	Manual	No	Sense	Manual	No	No	Wifi/Cellular

Figure 17 - Architectural concepts - Baseline architectures

Fully autonomous architectures would include the choices where all critical functions are performed without any human assistance. This assumes level 5 autonomy for propulsion and a proper support system to achieve fully autonomous cargo deliveries. The current state of art of technology, policy and infrastructure, would out the deployment timeline of level 5 autonomous trucks beyond the next ten years (which is the timeline under consideration for this thesis). Hence exploring these architectures is out of scope for this thesis.

Architectural Decisions		Truck - Human Interaction	Refueling	Pre-Post Trip Checks	Last Mile/ Destination Drive	Loading/ Unloading	Weight Checks	Payment	Access Control	Manul Override	Roadside assistance scheduling	Data Storage	Cabin Controls	Non Autonomy fault handling	Remote Control	Platoon Modes	Connectivity
Fully Autonomous	FA1	HMI	Fully Autonomous	Fully Autonomous	Fully Autonomous	Fully Autonomous	Realtime	On Board	Yes	No	Automated	Both	Sense and Actuate	Fully Autonomous	Full Propulsion control	No	Both
	FA2	HMI	Fully Autonomous	Fully Autonomous	Fully Autonomous	Fully Autonomous	Realtime	On Board	Yes	Yes	Automated	Both	Sense and Actuate	Fully Autonomous	Full Propulsion control	No	Wifi/Cellular
	FA3	HMI	Fully Autonomous	Fully Autonomous	Fully Autonomous	Fully Autonomous	Realtime	On Board	Yes	Yes	Automated	Cloud Only	Sense and Actuate	Fully Autonomous	Full Propulsion control	No	Both

Figure 18 - Architectural concepts - Fully autonomous architectures

The baseline and fully autonomous architectures are the extremities of the design space.

The third category is of hybrid architectural choices. In this space, one or more of the architectural decisions satisfy autonomy requirements and can be executed without human intervention. Each such combination would result in a unique architecture on the trade space explored in the next section. Figure below shows sample examples of such hybrid architectures

Architectural Decisions		Truck - Human Interaction	Refueling	Pre-Post Trip Checks	Last Mile/ Destination Drive	Loading/ Unloading	Weight Checks	Payment	Access Control	Manul Override	Roadside assistance	Data Storage	Cabin Controls	Non Autonomy fault	Remote Control	Platoon Modes	Connectivity
Hybrid	H1	HMI	Manual	Autonomous	Manual	Manual	Manual	Onboard	Yes	Yes	Manual	Both	Sense	Autonomous	Route Guidance	No	Wifi/Cellular
	H2	HMI	Autonomous	Manual	Manual	Manual	Manual	Onboard	Yes	Yes	Manual	Both	Sense	Autonomous	Route Guidance	No	Wifi/Cellular
	H3	HMI	Manual	Manual	Autonomous	Manual	Manual	Onboard	Yes	Yes	Manual	Both	Sense	Autonomous	Route Guidance	No	Wifi/Cellular
	H4	HMI	Manual	Manual	Manual	Autonomous	Manual	Onboard	Yes	Yes	Manual	Both	Sense	Autonomous	Route Guidance	No	Wifi/Cellular
	H5	HMI	Manual	Manual	Manual	Manual	Realtime	Onboard	Yes	Yes	Manual	Both	Sense	Autonomous	Route	No	Wifi/Cellular
	H6	HMI	Manual	Autonomous	Manual	Manual	Manual	Off Board	Yes	Yes	Manual	Both	Sense	Autonomous	Route Guidance	No	Wifi/Cellular

Figure 19 - Architectural concepts - Hybrid architectures

The last category is the architectural choices which support truck platooning. Truck platooning is considered to be an efficient short-term solution to realize partial autonomy with sizable fuel economy benefits. Platooning assumes the lead truck being manual and the chain of following trucks being fully or semi-autonomous.

Architectural Decisions		Truck - Human Interaction	Refueling	Pre-Post Trip Checks	Last Mile/ Destination Drive	Loading/ Unloading	Weight Checks	Payment	Access Control	Manul Override	Roadside assistance scheduling	Data Storage	Cabin Controls	Non Autonomy fault handling	Remote Control	Platoon Modes	Connectivity
Platoon	P1	HMI	Manual	Manual	Manual	Manual	Manual	Off Board	No	No	Manual	No	Sense	Manual	No	Yes	Both
	P2	HMI	Manual	Manual	Manual	Manual	Manual	Off Board	Yes	No	Manual	No	Sense	Manual	No	Yes	Both
	P3	HMI	Manual	Manual	Manual	Manual	Manual	Off Board	No	No	Manual	No	Sense	Autonomous	No	Yes	Both
	P4	HMI	Manual	Manual	Manual	Manual	Manual	On Board	No	No	Manual	No	Sense	Remote	No	Yes	Both

Figure 20 - Architectural concepts – Platooning architectures

The figure below shows a trade space of all architectures in the design space. The architectures are plotted for their technology readiness and estimated return on investment in a period of five years if deployed. The next section will explore the trade spaces and various tensions in technological readiness and estimated ROI.

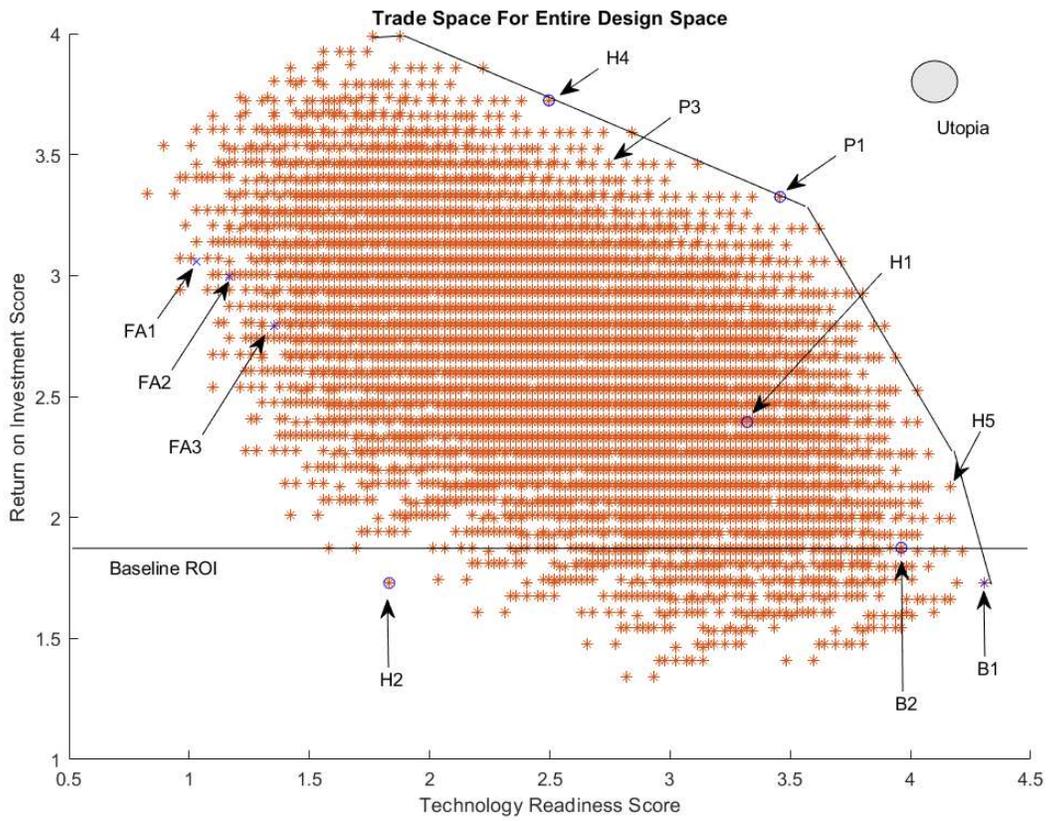


Figure 21 - Tradespace exploration - Entire design space

Chapter 4 - Market Research

A user survey was conducted across different industries understand the validity of the conceptual architecture developed and described in previous chapters and to recognize that the progression has as much to do with the societal acceptance as with technology readiness.

The survey was designed to gain understanding on the following factors

- 1) Technology readiness of the technologies required to design the subsystem concepts described in previous chapters
- 2) Readiness of the society for deploying these subsystems on road
- 3) Perceived return on investment on a 5-year period if these technologies are deployed today
- 4) Technological readiness to address certain off nominal scenarios which would be seen due to deploying autonomous solutions on road.

The survey was conducted with 81 participants across automotive, aerospace, robotics, defense, software, and manufacturing industries. The results from the survey were analyzed to understand the tensions between technology readiness, societal acceptance and ROI in an attempt to propose a technology roadmap for next decade

Following critical functions were scored on a scale of 1-5 where 1 is lowest / not ready and 5 is highest/ fully ready for the above mentioned factors

- 1) Fully autonomous refueling
- 2) Fully autonomous pre trip checks
- 3) Protection against truck vandalization and hijacking
- 4) Fault handling for non-propulsion related functions (for conditions like tire blowouts, unlocked cargo doors spilling cargo, accidents in areas of zero connectivity)
- 5) Truck Platooning
- 6) Loading/ Unloading cargo autonomously
- 7) Eliminating weigh stations
- 8) Activities after unloading is complete(would include driving the truck to parking garage, truck wash, state inspection, registration etc.)

The readiness of the technology was assessed to address following off nominal scenarios

- 1) Truck getting pulled over by police
- 2) Truck reaching destination facility at odd hours when the facility is closed
- 3) Intentional or unintentional filling of incorrect fuel
- 4) Truck getting vandalized
- 5) Cargo spilling on the freeway
- 6) Tire flats and blowouts (specifically in low connectivity areas)
- 7) Snow, dust, water getting accumulated on autonomy sensors
- 8) Truck entering a fuel station which is either closed or does not have enough fuel reserves

4.1 Methods

The survey results along with the architectural decisions were used to develop a model to plot the technology readiness, societal readiness and return on investment scores. The model assumes equal weightage to various architectural decisions and functions explored in the survey and previous chapters. Each function and off nominal scenario explored in the survey is mapped to a set of architectural decisions required to satisfy the function or off nominal scenario. The total technology readiness score (or ROI/ societal readiness score) is a sum of individual scores for each of the architectural decision mappings.

Each architectural decision is divided into three scores – baseline, fully autonomous and hybrid. The baseline architectural decision choices are allocated the highest technological readiness score since the technology is already deployed in the market. Adding levels of autonomy would decrease the readiness score accordingly. The return on investment score for all baseline architectural decisions is modeled to be a constant value. The return on investment scores for rest of the architectural decisions is weighed against this baseline score looking at the perceived ROI numbers from the survey. E.g. the survey shows perceived ROI of refueling architectures to be very low, hence they are weighed lower than “baseline” architectural scores as given the investment needed to achieve fully autonomous refueling is expected to be so large compared to the returns (by replacing humans) that the ROI would be negatively affected.

The trade space axes are then normalized to the same scale as that of the survey – 1-being lowest and 5 being highest. This normalization is performed to better compare the architectural space with the survey results.

Chapter 5 - Insights and Analysis of Architectures

The outreach was performed to understand critical tensions between various figures of merit. The goal of this exercise was to be able to prioritize functionality for autonomous cargo deliveries to provide guidance to the OEMs and fleet management on where to spend resources and infrastructure. The insights below would result in a technology roadmap discussed in the next chapter.

5.1 - Tensions in Technology Readiness, Societal Acceptance and ROI for critical functions

Several tensions are observed between the readiness of the technology, its perceived ROI if deployed and the societal acceptance. Figure 22 illustrates key tensions seen from the survey responses. The Y-axis shows people's perception of how ready the technology is (1 – low, 5 – high) (or societal acceptance – ie how ready society is to accept this technology deployed on roads) where as the X-axis is return on investment (1-low, 5-high) over a five year period if the said function is deployed today. The shape of the bubbles illustrates the spread of votes between various readiness and ROI levels. An ellipse with shorter horizontal (or vertical) axis indicates tight clustering of votes around a certain ROI (or TR) score (lower standard deviation). Similarly, longer vertical (or horizontal) axis would indicate a higher standard deviation stating that the survey respondents have a significant scatter along the respective axis. Appendix D provides all the numerical data which was used in creating this illustration.

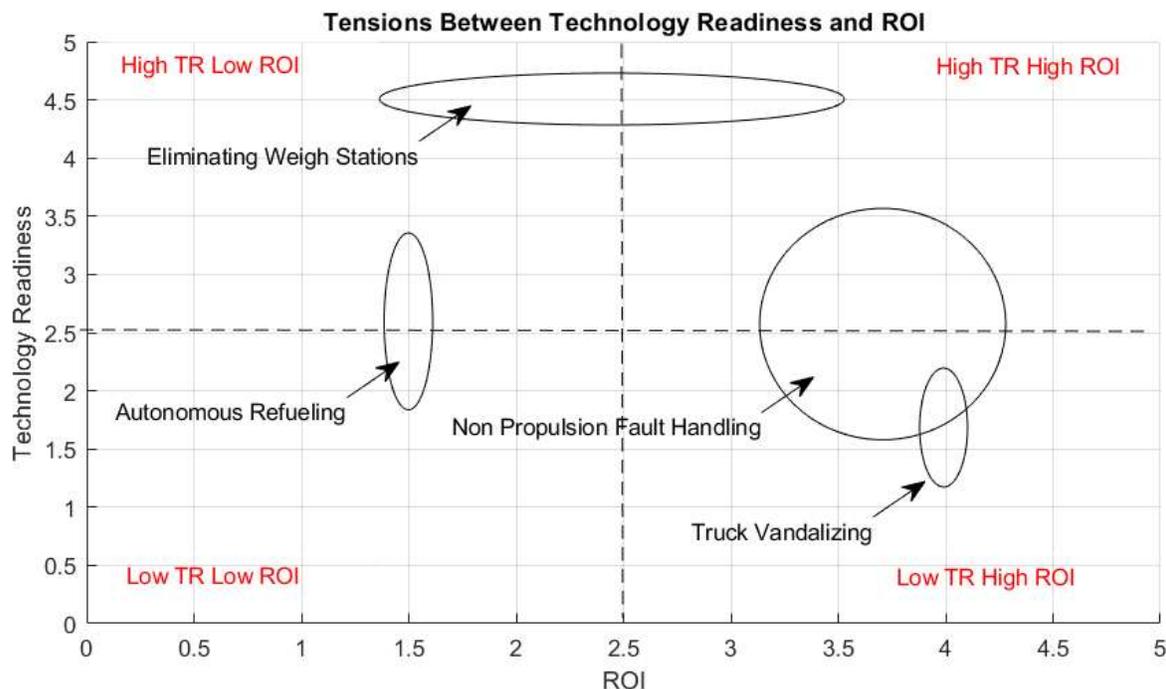


Figure 22a – Market Perception of TR and ROI for critical functions

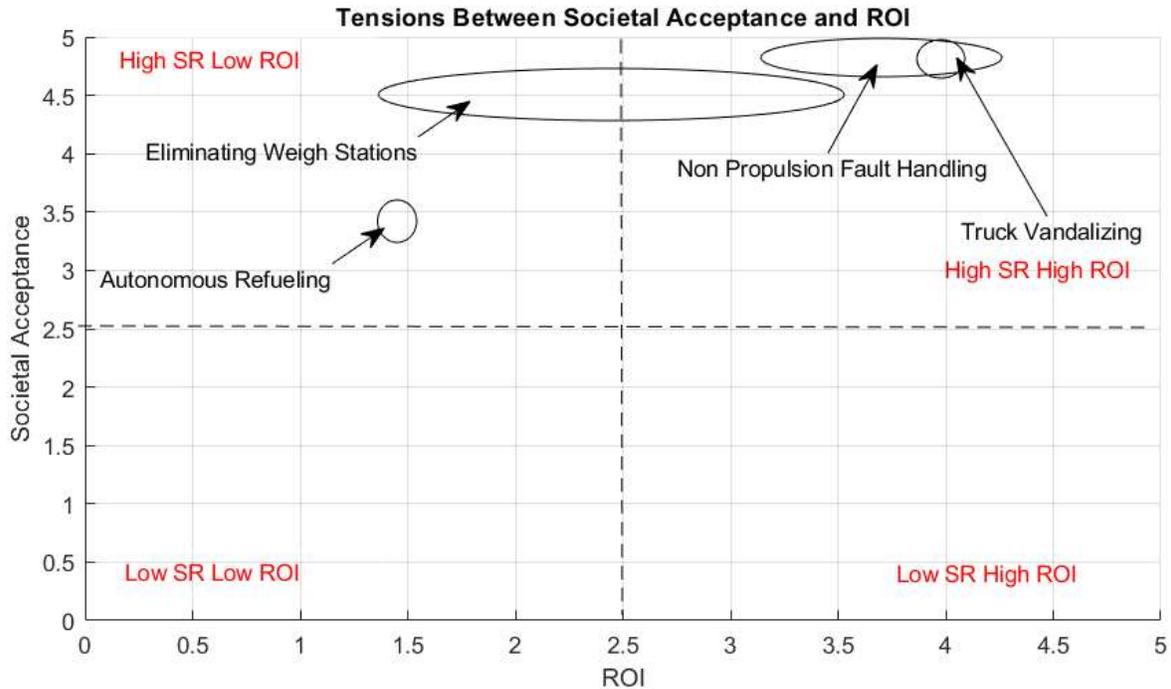


Figure 22b – Market Perception of SR and ROI for critical functions

Figure 22 further shows four quadrants based on low and high technology readiness (or societal readiness) and ROI scores. In Figure 22.a, protecting the truck against vandals lie in the lower right quadrant, meaning low technology readiness, but high perceived ROI (and same trend was seen with societal acceptance as well). Truck vandalization and hijacking is a serious problem leading to major losses in the fleet industry. Cargo thieves have caused billions of dollars of losses [6] for the fleet industry and this problem is growing. Hijackers specifically work with truck drivers to target specific trucks. The fleets have to budget significant investment to accommodate for such incidences yearly and hence an automated functionality to minimize such incidences is perceived to give faster paybacks. Similarly, hijacking or vandalizing a truck affects the driver as well. Several times the drivers are beaten and left for no help when hijackers are trashing the truck. This human capital loss drives the societal acceptance of using technology to avoid vandals higher on the scale (which is illustrated in Figure 22.b)

Investment in technology to prevent these would be highly beneficial and would see faster paybacks especially on routes to and from Miami, Los Angeles and New York. The technology to achieve this is still at a very low TRL – which is where the tension arises. Detection of vandals or hijackers can be achieved by onboard cameras and sensing devices, but prevention would require several technological advances (such as smash proof materials, high grade tires, actuators to prevent manual overrides, rerouting algorithms to detect and prevent approaching thieves etc.). Significant investments in resources (time, money, people) would be required to develop technologies that would achieve the desired protection, but once developed and deployed, this will see faster paybacks and increasing acceptance amongst fleets.

The bubble for non propulsion fault handling is much fatter (Figure 22.a), but still lies in the right quadrants. This states that the perceived ROI for this functionality is high, while the technology readiness was scored somewhere on the lower to medium scale. This category includes detection and action or prevention of all the faults outside autonomous propulsion which could be seen in an autonomous truck. These include faults like tire blowouts, tire flats, cabin or cargo door unlocking in an ongoing trip, unsecured cargo getting spilled on the freeway, connectivity losses, nonfunctional headlights, truck getting stuck in snow etc. Today, in all such scenarios the driver can take proactive or preventive actions like periodic checking of cargo straps, tire pressures etc. or can call for help if the truck gets stuck in hazard conditions. Achieving these functions without a driver would need not only sensing of these failure modes, but also actuation of some kind to minimize or prevent hazards

The survey participants scored the need of such fault handling high on return on investment. The primary reason behind the high score on ROI is the current fatality rate, legal fees for lawsuits, insurance premiums that the fleets must accommodate for in their yearly budget. Prevention of such instances would highly benefit fleets by saving hundreds or thousands of dollars. The tension arises due to lower technology readiness for actuation to minimize hazards. Several technologies exist today to sense such failure conditions. But the technologies needed to act about the failure detection are either very costly, or still at low TRLs. A similar tension is also seen between societal readiness and technology readiness for fault handling, where the survey indicated high levels of societal readiness to see this feature deployed on the trucks (Figure 22.b). This supports the literature which shows significant number of on road accidents and fatalities resulting in the society to see the critical need of fault handling in the absence of the driver as a critical function.

For instance, conditions to recover from an unlocked cargo door and spilling cargo, would require some significant technological resources. As an example, the truck can detect spilled cargo and come to a safe stop, but someone would have to pick up that cargo and load and secure it in the truck. Similarly, if the truck tire blows out in a region where the truck cannot establish outside connection, there would have to be a technological solution developed to locate such a broken-down truck and schedule assistance.

Autonomous refueling lies in the left quadrants (Figure 22.a) and is an ellipse with short horizontal axis. This states the perceived ROI for this function is low and this perception is consistent amongst majority of survey respondents. It is apparent that fully autonomous refueling (which involves not only aligning the truck at a fuel station, but also autonomously filling the fuel as well as executing payment) is not a critical need of today's fleet operations. This would add significant cost to the operations and none of the technologies today are market ready to be deployed to achieve autonomous refueling.

This technology is not going to yield savings to the fleet because regardless of how the truck gets filled, the amount of fuel needed by the truck would remain the same. This technology may yield savings on labor cost to fill fuel, but given the massive capital investment needed to develop and deploy this technology and infrastructure, this return on investment could take decades (with no apparent benefit to the fleets)

The opposite trend is seen in adding technology to eliminate weigh stations. The technology readiness to achieve real-time weight sensing is very high (market ready), but the survey respondents were unsure about the ROI this would generate. Eliminating weigh stations would help fleets save time spent in taking detours to get weighed, thus increasing throughput and hence revenue. The investment can be easily paid back quickly with this increased throughput, which is the reason some participants would have rated it high on the ROI scale. On the other hand, weigh station itself is outside the system boundary and repurposing the weigh stations for other use cases (like recreational areas, rest areas etc) would direct the paybacks to the government and not fleets. Considering this system under study, the ROI would not play a huge role in benefitting the fleets and hence others would have scored it lower on the ROI scale.

Figure 24 shows Truck Platooning was voted in favor for both figures of merit – Technology Readiness and ROI. Various levels of platoons are already being deployed in various regions across the US as shown in the figure below.

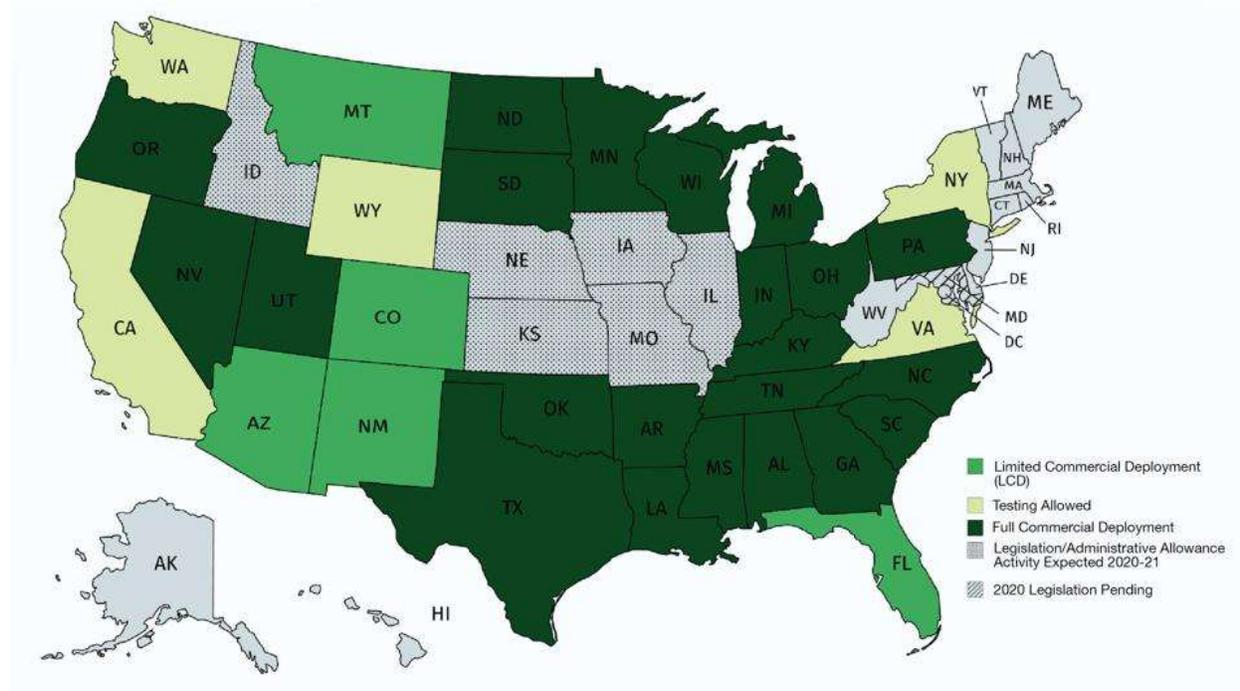


Figure 32 - Truck platoon deployment across US [7]

Platoons have proven to save almost 10% in fuel costs [7] on follower trucks due to reduction in aerodynamic drag. In addition to fuel savings, researchers have also shown platooning to increase safety and throughput. Safety is seen to increase by maintaining proper following distance at high speeds. It is also observed that the following distances can be optimized to accommodate a greater number of trucks on specific routes, leading to increased throughput. These advantages make the proposition attractive on the ROI axis. The technologies to achieve vehicle platooning already exist. Dedicated short range communication services [8] involve V2V and V2I communications which are tested on platoons to maintain following distance and achieve optimal acceleration and braking performance.

		ROI			
		1	2	3	4
TR	1	0.09	0.07	0.03	0.05
	2	0.01	0.01	0.06	0.09
	3	0.02	0.01	0.08	0.12
	4	0.03	0.02	0.12	0.17
	5	0.01	0.09	0.04	0.05

Figure 24 - Technology Readiness Score v/s ROI Score – Truck platooning

The plot below shows various critical functions stacked against their technology readiness and return on investment. It's clear that truck platooning is closest to utopia and on the pareto front. Truck platooning will provide high return on investment within net five years and the technology is also almost market ready to achieve this.

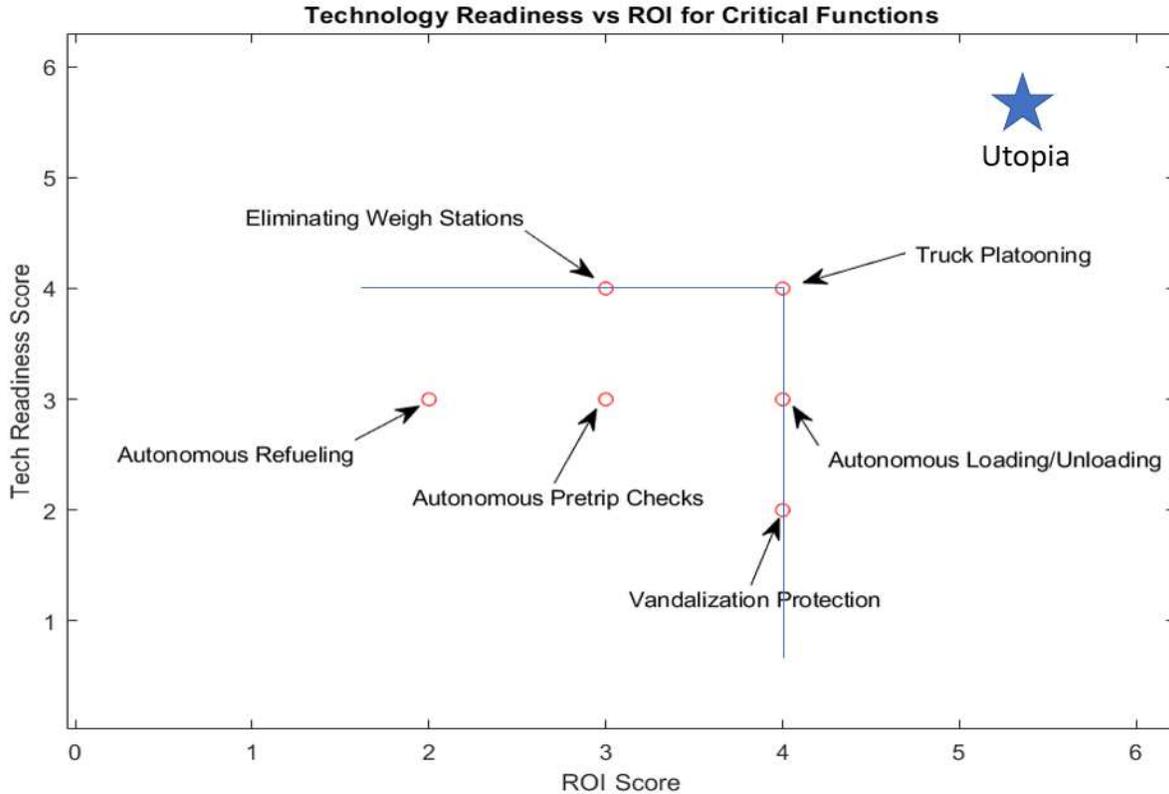


Figure 25 - Comparison of critical functions for Technology Readiness and ROI

The other two architectural choices on the pareto front are a) Eliminating weigh stations and b) Autonomous loading/ unloading.

Cargo weight can be easily sensed in real time by today's sensors and the connectivity platforms with 4G and LTE technologies provide an easy way to share this data with the DOT. Studies have

shown [9] that making detours through weigh stations, stopping on the scales, and doing all the paperwork causes significant travel time increases. There are a few concepts of operations deployed in the US for analyzing weighing-in-motion concepts [10]. The investment to equip the truck to be weighed in transit is minimal (compared with other technologies on board) and would instantly lead in increased throughput, reduced travel times (and hence truck wear).

Autonomous loading/unloading is on the pareto front due to its faster return on investment. Studies have shown increasing detention times for drivers over last several years [11]. As the truck driver gets paid per mile and can only drive eight hours per day, the more time they wait during their trips, the more they lose financially. The figure below shows that driver detention due to delays have significant impact on their HOS (hours of service) compliance

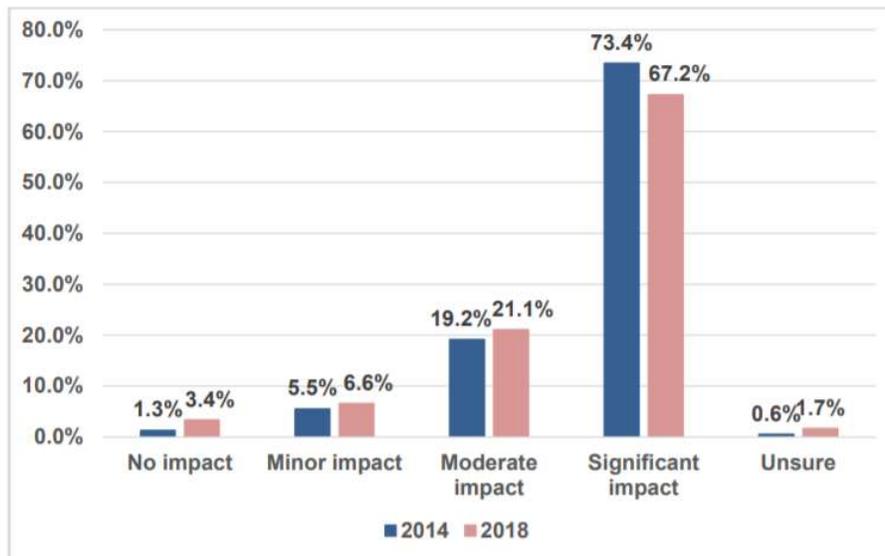


Figure 26 - Truck driver detention reasons [11]

Figure 27 shows the common causes of the delays.

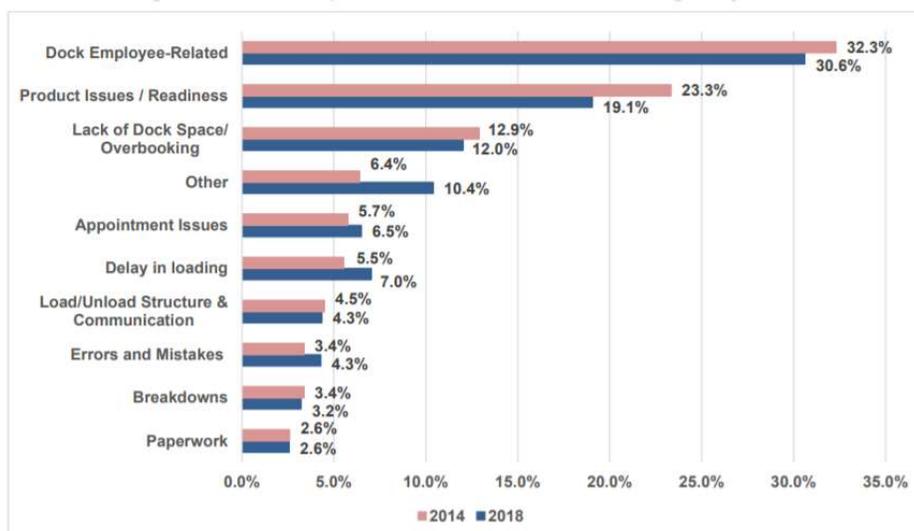


Figure 27 - Common causes of delays in fleet operations [11]

Delays related to dock employees or product readiness score very high on this chart. Delay in loading, lack of dock space is also some of the top causes of the delays. Delays also affect motor carriers as they cannot maintain their pickup and delivery times, additional asset and driver resources are required.

Hence automating several steps in docking, loading, unloading, inventory management sequence would result in sizable savings for fleets and increase their throughput. Companies like Amazon, working in warehouse automation, are developing technologies to facilitate autonomous preparation of deliveries. The technology readiness scores a less than some other functions because of the automation required in various steps of the entire process. Going beyond just loading and securing the cargo (which can be achieved using warehouse robots), there should be technology in place to perform inventory control, manifest creation and linking to DOT and truck scheduling to minimize overbooking or lack of dock space. Pieces of technology exist to perform these activities in isolation, but a full systemic solution is yet to be developed considering the emergence when these individual technological solutions come together.

5.2 - Architectures satisfying requirements on the pareto front

Function / Subsystem on Pareto Front	Architectural Decision
Truck Platooning	Platoon Mode – Yes Truck Human Interaction – HMI Last Mile Driving - Manual
Eliminating Weigh Stations	Data Storage – Both Connectivity – Wifi/Cellular Cargo Sensors - Yes
Autonomous Loading Unloading	Loading/Unloading – Autonomous Access Control – Authorized access Truck Human Interaction – HMI Pre trip checks – Autonomous

Figure 28 - Architectural decision mapping for critical functions

The figure below shows the architectures on the tradespace which would enable these functions on the truck.

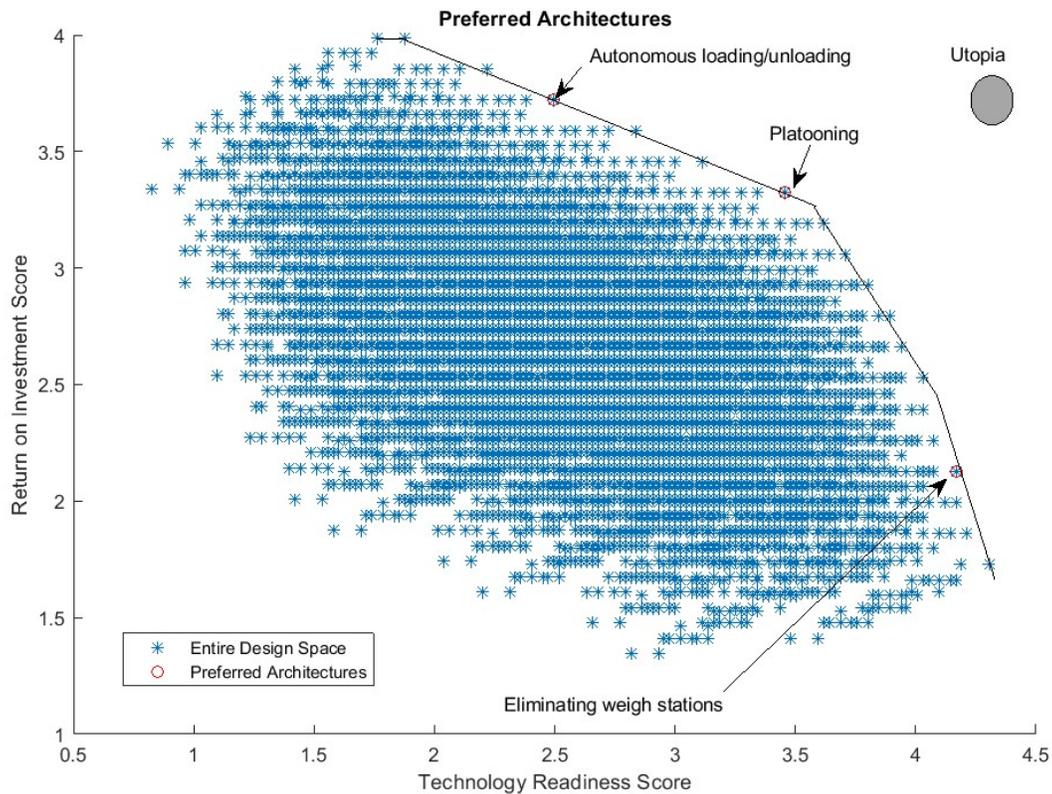


Figure 29 - Tradespace exploration – Preferred architectures

5.3 - Off Nominal Scenarios

To make the system robust, the critical functions should account for off nominal scenarios. Hence several off nominal scenarios were explored while designing the concept of operations for this system. The architectural decision choices were assessed to address each of these off nominal scenarios. Figure 30 shows the mapping of critical decisions needed to counter every off nominal scenario address in this thesis.

Off Nominal Scenarios	Architectural Decisions
Getting pulled by police	Truck Human Interaction – HMI Manual Override – Yes Remote Control – Full Propulsion Control Connectivity – Wifi/Cellular Payment – On truck Access Control – Authorized users only
Truck Arriving at unmanned/cash on toll station	Payment – On truck Connectivity – Wifi/ Cellular Manual Override – Yes Access Control – Authorized users only

Truck reaching destination at odd hours	Access Control – Authorized Access Manual Override – Yes Last Mile Drive – Fully Autonomous
Incorrect Fuel Is Filled	Refueling – Fully Autonomous Payment – On Truck
Truck Gets Vandalized	Remote Operation – Fully autonomous Truck Human Interaction – None Connectivity – Both (Wifi/Cellular and DSRC) Manual Override – No
Cargo door opens and cargo spills out	Cabin Controls – Sense and Actuate Non autonomy fault handling – Fully autonomous
Flat tire/ tire blowouts in low connectivity areas	Non autonomy fault handling – Fully autonomous Connectivity – DSRC Truck Human Interaction – HMI Access Control – Authorized users only Manual Override – Yes Remote Control – Full Propulsion Control
Snow/Dust/Water Accumulation on sensors	Non autonomy fault handling – Fully autonomous Manual Override – Yes Remote Control – Full propulsion control
Truck enters fuel station which is closed or is low on fuel	Refueling system – Manned Manual Override – Yes Remote Control – Full propulsion control

Figure 30 - Architectural decision mapping for off nominal scenarios

The mapping in the table above shows certain common architectural decisions that would be needed to counter off nominal scenarios. The figure 31 shows the mapping to subsystems explored in previous chapters that would be needed to account for the architectural decisions listed above.

Off Nominal Scenarios vs Subsystems	Refueling Subsystem	Sensor conditioning and calibration	Access control	Payment Subsystem	Weighing Subsystems	HMI	Cabin Controls	Manual Override	Tele operation
Truck gets pulled by police			x	x		x		x	x
Truck arrives at an unmanned, cash only toll station			x	x				x	
Truck reaches destination at odd hours when facility is closed			x					x	
Incorrect fuel is filled (someone fills gas instead of diesel)	x								
Truck gets vandalized (vandals smash windows, knife tires)									x
Cargo door opens and cargo spills on freeway		x					x		
Flat tire/ tire blowout in zero connectivity areas		x						x	
Snow, Dust, Water accumulation on autonomy sensors like LiDARS, Cameras etc		x							x
Truck enters fuel station which is closed and does not have enough fuel to go to another open fuel station	x							x	

Figure 31 - Subsystem mapping for off nominal scenarios

Setting these architectural decisions in the model, the plot below is generated to showing the entire design space to accommodate all the off nominal scenarios.

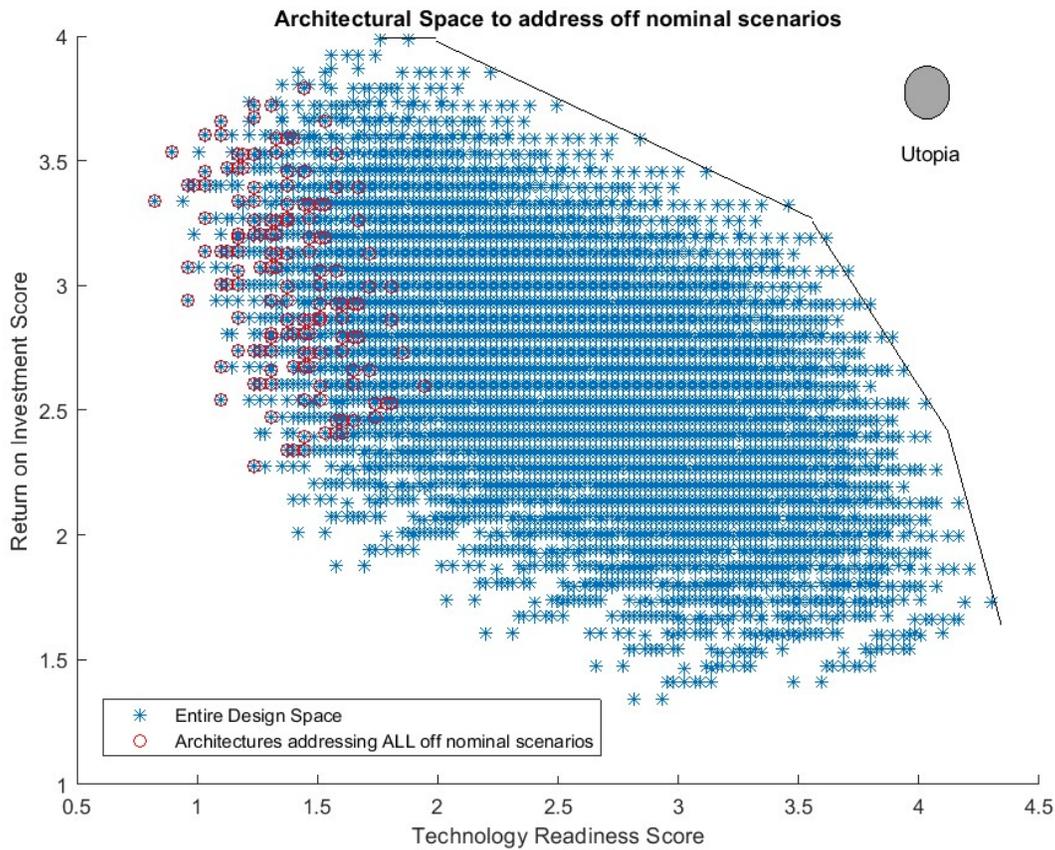


Figure 32 - Tradespace exploration – Architectures satisfying all off nominal scenarios

It can be clearly seen that fleets would see faster return on investment if technologies behind these architectural decisions are deployed on the trucks. It is also observed that the technology readiness for all these technologies is low as of today.

Hence prioritization is needed to address the most critical off nominal scenarios first. The survey attempted to get an understanding of which off nominal scenarios people are worried about the most. The plot below shows how the survey participants voted for each of the off nominal scenarios.

Accumulation of snow/dust/water on autonomy sensors like camera, lidars etc. is observed to be the most critical and most probable scenarios which directly results into safety hazards. This is followed by tire blowouts, which is also a very common occurrence in the US. According to [12], NHTSA estimates upwards of 78000 accidents per year due to tire blowouts, causing more than 400 deaths. Hence it would be advisable for the OEMs to focus on developing technologies to address these off nominal scenarios first as removing the driver will only make these scenarios worse.

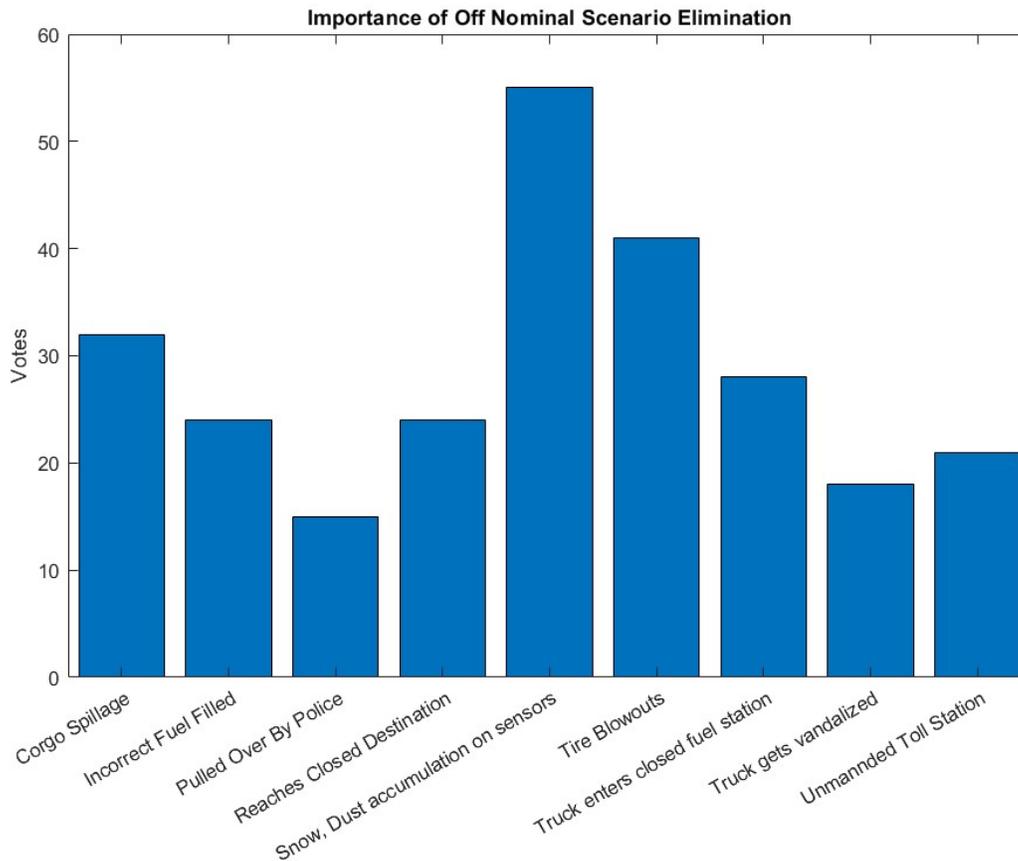


Figure 33 - Market Insights – Eliminating off nominal scenarios

The plot below overlays architectures which would account for addressing these off nominal scenarios to comparatively show the readiness and expected ROI for fleets compared to rest of the design space. The “o” data points are all the combinations of various architectural decisions which include the “non autonomy fault handling” decision and “remote control decision” needed for addressing this off nominal scenario. The “x” data point considers architecture with just “non-autonomy fault handling” set to “fully autonomous” and “remote controls” decision set to “route guidance”.

Remote route guidance is not a new technology in air traffic control industry. This is tried and tested and can be ported to the automotive industry. For handling faults like snow accumulation on the sensor, simple techniques like heat coils (similar to the ones seen on the rear window of several cars these days), air nozzles (similar to how today’s windshields are cleared) etc. can be implemented relatively easily. The technology is developed and market ready. Due to these two reasons, we can see the technology readiness score to address (just) this failure mode is fairly high. The ROI is also higher than “baseline”. It is not much higher as rest of the architectural decisions are set to baseline, which would assume that there is some sort of driver presence. In such a case, the failure mode can be addressed by the driver themselves and the added technology may not be

truly utilized. On the other hand, this technology coupled with other architectural decisions would further increase the ROI. As an example, if technology to counter this failure mode is implemented in a platoon (instead of a non-autonomous/ baseline truck), the ROI would be much faster as this technology would be most useful in situations where driver is not present.

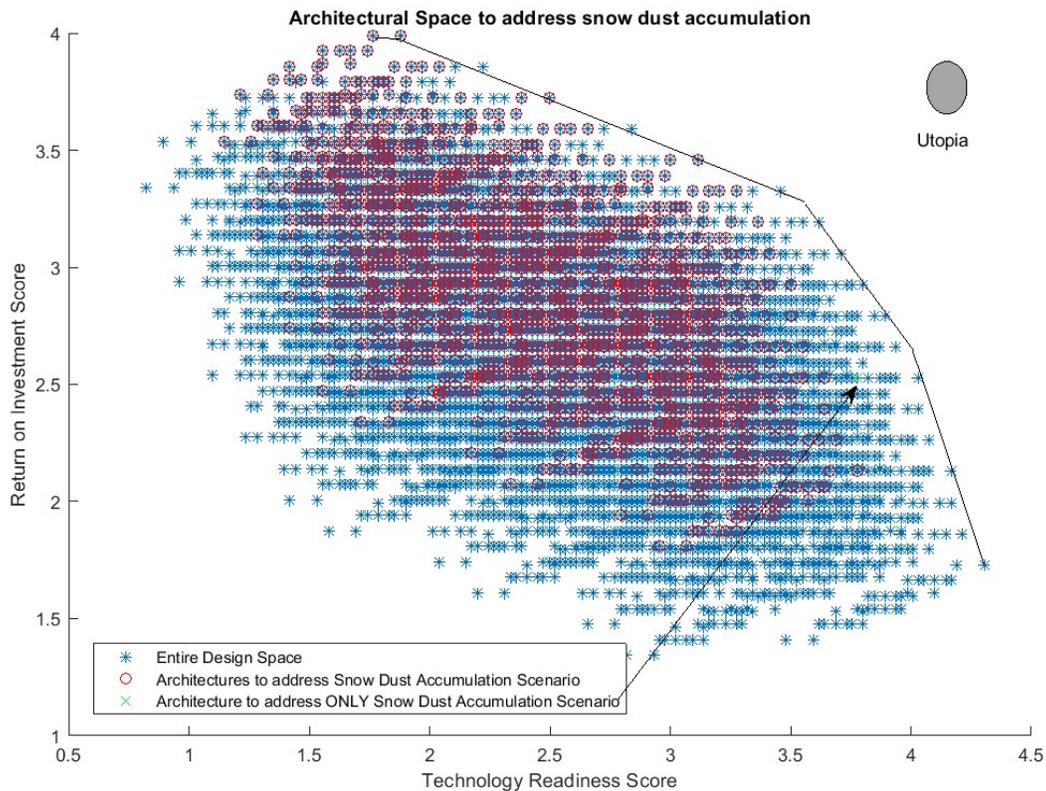


Figure 34 - Tradespace exploration – Architectures addressing snow, dust accumulation

The second most critical off nominal scenario to mitigate is observed to be tire blowouts. The plot below shows a trade space of all the architectures that would be helpful in countering this off nominal scenario. Compared to Figure 34 above, this set of architectures is seen to be closer to the pareto front. Given the amount of accidents, and fatalities due to tire blowouts, fleet spend a huge amount of financial resources to address the losses. Hence return on investment for would be much faster if technology is deployed to counter this scenario. From a technology readiness perspective, sensors to sense tire pressure, temperature, wear are already available in the market. Several diagnostics exist today to gauge the need for servicing tires before any mishap happens. Hence this scenario scored higher on the technology readiness scale. That being said, to bring these architectures on the pareto front, technological development needs to happen to be able to “take action” on such sensed failures. Presently, this is at driver’s discretion and the truck’s responsibility is only proper diagnostics.

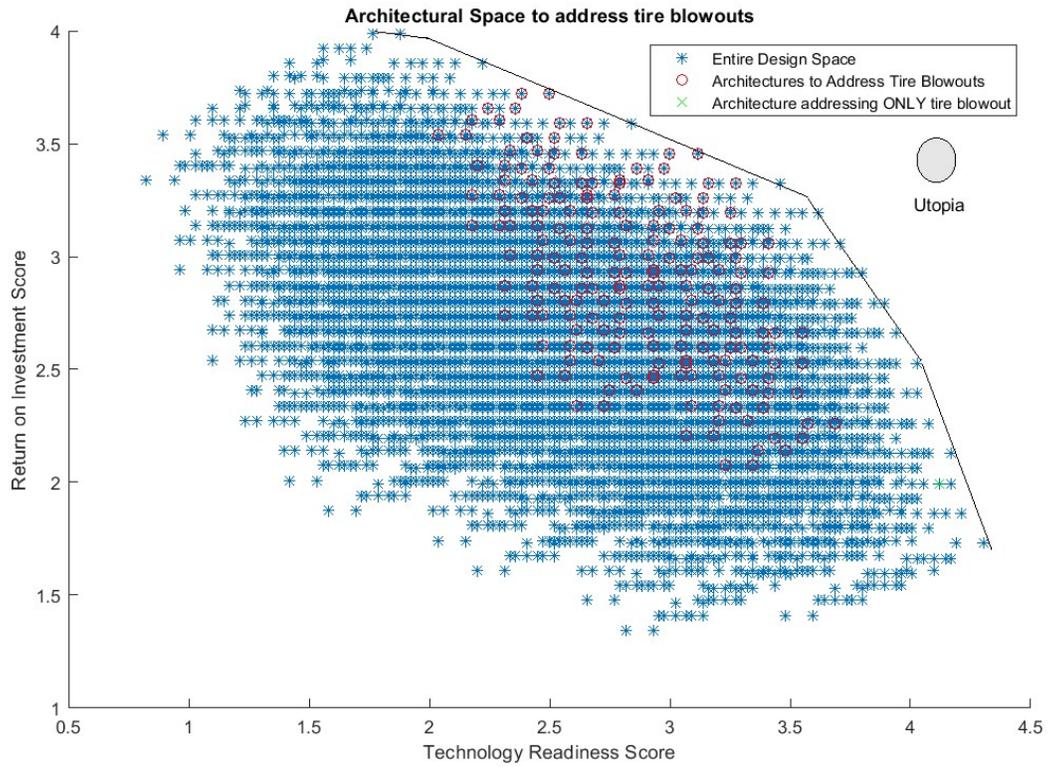


Figure 35 - Tradespace exploration – Architectures addressing tire blowouts

Chapter 6 - Technology Roadmap

The prior chapters illustrate four groups in which the design space can be categorized – Baseline, Fully Autonomous, Hybrid and Platoons. The fully autonomous architectural roadmap is out of scope for this thesis as we envision the realization of it would be beyond next ten years, which is where this thesis tries to put its focus. The hybrid architectures would be various combinations of different architectural decisions resulting in varied degrees of autonomy in the system. The choice between these architectural decisions would be guided by the technology readiness, societal readiness and perceived return on investment of the said choice and the importance of mitigating certain critical off nominal failure modes arising from autonomous cargo transport. To understand these figures of merits a market survey was conducted across multiple industries. The results of the survey and assessment of today's technology are the guiding factors for the technology roadmap described in this chapter.

As illustrated in Chapters 4 and 5 there is a very high societal readiness to see technologies deployed in the field that mitigate non propulsion related hazards. Most of the technologies today are deployed to detect these hazards on which the driver takes relevant action. In addition to these, there are several instances of trucks getting vandalized or hijacked during interstate travel. Fleets allocate a big chunk of investment to cater to such off nominal scenarios which also require expensive insurance, warranty, and legal frameworks. This is reflected in a very high perceived return on investment for deploying technologies that cater to these scenarios. The literature also indicates fleets spending a lot of money on downtime and delays during loading/ unloading activities. Automating loading/ unloading activities using warehouse robotics would help in reducing this downtime resulting in an increase in daily throughput which translates to revenue.

The readiness of technologies that will address such protection against vandalism, non-propulsion related hazard protection and increasing daily uptime of fleets is either low, or an integration challenge in automotive sector. The development and integration of technologies discussed in this chapter can be prioritized in the following manner

- a) Low TRL technologies with higher perceived ROI and societal readiness if deployed – Technologies that will protect the truck from getting vandalized or hijacked, Technologies that will prevent hazards after detecting off nominal behavior
- b) Market ready or mostly market ready technologies which can be deployed in a short time – Technologies to sense weight real-time, technologies to facilitate platooning etc.
- c) Market ready technologies with integration challenges – technologies such as to prevent malicious actors from filling incorrect fuel. All the pieces of technology to detect and prevent incorrect refueling exist in the market (cameras to detect what is being filled, image processing software, proximity/capacitive sensors to detect fuel port status, electromagnetic actuators to lock/unlock fuel power, electric motors to present and align fuel nozzle etc.) but is a huge integration challenge to deploy successfully on the truck.

This chapter discusses such technologies, their market trends and proposes a roadmap to realize technology deployment to address critical needs of the fleets to achieve high uptime, high revenue and hazard free operation.

6.1 - Technology Trends

The key elements required to realize the benefits of the hybrid and platooning architectures are the technologies listed below. These would play a critical role on addressing majority of the critical functions listed in the appendix B.

Key technologies required to realize partial/full autonomy in long haul cargo transport

- 1) Connectivity – With the absence of the driver, a high speed, reliable connectivity is extremely important while the truck is enroute. Some of these technologies would be LTE, 5G, 6G, DSRC etc.
- 2) On board hardware – This would include all the sensors and actuators that would have to be mounted on the truck to sense and act on any off nominal instances (like increasing tire temperatures, unlocked cargo doors, unstrapped/loose cargo etc.). These would include technologies like pressure, temperature, proximity, magnetic sensors, linear motors, electromagnets as actuators. This also includes hardware required for autonomous propulsion like cameras, LiDARs, Radars etc.
- 3) Compute – Increasing computational speeds, high bandwidth communication media are needed to run embedded real time algorithms that make autonomous propulsion decisions. This requires higher memory, higher number of cores improved semiconductors to achieve the increasing need of high compute. These will include technologies like the Phi/ Nvidia series of graphic processors, CAN-FD, Ethernet communication media etc.
- 4) Data storage – On and off board data storage is required to store all the relevant data to be able to a) analyze it to improve fleet performance and b) recreate field issues and resolve critical errors in the functionality. The amount of data generated by one vehicle per day is increasing exponentially and would require not only bigger digital space, but improved technology to minimize disk wear due to repeated writing of such data. Compression technologies would also be required to be able to make efficient use of the storage space.

This chapter discusses key enablers for autonomous transportation and how the current trends are guiding today's decision of autonomy in long haul cargo transportation. The figure below shows the criticality of such technologies across various architectures on the pareto front as discussed in Chapter 5. As it is observed in the figure, the technologies discussed in this chapter become more and more critical as we move towards higher degrees of autonomy.

2G and 3G technologies are not sufficient for today's needs and hence there is an increasing effort to move towards higher bandwidth, faster cellular connectivity technologies for automotive applications. Similarly DSRC and V2V technologies are critical for platoon architectures. With

higher degrees of automation, multi core processors with more than a terabyte of storage become a necessity given the amount of data generated by the vehicles. Similarly, the communication media bandwidth requirements increase, making protocols like CAN-FD (Flex Data Rate) or Ethernet a necessity in automotive. The hybrid architectures which address fault responses or facilitate autonomous loading/unloading activities would require onboard sensors and actuators to facilitate critical functions. Autonomous propulsion requires state of the art cameras, LiDARs which become a necessity as vehicles would transition towards full automation.

Technology Category	Technology	Hybrid					
		Baseline	Platooning	Hybrid (Real time weight sense)	Autonomous loading/unloading	Non propulsion fault handling	Fully Autonomous
Connectivity	2/2G	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	LTE	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	5G	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	DSRC	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	V2X	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
Compute and Communications	Single Core	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Multicore	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	CPU	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	GPU	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Cloud Compute	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	CAN	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	CANFD	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Ethernet	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
Data Storage	Less than Terrabytes	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	More than Terrabytes	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Compression Technologies	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
Autonomy hardware	Cameras	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	LiDAR	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Radar	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
Other hardware	Proximity sensors	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Magnetic Sensors	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Temperature/ Pressure sensors	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Displays	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Touch Sensors	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Motors	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Electromagnets	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient
	Solenoids	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient	Not Sufficient

Figure 36 – Technology criticality across architectures on pareto front

Over last few decades, several technologies like graphic processors, multicore architecture, parallel processing technologies, increased core speeds are developed for better and faster processing. Figure 36 below [18] shows the main market players enabling this transition.

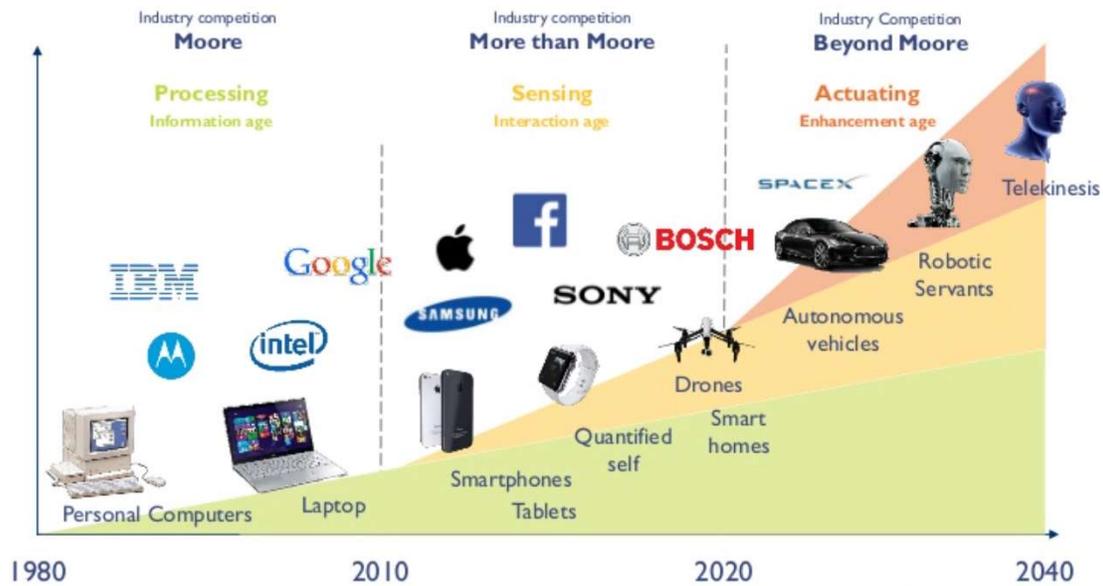


Figure 37 - Competitive landscape for processing, sensing and actuating technologies [18]

The sections below discuss these technologies, their current and future trends and how they would aid in deploying pareto front architectures within the span of next decade.

6.1.1 - Connectivity

Connectivity is extremely critical design variable in realizing autonomy. This includes remote connectivity of the vehicle to a control room as well as short range connectivity to other surrounding vehicles. Connectivity also goes hand in hand with data transfer speeds. Higher speeds, lower latency would enable using wireless technologies in safety critical applications like controlling the vehicle remotely. The current direction of connectivity technology is moving towards higher bandwidth and faster data transfer speeds. Over the last decade, in cellular technologies, we have seen a shift from 2G/3G to LTE and 5G which has enabled us to advance from text messages to video streaming and also some limited tele operations. The wireless world research forum [14] predicts future trends in connectivity and discusses infrastructural challenges that would have to be overcome to meet the increasing data speeds needs. Figure 38 below shows the technology development in cellular technologies over last couple decades.

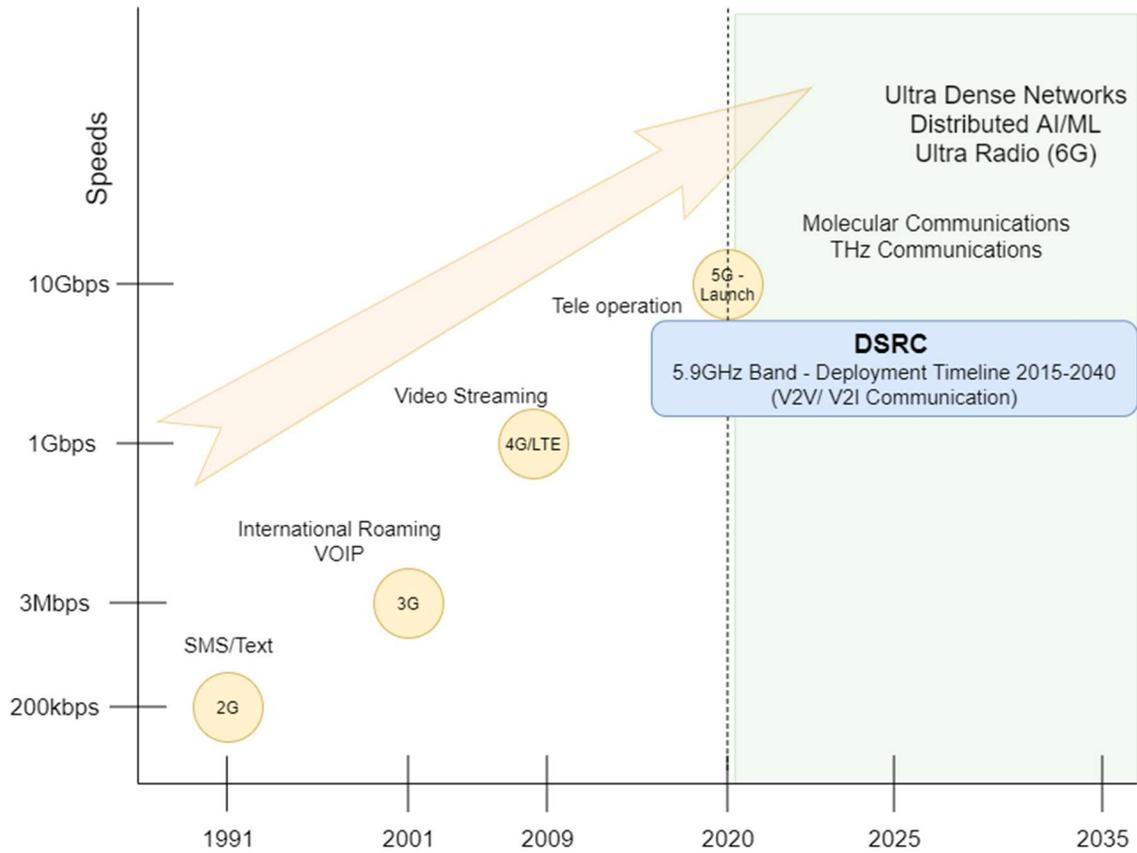


Figure 38 - Technology trends and roadmap - Connectivity technologies

In addition to wifi and cellular technologies, dedicated short range communication technologies (DSRC) is also critical. The spectrum is seen particularly useful for vehicle-to-vehicle communication because it can support very low-latency, secure transmissions, and fast network acquisition. Truck platooning architectures would utilize this media in addition to other applications like mobility and logistics, field equipment-to-center communications, road weather and traveler information and would serve as a functional requirement for all safety critical V2X applications. The USDOT report to congress [15] describes this technology in detail and ongoing efforts for realization and the technology readiness. Figure 39 [20] below from a study conducted by center of automotive research in Ann Arbor, MI, shows trends in V2V technology for automotive

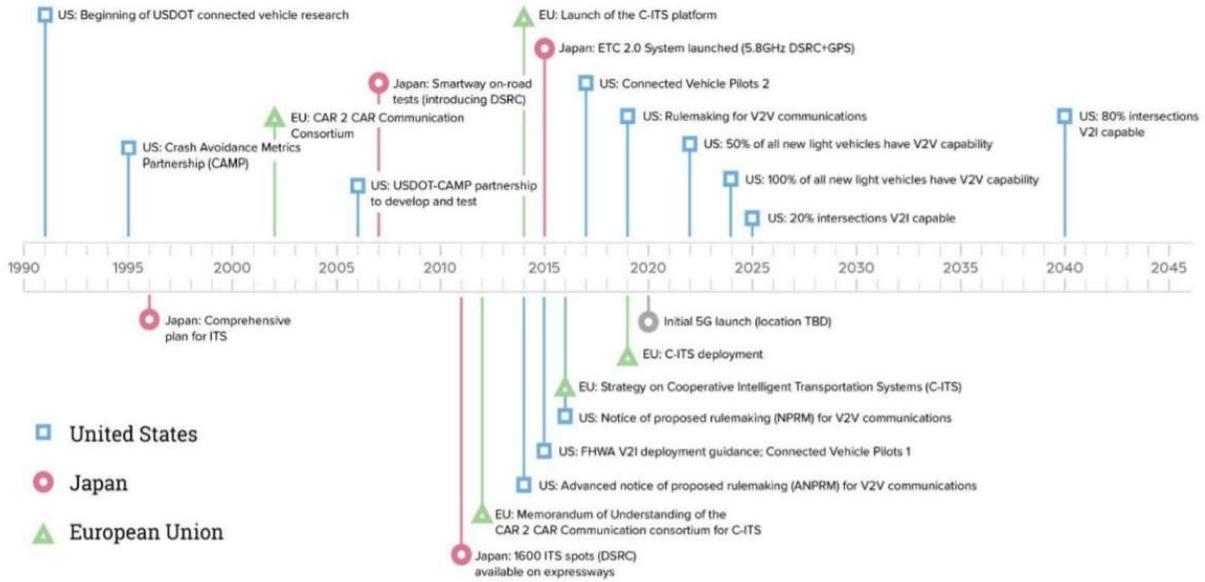


Figure 39 - Technology trends and roadmap – V2V technologies [20]

6.1.2 - On board hardware

The suite of hardware can be categorized into two buckets. Sensors and actuators for sensing non propulsion related failure modes and hardware and compute required for autonomous propulsion. Figure 40 below from McKinsey [18] show various autonomy functions and sensor fusion required to eliminate failure modes. According to the report, a fusion of radar and camera is most likely in next five to eight years.

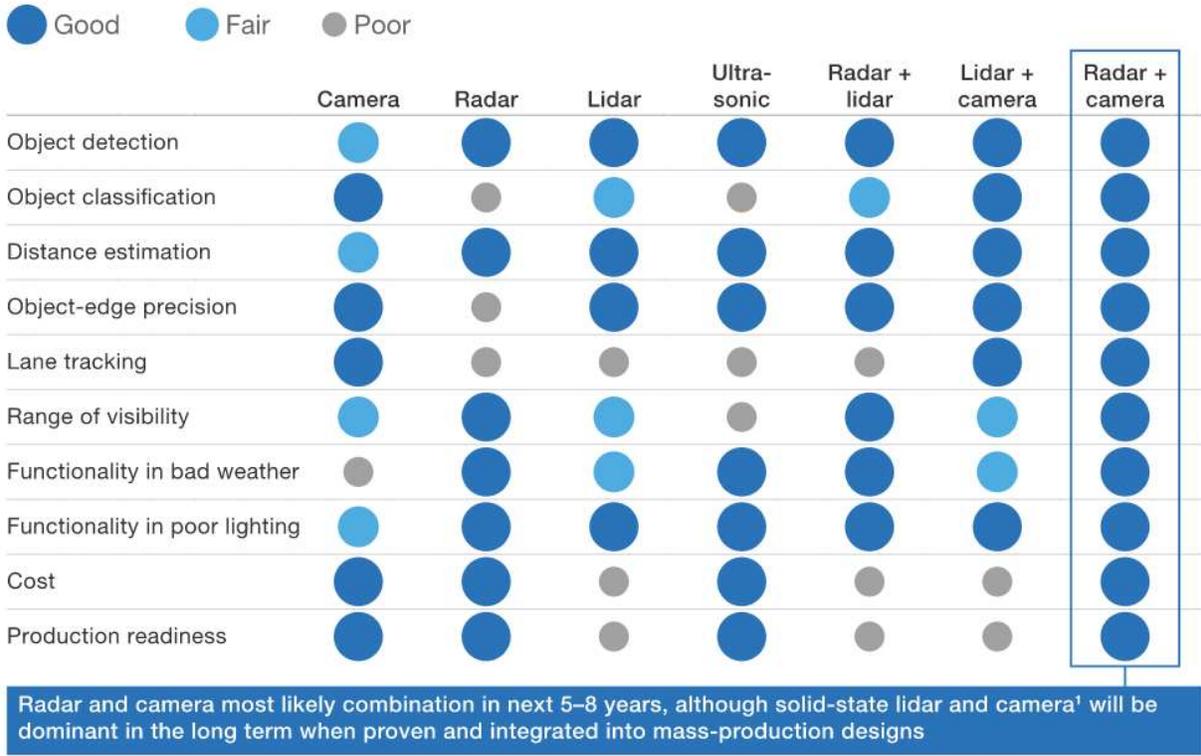


Figure 40 - Autonomous vehicle perception technologies [18]

Recently, in 2019, Infineon technologies have made additions to their Aurix families to support radar applications while in January 2020, Continental AG announced construction of a new plant in the US to manufacture radars.

Similarly, the figure 41 below using data from [18] shows the evolution of cameras over the last decade. Resolution has been steadily improving while the technology is moving towards dual / stereo camera pairs to sense depth and minimize blind spots.

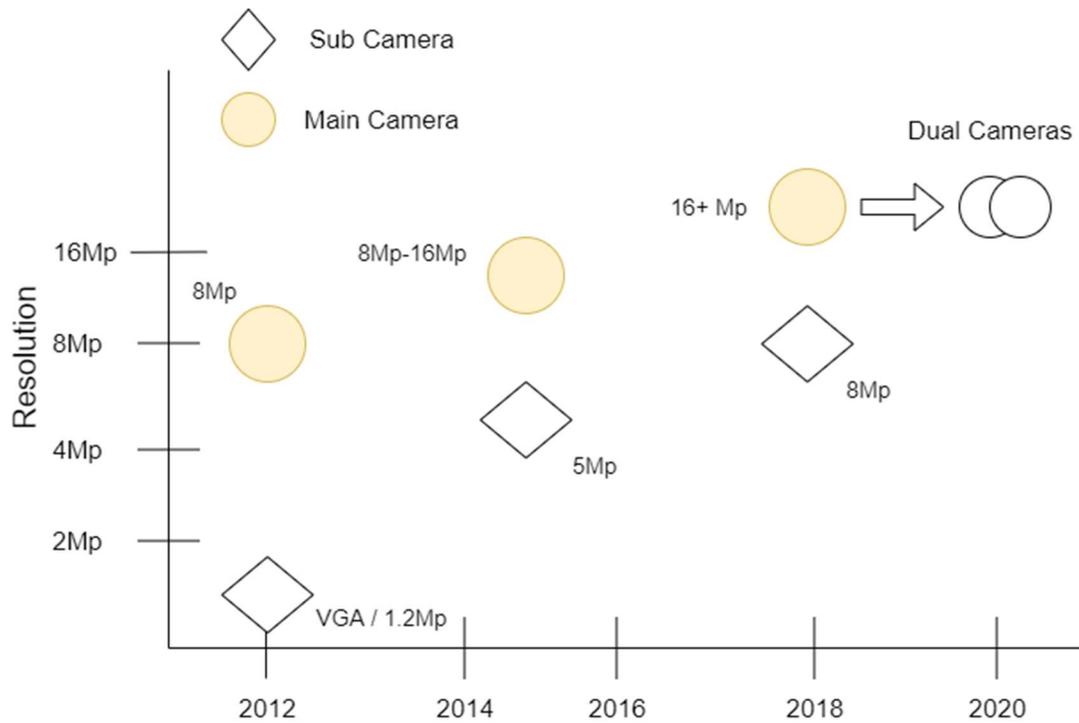


Figure 41 - Technology trends and roadmap – Camera technologies

The technology trends in cameras and radars and advances in computer vision would lead in accelerating progress of sensing for autonomous propulsion.

The second category of hardware would be all the sensors and actuators that are required to be on board for all the non-propulsion related functions. These sensors can be divided into categories like inertial (accelerometers, gyroscopes etc.), environmental (pressure, temperature, humidity, leakage etc.) and optical (vision, proximity, multi spectral etc.). Several non-propulsion related degraded and failure modes called out in Appendix A would require some sort of sensing and actuation using these types of sensor technologies. Figure 42 below [21] shows the key players today in this space.

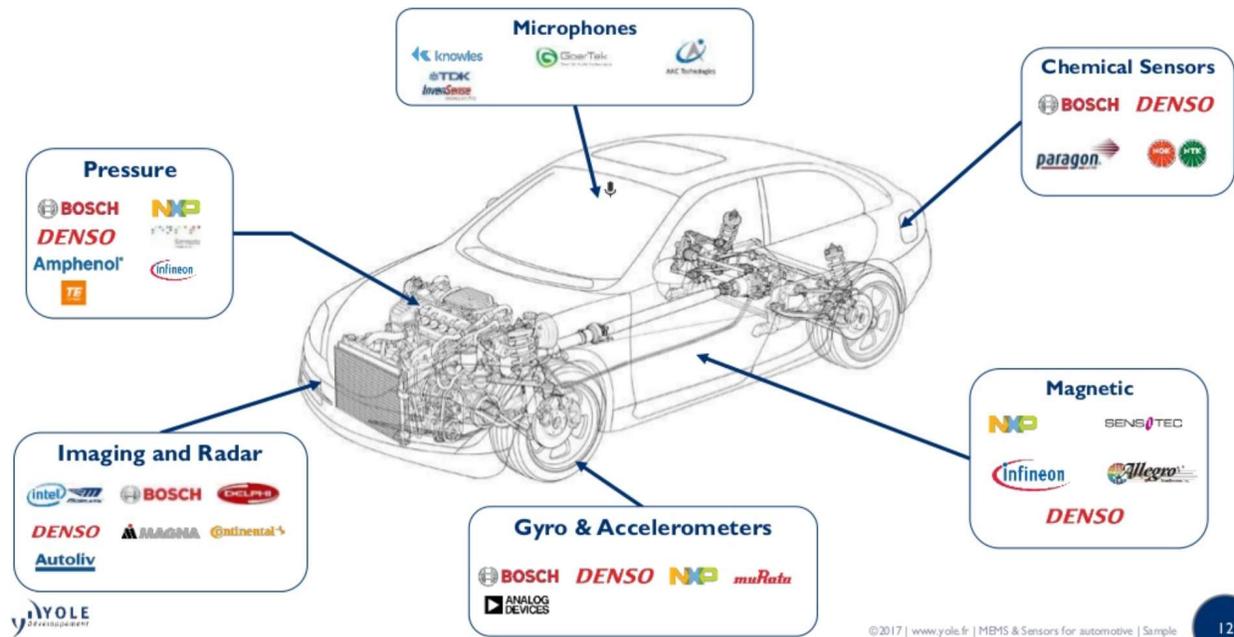


Figure 42 - Automotive technologies and players [21]

The increase in volume of various types of sensors (chemical, inertial, ultrasonic, TPMS, pressure, magnetic) outside of propulsion sensing will play a key role in pushing the current low TRL technologies towards market adoption. Deployment of these sensors in vehicles will directly results in addressing some of the off nominal scenarios described in previous chapters and designing emergency and contingency operations for the degraded and failure modes.

6.1.3 - Compute and Storage of Data

Today's technological needs have already increased the reliance of high-fidelity data. Generating insights from massive amounts of data using advanced machine learning algorithms and neural networks is becoming a necessity. Performing such analysis on an embedded systems in a vehicle, with limited compute power and stringent reaction timing requirements would be the next technological breakthrough. According to [13] new heterogeneous computing solutions will emerge involving new computing paradigms such as neuromorphic processors that yield low power consumption, fast inference, and event-driven information processing. The article further suggests the emergence of universal memories will offer the capacity and persistency features of storage, combined with byte-addressability and increased access speed of memory. Persistent memories can remove the distinction between runtime data structures and offline data storage structures, resulting in faster start-up times and recovery in case of failover. Advancements in non-volatile memory technologies will be crucial to meet strict latency requirements. These data needs would place high demands on hardware performance such as access latency, capacity, bandwidth, energy consumption and cost performance which has necessitated the need of hardware advancements.

Processor technologies have shifted their focus from higher clock speeds to creating more cores per processor. After 2005, processor technology entered a multicore era to enable parallel computing. In future, the transistor counts, and number of cores are expected to increase exponentially. The important figures of merit for processor technologies are number of cores, core frequency, memory capacity and bandwidth and cache capacity.

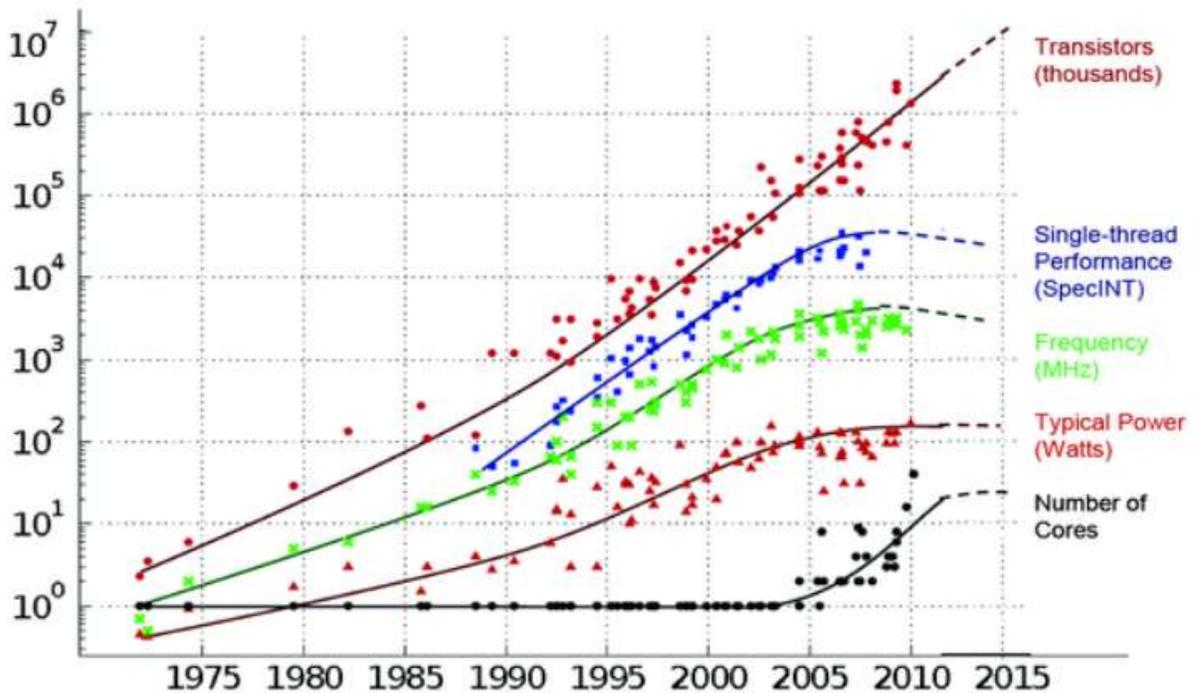


Figure 43 - Technology trends and roadmap - Processor technologies [17]

Figure 44 shows a comparison between various processors across these figures of merit.

Type	Xeon E7-8890 V4	Xeon Phi 7290F	Xeon Phi 724P	NVIDIA Tesla V100
#core/#thread	24/48	72/288	68/272	5120 CUDA cores/640 tensor cores
Core frequency	2.20 GHz	1.50 GHz	1.3 GHz	1.455 GHz
Memory capacity	3.07 TB	384 GB	16 GB	16 GB HBM2 VRAM
Cache capacity	60 MB L3	36 MB L2/16 GB HBM	34 MB L2	6 MB L2
Memory type	DDR4-1866/4 channels	DDR4-2400/6 channels	MCDRAM/16 channels	HBM2
Memory bandwidth (GB/s)	85	115.2	500	900
Price	\$7174.00	\$3368.00	\$3324.00	\$149,000.00

Figure 44 – Figures of Merit for Processor technology [16]

With increasing parallel processing for the performance gap between CPU and storage would have to be balanced. This I/O bottleneck constraining data intensive computing can be addressed by NVMs. Flash memory technology is a mature technology at present. In addition to NVM, 3D stacking technologies can deliver high performance data caching for multicore processors. This new hardware advances in processor and storage technologies would enable faster and more efficient query and transaction processing.

Various communication technologies are also being developed and becoming mainstream in automotive applications to accommodate for higher data rates and increasing bandwidth. Ethernet is now being adopted as a common backbone for all in vehicle communications. CANFD is seeing wider adoption in automotive which enables transmission of up to 64 bytes of data in a single frame compared to only 8 bytes of data in a standard CAN frame. The figure 45 below shows the evolution and adoption of communication protocols in automotive. The industry is moving towards adopting protocols that enable higher data transfer rates. Hence we can expect to see ethernet and CANFD becoming more mainstream within next decade

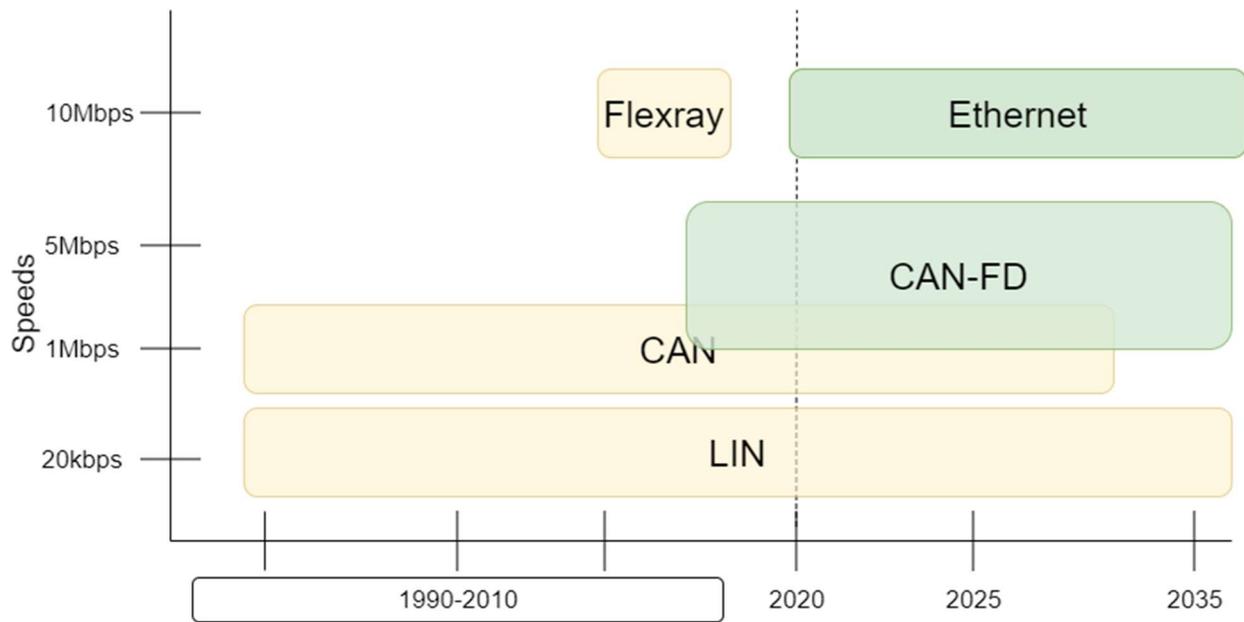


Figure 45 - Technology trends and roadmap – Automotive communication technologies

6.2 - Technology Roadmap

This section proposes a technology roadmap for adoption of autonomy in long haul cargo transport. The insights are based on the survey results and the state of art of key technologies required to address architectural concepts described in previous chapters. These key technologies are connectivity, on board sensors and actuators, data processors/ compute and data storage technologies and computational power/speed.

The figure below shows a potential roadmap of technology adoption in autonomous trucking which would facilitate certain types of functions to be carried out autonomously. The figure is categorized into six sections. The first five sections are various critical technology categories required to realize varied degrees of autonomy in long haul cargo transport. The last section leverages insights from trends in these individual categories and proposes a roadmap for deploying autonomy in trucking. The bars in each category represent the maturity of the technology. The starting point (year) for each bar represents the year where initial proof of concept/ pilot deployments of the said

technology have been/would be seen, whereas the ending of the bar would represent technology maturity or potential widespread adoption (or disruption) of the said technology. The overlapping bars in the same technology category would represent the presence of both technologies in the market at the same time.

Within next 5 years we would see more wider adoption of 5G networks. 5G speeds will enable tele operation facilitating controlling of vehicles remotely. As the technology progresses over the decade, it is possible to see remote control of autonomous vehicles within next 10 years. This will also be aided by advances in 6G and ultra-dense networks. These will enable data intensive algorithms to run on the cloud and update the vehicle remotely, saving embedded computer power. The DSRC adoption roadmap spans two decades, so there is expected to have continuous development of this technology to enable V2X communications. Truck platooning and DSRC trials are ongoing and it is expected to grow over the next five years. Platooning is expected to become widespread even before any other type of autonomy is deployed. We expect drivers to be present in the follower trucks for redundancy, but the truck itself would be capable of following the lead truck autonomously using DSRC technologies.

The advances in camera resolutions and radars would facilitate better depth tracking, minimizing blind spots and push for the adoption of autonomous propulsion in next 5 years. Autonomous propulsion market is extremely competitive with big players like Bosch, Denso, Autoliv, Intel making significant investments in these technologies. Non propulsion hardware like pressure sensors, ultrasonics, proximity, optical sensors etc. would provide necessary hardware capabilities to sense and act on non-propulsion related failure modes described in previous chapters. Performing autonomous pre trip checks and periodic checks while the vehicle is being driven would be possible with this hardware and associated software. Bosch and Denso are key players in this segment as well along with Infineon and NXP semiconductors.

Within next 5 to 10 years, we are bound to see significantly higher adoption of CANFD and ethernet communication media within vehicles. Increasing reliance on higher data transfer speeds would enable the adoption of these protocols. Such protocols will enable higher amounts of data transfer to the cloud via connectivity technologies described above. Availability of such high fidelity, time series data would help characterize driving scenarios, environmental/ road conditions, which would enable improving route guidance algorithms. This computation would also be supported by advances in semiconductor technology with adoption of higher cores and parallel processing. Data storage, data processing and data transfer technologies will enable higher levels of autonomy in trucking specifically to address safety critical off nominal failure modes as well as environmental conditions, road blockages, weather conditions more efficiently.

Several technologies mentioned above feed directly into satisfying certain critical autonomous functions. DSRC and V2X technology maturity directly affects efficiency of truck platooning. Autonomous fault handling concepts would require matured processor technology (multicore, high speed processors), embedded compute and state of the art sensor and actuator technology to detect failures. Autonomy hardware like radars and cameras with associated software is critical for autonomous propulsion where as cloud compute technologies and 5/6G networks can push the

boundaries of achieving L5 autonomy where the vehicles would be able to learn from each other by continuously sharing high fidelity ODD data and running/ refining models on the cloud.

Having said that, standalone technology development is not sufficient to fully realize autonomy. The technologies in all these categories would have to be vetted not only in a standalone manner, but also within an automotive environment. The next section discusses some challenges that would be seen while adopting these technologies.

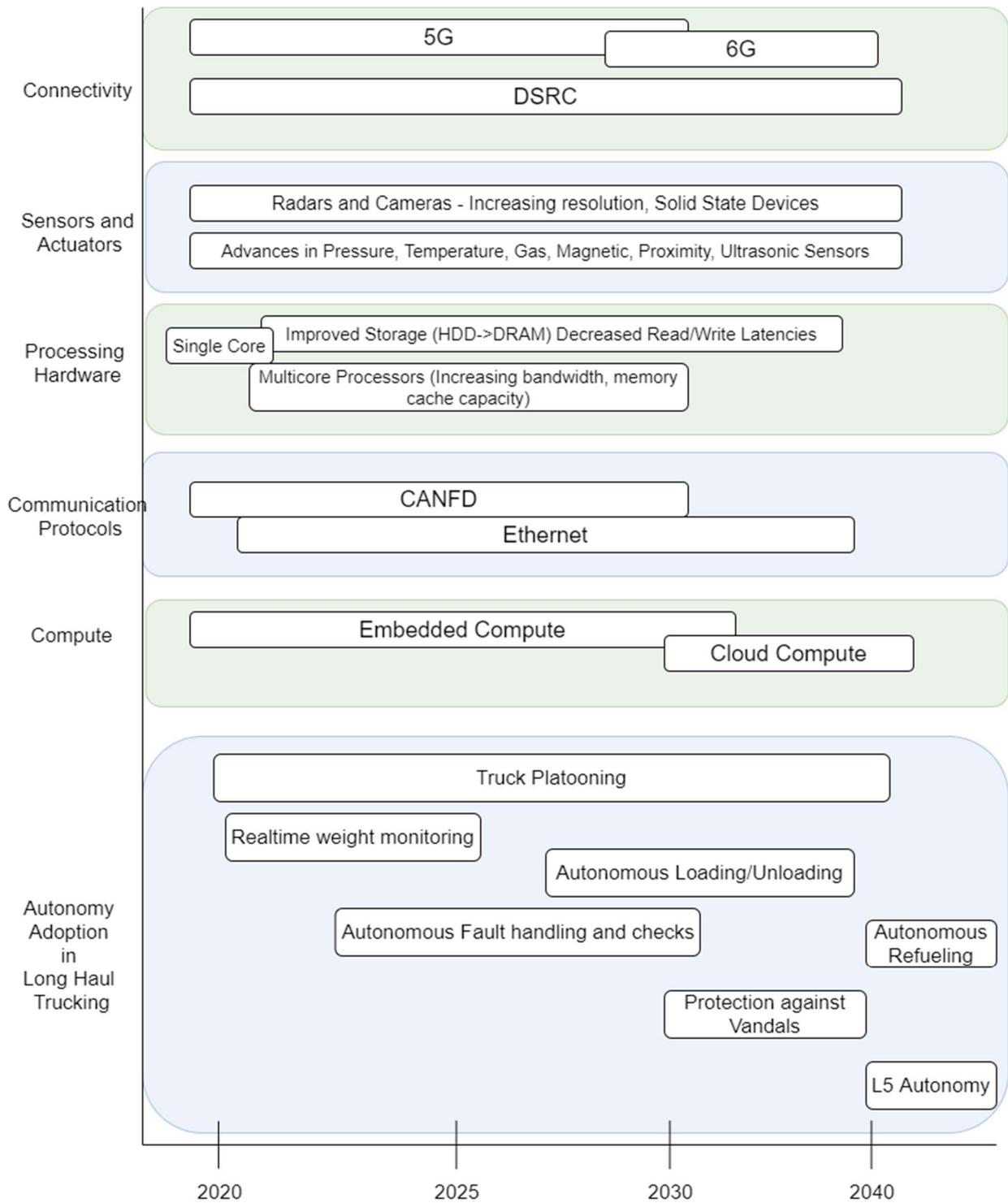


Figure 46 - Technology roadmap – Autonomous cargo transport

6.3 – Challenges in adoption – Technology Maturity, Integration, and Tuning

The previous section provides insights into technology trends in various categories and a potential adoption roadmap for the trucking segment. Various levels of autonomy require various technologies to be market ready and able to be integrated in an automotive environment. The roadmap shown in Figure 47 assumes autonomy in trucking will be feasible once the respective technology is market ready. This assumption is not completely true. The complex operational design domain presents three challenges the market needs to overcome in order to see these technologies deployed in automotive domains

- A) Technology maturity – Needless to say, various critical functions required to achieve partial of full autonomy rely on the maturity of the technology. E.g. Fully autonomous propulsion will not be possible without mature Camera, LiDAR and Radar technologies. Similarly, without having proper sensors like pressure, temperature, and load sensors, it would not be feasible to detect faults and build software to address real-time failures without the presence of the driver. For such safety critical software, a multicore high-speed processor would be required and hence the technology needs to exist in the market.
- B) Technology integration – The second challenge that the sector would have to overcome is technology integration. Even though the technologies in the above categories are mature and market ready it would not mean that they can be deployed in a trucking environment. Market readiness is a necessary condition, but not sufficient. These technologies would have to be integrated onboard and should be compatible with each other. As an example, a mature camera and LiDAR would still require computer fusion to properly detect blind spots. Pressure and temperature sensors are widely available in the market for several decades and we have seen their adoption in automotive over last few years, but the sensed data from these sensors would have to be now used for failure detection (while minimizing false positives due to sensor noise) and executing proper safety maneuvers and safe states. Similarly displays (LCD, LED) and controls (Joysticks, push buttons, bio metrics, capacitive touch sensors) and widely available in the market but would have to be integrated in a truck to achieve access controls and HMI. Lessons from the airline industry can be leveraged while developing these solutions, but the takeaway is that this integration exercise would be needed which would involve additional hardware design, fixtures, software integration and testing for failure modes. Technology integration outside the system boundary is also critical. E.g. Connectivity technologies would be required to not only be matured, but also deployed across different geographic areas to minimize connectivity blackouts. This presents a multidisciplinary integration challenge where the semiconductor industry, telecom companies, governments (city and federal) and data providers are all key stakeholders in the integration.
- C) Technology tuning – The last challenge that the industry would have to overcome after technology maturity and integration is tuning for the specified operational design domain. The onboard sensors, hardware would have to be calibrated for each use case. A long-haul flat bed truck towing cars would require different calibrations for strapping the cars onto the flatbed compared to a box truck which is hauling e-commerce boxes. Similarly,

development and integration of real time weight sensors would require additional calibration to act differently based on the gross vehicle weight ratio of each vehicle since the weight requirements from DOT vary with the gross vehicle weight.

Chapter 7 - Conclusions

The study took a systems approach to rethink the design decisions that would be needed to achieve autonomous long-haul cargo transport. The thesis investigated several nominal and off nominal operational scenarios to study critical functions required to address them. It focused on architectural decisions and technologies outside autonomous propulsion, that would be needed for designing a system to satisfy the critical functionality and proposed a technology development roadmap for the next decade using the current state of art and insights from the model developed as a part of this work.

The thesis asked two fundamental questions –

- 1) What technologies, outside autonomous propulsion, would be required to realize a true automated long-haul cargo transport
- 2) How much of automation can be realistically achieved in next decade given the technology readiness, societal acceptance and perceived return on investment of these technologies.

Chapters 2 and 3 use principles of system architecture [32] to design concepts required to achieve autonomous cargo deliveries. The critical functionality outside autonomous propulsion that would be required to realize automation is

- 1) Ability to detect and act on failures in pre-trip and periodic checks – This would require a certain set of sensors and actuators to execute these checks and predetermined fault reactions when a failure is observed. Most of the “reactions” are performed by the driver today which would have to be automated.
- 2) Ability to interact with human agents enroute – There are several instances when a truck driver has to interact with outside world. The automated truck would have to perform these interactions. These interactions could involve requesting data, displaying data, executing payments etc.
- 3) Access control for authorized users – It would be important to restrict access of unauthorized personnel from entering the truck. Some sort of access control and protection against vandalism would be needed to minimize operational losses due to unauthorized access.
- 4) Ability to connect with remote servers and/or schedule remote roadside assistance when required – For any off nominal scenarios where the truck has to get pulled over, there should be a way to schedule assistance.

The thesis modeled all the architectural decisions according to relative scores received from the market outreach to perform a tradespace analysis. Chapters 4 and 5 illustrate several tensions between technology readiness, societal acceptance and perceived ROI for various architectures satisfying all or parts of the critical functions. The main takeaways from the architectural tradespace analysis were

- 1) Full automation (eliminating driver completely from all the activities during cargo deliveries) although would realize higher ROI, would not be seen in next decade. The

technologies required for automating a complete end-to-end system are not market ready and looking at the current technology trends, it is unlikely to be ready within next 10 years.

- 2) Partial automation is the way forward to increase ROI.
- 3) In partial automation, platoon architectures score the most on the trade space. The primary reason for this is that platooning can be deployed even in non-autonomous trucks by installing DSRC technologies and associated software for trucks to enter/exit and follow a platoon. All the technology required to achieve this is market ready and deploying platooning would realize significant fuel savings in a short period of time.
- 4) Other types of partial automation that is possible to be deployed in next ten years to maximize ROI would be
 - a. Transitioning towards real-time weight monitoring. This would save significant time the trucks waste in taking a detour towards weighing stations. All the technologies required for achieving this are market ready and relatively inexpensive. Once the system transitions to real-time weight monitoring, the real estate dedicated for weigh stations can be used for other eco-friendly purposes (recreational areas, tree plantations etc.).
 - b. Fault handling – This would become a critical need to increase societal acceptance of autonomous trucks. Achieving fault handling would also increase ROI significantly as fleets incur significant losses due to truck downtime and/or on road accidents. Fault detection technologies are seen in almost every vehicle in the market. The focus would be on technology development to take actions on detected faults in the absence of the driver. Several technologies are deployed in some form or fashion in various non-automotive applications which can be used to design a system that would handle faults gracefully in the absence of the driver.
- 5) Some architectures affect the ROI negatively which suggests the current state of art is better than the proposal. Autonomous refueling is such an example where the ROI cannot be justified looking at the investment needed to achieve fully autonomous refueling. The existing infrastructure of humans filling fuel should be made more robust by deploying technologies on board to prevent off nominal scenarios like filling incorrect fuel. Furthermore, the investment needed to automate fuel stations lies outside the system boundary (truck/fleet) which would further discourage the market to make such an investment as the gains realized by eliminating humans are minimal compared to the capital required.
- 6) Vandalism and hijacking are some serious concerns. A solution to prevent vandalization and hijacking of trucks would significantly reduce the operational losses of the fleet. Although the technology readiness to achieve this is very low and we do not see a way that the market would focus on this in the coming decade.
- 7) There are several processes, partnerships, infrastructure that needs to be developed outside the system boundary to truly realize automation. The thesis alludes to some such requirements but does not go into analyzing them in detail. Proper warranty protections, insurance plans, legal framework and policies and standards would be required to deploy autonomous trucks on freeways. Certain road infrastructure like dedicated lanes, roadside sensors, areas for trucks to pull over to form platoons etc. would also have to be designed.

7.1 Areas of further study

Autonomous vehicle is a complex system with a very low tolerance to failures. The system consists of interactions between several stakeholders – truck as a system, fleet management, OEM, software stack providers, government, lawyers, citizens and third-party companies like roadside assistance, insurance companies etc. This work focusses just on the truck as a system and considers only technological concepts. Other areas where investigation is required would be

- 1) Interaction between the above-mentioned stakeholders – It would be necessary to model these interactions and analyze the undesired emergence that may occur. It is also important to model and account for delays (e.g. regulations and standards take years to be developed and in certain cases only accelerated after occurrences of certain accidents). There needs to be a study to see how such delays can be avoided and regulations and standards are put in place proactively (not reactively)
- 2) Another area of study would be various models for insurance and warranty. Proper ownership models would be needed in case of failures since this is a multi-stakeholder product (truck is owned by the fleet; truck is developed by an OEM and autonomy stack is supplied by a software tech company). Legal framework would also have to be studied.
- 3) It would be useful to study the effect of automating cargo transport on economies and cities. Autonomous trucks would eliminate the need of rest stops. Economies of several cities in the middle of the US are built on the fact that the city serves as a hub of truckers to rest at night on predetermined routes. Eliminating rest stops could destroy these economies and such an analysis of economic impact could be a great topic of research.
- 4) Cybersecurity would be an important topic for further research. Increasing automation and connectivity would increase the vulnerability to cyber-attacks. Proper technological solutions would have to be put in place to avoid cyber-attacks on autonomous trucks.
- 5) Finally, the thesis does not discuss infrastructural needs outside the system boundary that would be required to realize autonomy like dedicated lanes to autonomous trucks, satellite/GPS network, pull over areas to form platoons and roadmaps to achieve these would be another area of investigation.

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Appendix A – Operational Scenarios

OS 1 - Interaction with human agents

1) Interaction with weight station agent

- a. (Normal) Truck weighs itself on the weigh scales, produces a receipts and resume trip

ID	OS-1.1
Condition	Normal operating condition
Objective	Truck weighs itself on the weigh scales, produces a receipts and resume trip
Operational Events	<ol style="list-style-type: none"> 1) The truck approaches a weigh station 2) Truck senses signals from DOT weigh scanners and decides to take a detour to get itself weighed 3) The truck approaches the weigh scales, aligns itself properly and completes weight scanning 4) The truck produces a receipt and appropriate paperwork to the DOT agent in charge. 5) The DOT agent checks the paperwork and “clears” the truck to resume trip
Actors	DOT Agent Truck
Pre conditions	Proper alignment on the weigh scales
Post Conditions	There should be a way for the DOT agent to “clear” the truck to resume its trip
Sensors	Detection of alignment
Actuators	User control to clear the truck to resume trip
Inputs	NA
Outputs	Weight data display/ receipt Other paperwork

- b. (Normal) Truck mis-aligns on the weigh scales. Alignment of the truck on the weigh scales according to DOT agents instructions

ID	OS-1.2
Condition	Normal operating condition
Objective	Alignment of the truck on the weigh scales according to DOT agents’ instructions
Operational Events	<ol style="list-style-type: none"> 1) The truck approaches a weigh station 2) Truck senses signals from DOT weigh scanners and decides to take a detour to get itself weighed 3) The truck approaches the weigh scales, but stops without aligning itself properly on the scales 4) The DOT agent at the station approaches the vehicle and gets control access 5) The DOT agent uses vehicle controls to align the truck on the scales 6) The DOT agent gives back control to the truck to perform the weighing routine 7) The truck completes the weighing routing and provides appropriate receipt to the agent 8) The agent checks the receipt and clears the truck to resume the trip

Actors	DOT Agent Truck
Pre conditions	There should be a way to detect the truck is not properly aligned on the scales Upon detecting mis-alignment, the truck should allow user access control
Post Conditions	There should be a way for the DOT agent to “clear” the truck to resume its trip
Sensors	Detection of alignment
Actuators	User control to align the truck User control to clear the truck to resume trip
Inputs	Control input from DOT agent to align the truck
Outputs	Weight data display/ receipt Other paperwork

- c. (Degraded) Alignment of the truck on weigh scales when DOT agent cannot take control and requires control room to remotely operate the truck

ID	OS-1.3
Condition	Degraded operating condition
Objective	Alignment of the truck on the weigh scales according to DOT agents’ instructions when access control is not operational
Operational Events	<ol style="list-style-type: none"> 1) The truck approaches a weigh station and senses signals from DOT weigh scanners to take a detour to get itself weighed 2) The truck approaches the weigh scales, but stops without aligning itself properly on the scales 3) The DOT agent at the station approaches the vehicle and attempts to get control of the truck to do the alignment. 4) The DOT agent fails to get access control. 5) The DOT agent establishes contact with the control room and raises the concern 6) The control room operators remotely align the truck 7) The control room operators begin the weighing process and then give control back to the truck 8) The truck displays weight data 9) The DOT agent correlates the weight data and clears the truck for resuming the trip
Actors	DOT Agent Truck Control room
Pre conditions	The DOT agent is unable to get access control to manually align the truck
Post Conditions	There should be a way for the DOT agent to “clear” the truck to resume its trip
Sensors	Detection of alignment Connectivity to control room
Actuators	Remote control to align the truck User control to clear the truck to resume trip
Inputs	Remote commands from the control room to align the truck
Outputs	Command/response acknowledgement from control room to ensure secure control Weight data display/ receipt Other paperwork

d. (Failure) Weigh scales out of calibration

ID	OS-1.4
Condition	Failure operating condition
Objective	Truck is not able to weigh itself as the weigh scales are out of calibration
Operational Events	<ol style="list-style-type: none"> 1) The truck decides to weigh itself and re routes itself on the scales 2) The truck aligns itself correctly and completes the weigh routine 3) The station publishes a weight number which is an order of magnitude higher than the actual weight due to mis calibration of the sensor 4) The DOT agent is unaware of the miscalibration, trusts the weight number produces and flags the truck for halting the trip 5) The truck cannot resume the trip leading to operational delays and revenue loss
Actors	DOT Agent Truck
Pre conditions	The weigh station is mis calibrated and the DOT agent is unaware of this issue
Post Conditions	<ol style="list-style-type: none"> 1) There should be a way for truck to independently calculate its own cargo weight. 2) The truck must compare its measurement with weigh stations response. If they differ outside a certain threshold, the truck should establish connectivity to the control room and raise the issue. 3) The control room should be able to correlate the weigh data from other trucks weighed on that station and appropriately clear the truck if the station is deemed faulty 4) The truck should produce appropriate paperwork for the DOT agent for them to clear the truck for resuming the trip
Sensors	Independent weight sensing and correlation to weigh stations number. Connectivity to control room Ability to correlate with data from other trucks
Actuators	
Inputs	Weight data from other trucks in similar time period Trucks independent weight measurement
Outputs	Command/response acknowledgement from control room to ensure secure control Appropriate paperwork to deem the station mis calibrated.

2) Interaction with “Cash only” Toll station agent

- a. (Normal) – Truck enters a cash only toll station. The station agent is able to scan the truck, deduct appropriate tolls and allow the truck to resume the trip**

ID	OS-1.1
Condition	Normal operating condition
Objective	Truck arrives at the cash only toll station, interacts with the toll agent who charges the toll and then the truck resumes the trip
Operational Events	<ol style="list-style-type: none"> 1) The truck approaches a toll station and comes to a stop 2) The truck enables its interactive displays to interact with the toll agent 3) The agent looks at the entry/exit waypoints the truck has traversed on the said freeway

	<ol style="list-style-type: none"> 4) The agent uses the onboard payment system to deduct the appropriate charges 5) The agent uses the interactive display on the truck to tell the truck to resume its trip and opens the toll gates 6) The truck resumes the trip
Actors	Toll Agent Truck
Pre conditions	Truck arrives at a cash only toll station. The station is equipped with deducting charges using a debit/credit card
Post Conditions	Appropriate charges are deducted, and the truck resumes its trip
Sensors	Tolls scanners / cameras Interactive displays/ touch screens/ voice sensors Card readers
Actuators	Payment machines
Inputs	Commands to deduct charges, resume trip Payment option inputs from the agent
Outputs	Entry/exit data points displayed to the agent Payment confirmation receipt

- b. (Degraded) – Truck enters a cash only toll station. The station agent is not able to execute the toll payment leading to delays in trip

ID	OS-1.1
Condition	Degraded operating condition
Objective	Truck arrives at the cash only toll station, but the toll agent is not able to deduct proper payment
Operational Events	<ol style="list-style-type: none"> 1) The truck approaches a toll station and comes to a stop 2) The truck enables its interactive displays to interact with the toll agent 3) The agent looks at the entry/exit waypoints the truck has traversed on the said freeway 4) The agent uses the onboard payment system to deduct the appropriate charges but fails 5) The agent establishes contact with the control room 6) The control room deducts appropriate charges and provides a receipt to the agent and to the truck 7) The agent uses interactive displays to “tell” the truck to resume the trip
Actors	Toll Agent Truck Control room
Pre conditions	Agent is not able to deduct toll charges using onboard system. Cellular connectivity to the control station is present
Post Conditions	Appropriate charges are deducted, and the truck resumes its trip
Sensors	Tolls scanners / cameras Interactive displays/ touch screens/ voice sensors Card readers Cellular connectivity
Actuators	Payment machines

Inputs	Commands from truck to agent displaying (failed) payment status Commands to control room for toll payments
Outputs	Payment deduction via control room Commands from control room to the agent and truck regarding the payment status

- c. (Failure) – The truck enters a cash only toll station and the station is not manned. The truck just sits there indefinitely

ID	OS-1.1
Condition	Failure operating condition
Objective	Truck arrives at an unmanned, but cash only toll station. The truck should have a way to not sit there indefinitely waiting for an agent
Operational Events	<ol style="list-style-type: none"> 1) The truck approaches a toll station that is supposed to be manned, but is not. 2) The truck senses the absence of toll agent and establishes contact with the control room 3) The control room (or the truck itself) deducts appropriate toll charges. 4) The control room actuates the toll gate and lets the truck resume the trip
Actors	Truck Control room
Pre conditions	Agent is not present at the toll station Toll station gates can be remotely operated by the control room
Post Conditions	Appropriate charges are deducted, and the truck resumes its trip
Sensors	Cellular connectivity Cameras (to detect agent absence) Toll gate status sensor (open/closed) – proximity, infrared
Actuators	Motors to control toll gates electronically
Inputs	Commands from truck to agent displaying (failed) payment status Commands to control room for toll payments
Outputs	Payment deduction via control room Commands from control room to the agent and truck regarding the payment status

3) Interaction at fuel station

- a. (Normal) – Truck enters a fuel station, an agent at the station fills the appropriate fuel and clears the truck to resume the trip

ID	OS-1.1
Condition	Normal operating condition
Objective	Truck arrives at a fuel station and gets the correct fuel filled in by an agent
Operational Events	<ol style="list-style-type: none"> 1) The truck arrives at a fuel station and aligns itself at an open fuel pump 2) The truck turns off the engine and enter “refueling mode” 3) An agent approaches and uses the interactive displays to “talk to the truck” 4) The agent selects appropriate fuel and uses the on board controls to unlock the fuel port 5) The agent fills the correct fuel and secures the fuel port 6) The agent uses the onboard payment portal to deduct appropriate payment.

	7) The truck performs its post-fill-up-checks and resumes the trip if everything checks out
Actors	Fuel Agent Truck
Pre conditions	Fuel station is manned There is atleast one open fuel pump
Post Conditions	Appropriate charges are deducted, and the truck resumes its trip
Sensors	Cameras Fuel level sensor Touch screen / HMI Fuel port ajar/open sensors (proximity, magnetic) Fuel type sensor (?) – diesel vs gas/petrol
Actuators	Fuel port door lock/unlock actuators Payment portals
Inputs	Refuel mode Fuel type Fuel amount
Outputs	Fuel receipt Post refuel checks (is the amount of fuel filled correct and sufficient to resume the planned trip, is the fuel filled correct fuel, is the fuel port door locked and secured, is the payment successful etc.)

b. (Degraded) – Truck enters a fuel station and the station is not manned

ID	OS-1.1
Condition	Degraded operating condition
Objective	Truck arrives at a fuel station, but the fuel station is not manned
Operational Events	<ol style="list-style-type: none"> 1) The truck arrives at a fuel station and aligns itself at an open fuel pump 2) The truck turns off the engine and enter “refueling mode” 3) The station agent is absent 4) The truck detects their absence and initiates and looks for another fuel station in the vicinity (such that the extra fuel needed to get routed to an alternate fuel station will not disrupt the operations) 5) The truck routes to an alternate fuel station and get the fuel filled. 6) If an alternate fuel station is not in the vicinity such that the truck can safely get routed to it, the truck initiates a connection to the control room. 7) The control room dispatches assistance at the truck location to fill fuel.
Actors	Truck Control room
Pre conditions	Fuel station is unmanned
Post Conditions	Truck successfully gets filled and resumes the trip
Sensors	Cameras
Actuators	Software to reroute the truck safely to an alternate fuel station OR Commands sent to the control room for refueling assistance

Inputs	Refuel mode Alternate fuel station maps
Outputs	Rerouting to alternate fuel station Dispatched refueling assistance

- c. (Failure) – Truck enters a fuel station. The person at the fuel station fill diesel instead of gas and clears the truck to resume the trip

ID	OS-1.1
Condition	Degraded operating condition
Objective	Detecting and recovering from incorrect refueling
Operational Events	<ol style="list-style-type: none"> 1) The truck arrives at a fuel station and aligns itself at an open fuel pump 2) The truck turns off the engine and enter “refueling mode” 3) The fuel agent fills incorrect fuel 4) The truck performs its post trip checks and detects the fuel filled is incorrect 5) The truck aborts the trips and establishes connection with the control room 6) The truck logs the complaint along with the agents photo id 7) The control room dispatches roadside assistance to tow the truck 8) The control room initiates inquiry against the agent who filled incorrect fuel
Actors	Truck Control room Fuel agent Roadside assistance
Pre conditions	Incorrect fuel is filled
Post Conditions	Truck is towed to nearest maintenance station Inquiry is lodged against the fuel agent
Sensors	Cameras Fuel type sensors
Actuators	
Inputs	Refuel mode Fuel type, level / post refuel checks
Outputs	Complaint lodged, inquiry against fuel agent Roadside assistance dispatch

4) Interaction at facility security gate

- a. (Normal) – Truck reaches destination at regular hours. At the gate, the security agent scans the truck and allows it to enter the facility

ID	OS-1.1
Condition	Normal operating condition
Objective	Interact with the facility gate security to finish after hours delivery
Operational Events	<ol style="list-style-type: none"> 1) The truck arrives at the destination after hours 2) The delay in arrival is already communicated by the truck to the control room.

	<ol style="list-style-type: none"> 3) The control room has already sent a notification to the destination facility security about the truck's delayed arrival 4) Upon arrival, the security guard uses interactive displays to scan for the truck id and the manifest 5) Upon verifying proper paperwork, the guard opens the facility gates and lets the truck in 6) The truck enters the facility and proceeds to the loading dock
Actors	Security agent Control room Truck
Pre conditions	Truck is delayed in reaching the destination and the trip delay is communicated by the truck to control room to the destination facility security
Post Conditions	Truck successfully enters the facility and proceeds to the unloading dock
Sensors	Scanners Interactive displays to present necessary paperwork
Actuators	User controls to ask for documents to verify trucks ID and manifest
Inputs	Truck ID Manifest
Outputs	Access to the facility

- b. (Degraded) – Truck reaches destination at odd hours and the security agent does not allow the truck to enter the facility**

ID	OS-1.1
Condition	Degraded operating condition
Objective	Contingency plan in cases where the security guard does not allow the truck to enter the facility
Operational Events	<ol style="list-style-type: none"> 1) The truck arrives at an altered destination facility 2) This destination change has not been communicated with the destination facility managers and hence the facility is not expecting this truck to be arriving 3) Upon checking the trucks ID and manifest, the facility security does not find any records of this trucks expected arrival. Hence the facility security does not let the truck enter the facility 4) The security guard uses an interactive display to let the truck know about this decision and a reason 5) The truck establishes connection to the control room and raises this concern 6) The control room cross checks the internal records and verifies the truck's change in destination plans 7) The control room connects with the destination managers/ facility security and the truck to update the manifest. 8) Upon receiving updated manifest, the security verifies the truck's identity and uses interactive displays on the truck to allow the truck into the facility 9) The guard opens up facility gates 10) The truck enters the facility and drives upto the unloading dock
Actors	Security agent Control room Truck

Pre conditions	The facility managers/ security have no knowledge about this trucks arrival. The updated manifest has not been shared with the destination.
Post Conditions	Truck successfully enters the facility and proceeds to the unloading dock
Sensors	Scanners Cellular Interactive displays to present necessary paperwork
Actuators	User controls to ask for documents to verify trucks ID and manifest
Inputs	Truck ID Manifest Queries / Responses to/from the control room
Outputs	Access to the facility

- c. (Failure) – Truck reaches the destination. The gate is locked and there is no security agent to summon next steps.

ID	OS-1.1
Condition	Failure operating condition
Objective	Fall back planning when the facility gate is locked and there is no security to let the truck enter
Operational Events	<ol style="list-style-type: none"> 1) The truck arrives at the destination after hours 2) The gate is locked and there is no facility security to verify the manifest and let the truck in 3) The truck senses the absence of facility security. 4) The truck uses its stored route data until destination and finds an area nearby where it can be parked for the night (could be a rest stop, off ramp, mall parking etc.) 5) The truck establishes connection to the control room and raises this concern 6) The truck parks itself at a safe parking area 7) The truck wakes up next day and drives to the destination facility during its open hours 8) The control room communicates the delay in shipment to the destination along with the reason for the delay
Actors	Control room Truck
Pre conditions	Truck is delayed in reaching the destination, destination is locked and there is no security guard to let the truck in
Post Conditions	Truck parks itself at a safe place for the night and is able to enter the facility next time when the facility reopens
Sensors	Scanners Route sensing/mapping software to enable detection of nearest park areas
Actuators	Self direction to nearest parking area
Inputs	Data / route maps or scans
Outputs	Route to the nearest parking area

5) Interaction with cops

- a. (Normal) – Truck gets pulled over by the cop. The cop checks registrations, permits and clears the truck for resuming the trip

ID	OS-1.1
Condition	Normal operating condition
Objective	Interaction with a cop
Operational Events	<ol style="list-style-type: none"> 1) A cop trails the truck with lights flashing 2) The truck should sense this, reduce speed and pull over to the side of the road 3) The truck should present an interactive display as the cop approaches the truck 4) The truck should make available all the paperwork needed by the cop to verify identity (permits, registration, state inspection, weigh scale data, speed profile, unpaid tickets etc.) 5) The display should have a seamless way to interact with the cop 6) After verifying all the documents, the cop either releases the truck without any penalty or gives a warning or a ticket 7) The truck resumes trip 8) The ticket is scanned into trucks system and the payment is made in due time
Actors	Cop Truck
Pre conditions	Cop is trailing the truck with lights flashing
Post Conditions	Truck resumes the trip after interacting with the cop
Sensors	Interactive displays to present all necessary permits Scanners to verify truck’s identity
Actuators	
Inputs	Request from cops to show relevant documentation Some way to input details of a ticket into the software
Outputs	Clearing the truck to resume the trip

- b. (Degraded) – Truck gets pulled over by the cop. The cop requires a bunch of paperwork which the truck is unable to provide

ID	OS-1.1
Condition	Degraded operating condition
Objective	Verifying documents when trucks system fails to produce requested documents
Operational Events	<ol style="list-style-type: none"> 1) A cop trails the truck with lights flashing 2) The truck should sense this, reduce speed and pull over to the side of the road 3) The truck should present an interactive display as the cop approaches the truck 4) The cop requests for specific paperwork 5) The truck is unable to provide that paperwork (say due to malfunctioning system) 6) The truck should initiate a voice call to control room and establish a connection between a human agent and the cop 7) The human agent should be able to send the requested paperwork to a central system where the cop can verify it 8) After verifying, the cop clears the truck to resume the trip
Actors	Cop Truck

	Control room
Pre conditions	Truck is not able to provide the relevant paperwork which is requested by the cop
Post Conditions	Cop is able to verify the paperwork and clear the truck to resume the trip
Sensors	Interactive displays to present all necessary permits
Actuators	Call functionality to speak with a human agent System to share documents with law enforcement
Inputs	Request from cop to produce certain documents Call initiated to control room
Outputs	Sharing requested documents Verifying paperwork and releasing the truck

- c. (Failure) – Truck gets pulled over by the cop for violating regulations. The truck is told to cancel its trip

ID	OS-1.1
Condition	Failure operating condition
Objective	Interaction with a cop
Operational Events	<ol style="list-style-type: none"> 1) A cop trails the truck with lights flashing 2) The truck should sense this, reduce speed and pull over to the side of the road 3) The truck should present an interactive display as the cop approaches the truck 4) The cop requests for specific paperwork and upon verifying the paperwork asks the truck to abort the trip (say due to expired registration, no permits etc.) 5) The cop enters the request into the trucks system via interactive displays 6) The truck overrides its current program to obey what cops have instructed 7) The truck (may) give destination options to the cop to select from – aborting right there at curbside, aborting at the nearest/ next destination, aborting at a nearest parking area etc.. Upon 8) Upon getting relevant directions from the cop, the truck self drives to the “abort” location and parks itself. 9) The truck establishes connection with the control room and stays at the location until updated paperwork has been uploaded by the control room onto the truck. 10) Once that is done, the truck notifies the cops and resumes the trip
Actors	Cop Truck Control room
Pre conditions	Cop asks the truck to abort the trip
Post Conditions	Truck aborts the trip and awaits for updated paperwork before it resumes the trip
Sensors	Interactive displays to present all necessary permits User inputs to interact with the cop
Actuators	
Inputs	Request from cop to produce certain documents Inputs from the cop for aborting destination Request to control room to updated necessary documents

Outputs	Rerouting to abort-destination

OS 2 - Pre/Post Trip Activities

1) Loading/ Unloading of Cargo

- a. (Normal) – The loading personnel loads the cargo, enters inventory details in the manifest, links the manifest to the DOT servers and clears the truck to start the trip

ID	OS-1.1
Condition	Normal operating condition
Objective	To load the cargo in the truck, perform inventory check and clear the truck to begin the trip
Operational Events	<ol style="list-style-type: none"> 1) The loading personnel scans each item 2) The person loads the item on the truck and secure each item 3) The person links all the scanned inventory to the DOT servers (this is used by the servers to decide whether and when the truck has to get weighed at the weigh stations) 4) The person uses interactive controls to “tell” the truck that loading is complete 5) The truck locks cargo doors and begins pre-trip checks
Actors	Loading personnel Truck
Pre conditions	Truck shall be in “loading” mode (cargo door unlocked) Personnel should be present to load the cargo
Post Conditions	The truck should sense “loading complete” inputs and begin pre-trip checks The servers should connect scanned inventory with DOT servers
Sensors	Cameras to sense if proper cargo is loaded Strip tension sensors to sense if cargo is properly secured QR scanners
Actuators	Door locking mechanism post “loading complete”
Inputs	Inventory details entered by loading personnel “loading complete” trigger
Outputs	Commencement of pre-trip checks

- b. (Normal) – The personnel unloads the cargo and directs the trucks for the next destination

ID	OS-1.1
Condition	Normal operating condition
Objective	To unload the cargo and direct the truck to next destination
Operational Events	<ol style="list-style-type: none"> 1) The truck detects “trip complete” and enters “unloading” mode 2) The unloading personnel unloads all the cargo 3) The person uses interactive displays to tell the truck unloading is finished 4) The person uses interactive displays to enter the next destination for the truck and “clears” the truck to resume rest of its trip 5) The truck detects user inputs and enters “trip mode”
Actors	Unloading personnel Truck
Pre conditions	Truck shall be in “unloading” mode (cargo door unlocked) Personnel should be present to unload the cargo

Post Conditions	The user should be able to tell the truck unloading is complete The user should be able to input the next destination for the truck The truck shall commence the remainder of the trip upon detecting inputs from the user
Sensors	Cameras to sense whether the cargo is unloaded
Actuators	
Inputs	“Unloading complete” input from user Inputs to direct the truck to next destination
Outputs	Commencement of pre-trip checks

c. (Degraded) – The loading personnel loads the cargo but does not secure the straps properly

ID	OS-1.1
Condition	Normal operating condition
Objective	To adjust strap tensions upon detecting improper securing of cargo
Operational Events	1) The loading personnel loads the cargo on the truck but forgets to strap the cargo 2) The loading personnel uses interactive controls to “tell” the truck loading is complete 3) The truck senses cargo strap tensions and gives a notification to the person to adjust the straps per standards OR the truck itself adjusts the strap tension 4) The truck enters “loading complete” mode and begins pre-trip checks
Actors	Loading personnel Truck
Pre conditions	Loading personnel has not secured the cargo properly
Post Conditions	Cargo is secured properly
Sensors	Strip tension sensors to sense if cargo is properly secured
Actuators	Actuators to adjust strap tensions Displays to instruct person that cargo needs to be secured properly
Inputs	“Loading complete” trigger Strap tensions
Outputs	Instruction (or action) to adjust strap tensions

d. (Failure) – The loading personnel does not load the full cargo

ID	OS-1.1
Condition	Normal operating condition
Objective	To detect and take proper action when entire cargo is not loaded
Operational Events	1) The loading personnel enters “loading complete” without loading the full cargo 2) The truck scans the loaded items and cross checks them with the inventory 3) The truck detects that all items were not loaded 4) The truck instructs the personnel to complete loading
Actors	Loading personnel Truck Cellular connectivity DOT servers
Pre conditions	Inventory manifest has been uploaded correctly Cellular connectivity is present

	Loading person clear the truck to commence trip without loading the full cargo
Post Conditions	Instructions to the loading personnel to finish loading
Sensors	Cameras, scanners (or other sensors) to detect cargo
Actuators	Cellular connectivity to cross check against inventory
Inputs	“loading complete” trigger Inventory manifest
Outputs	Queries to DOT servers to cross check manifest Instruction to tell cargo is not fully loaded

2) Pre trip safety checks

- a. (Normal) – The truck undergoes all the pre safety checks correctly and begins the trip. These include checking for – autonomy hardware/software functions, tire pressures, oil, fluid checks, brake functionality, cargo straps, vehicle fault conditions / check engine lights, vehicle head/tail light functionality, hazmat documentation (if needed), registrations, manifest etc..

ID	OS-1.1
Condition	Normal operating condition
Objective	To detect loading is complete, begin and complete all the checks necessary for commencing the trip
Operational Events	<ol style="list-style-type: none"> 1) The loading personnel enters “loading complete” 2) The truck detects all the proper cargo was loaded and secured. Then begins pre-trip checks 3) The truck checks for all autonomy hardware functions (sensor ranges, accuracy, precision). 4) The truck performs sensor re calibration if needed 5) The truck checks for fluid leaks 6) The truck checks for tire pressure, tire flats, brake functionality, check engine lights or any active faults 7) The truck checks for proper active registrations, state inspections and other documentation (hazmat docs, border crossing permits etc.) as needed. 8) If any issue found, the truck notifies proper personnel else it transition to “trip mode”
Actors	Truck Cellular connectivity
Pre conditions	Loading is complete and it is indicated to the truck
Post Conditions	Truck is cleared to begin the trip OR Truck notifies appropriate personnel for further action
Sensors	Pressure Gas Temperature Scanners Leakage Weight
Actuators	Actuators needed to test proper functionality of autonomy sensors, brakes Actuators needed for sensor calibrations
Inputs	“loading complete” trigger Contacts of personnel who needed to be notified in case pre-trip checks fail

Outputs	Indicators to display pre-trip check results Connections to relevant personnel to address pre-trip check results

- b. (Degraded) – The truck performs all the pre trip checks, but flags a certain failure and does not begin the trip.

ID	OS-1.1
Condition	Degraded operating condition
Objective	To detect loading is complete, perform pre-trip checks and flag the failures. Contact appropriate personnel to address failures
Operational Events	<ol style="list-style-type: none"> 1) The loading personnel enters “loading complete” 2) The truck detects all the proper cargo was loaded and secured. Then begins pre-trip checks 3) The truck complete all the checks and detects certain failures 4) The truck contacts the maintenance crew to schedule maintenance. 5) The truck transitions into “maintenance mode” 6) The crew comes onsite. 7) The truck grants access control to the crew. 8) The crew fixes the failures and instructs the truck to redo all the checks 9) If checks are complete and passed, the truck transitions out of maintenance mode 10) The truck commences the trip
Actors	Truck Cellular connectivity Maintenance crew
Pre conditions	Failure is detected during pre-trip checks
Post Conditions	Truck is ready to begin the trip after the failure is correctly fixed
Sensors	Access control sensors (bio metric, haptic etc.) to grant access to maintenance crew
Actuators	Various actuators needed to fix pre-trip check failures (aka maintenance toolkit)
Inputs	“loading complete” trigger Contacts of personnel who needed to be notified in case pre-trip checks fail Access request to begin maintenance.
Outputs	Indicators to display results Maintenance receipts

- c. (Failure) – The pre trip checks are not executed by the truck and the truck starts the trip (e.g the 12V battery powering the controllers is dead while cargo loading – so the controller have no way know that pre trip checks are needed, or truck start trip in a manual override mode for the first leg and then the driver lets it off autonomously)

ID	OS-1.1
Condition	Failure operating condition
Objective	To detect conditions where pre-trip checks were not performed before commencing a trip
Operational Events	<ol style="list-style-type: none"> 1) The truck shall store historic data in its black box 2) The conditions were aligned such that pre-trip checks were not performed by the truck (e.g the 12V battery powering the controllers is dead while cargo loading –

	<p>so the controller have no way know that pre trip checks are needed, or truck start trip in a manual override mode for the first leg and then the driver lets it off autonomously)</p> <ol style="list-style-type: none"> 3) The historic data should be used to detect that the truck was loaded and a new trip was started, but pre-trip checks were not performed 4) The truck should notify the driver / user about this condition 5) To be more conservative, the truck should limit certain operations to minimums (limp home mode?) 6) The truck should commence pre-trip checks whenever the truck comes to a stop / next destination. 7) The truck should resume trip only if all the checks pass.
Actors	Truck
Pre conditions	Pre trip checks were not performed before truck began its trip
Post Conditions	Truck notifies appropriate personnel The truck enters “limited operation mode” The truck performs checks next time the engine is turned off.
Sensors	
Actuators	
Inputs	Previous trip metrics (route, time of completion, cargo inventory, pre/post trip checks timestamp) Current trip metrics (route, time of commencement, cargo inventory, pre trip check timestamp)
Outputs	Contacting appropriate personnel about this condition Limited operation mode

3) Directing the vehicle to depot/ maintenance area

- a. (Normal) – After unloading the cargo, the user directs the vehicle to the depot. The truck self drives to the depot and parks itself and schedules maintenance

ID	OS-1.1
Condition	Normal operating condition
Objective	After unloading is finished, the truck drives itself to the depot and parks
Operational Events	<ol style="list-style-type: none"> 1) The loading personnel enters “unloading complete” and keys in the depot/ parking garage as the next destination 2) The truck performs all the post-trip checks. 3) The truck senses parking as the next destination 4) The truck drives to the spot and parks
Actors	Truck Unloading personnel
Pre conditions	Unloading is finished properly The next stop entered is parking Availability of parking space and its knowledge to the truck
Post Conditions	
Sensors	Autonomy sensors for self parking Local parking mapping in case of lost connectivity inside depot/ warehouses/ parking structures
Actuators	Various actuators needed to fix pre-trip check failures (aka maintenance toolkit)

Inputs	“Unloading complete” trigger and next destination set to parking Parking space availability
Outputs	Indicators to display results Maintenance receipts

- b. (Degraded) – The user directs the truck to the depot for parking, but parking space is not available.

ID	OS-1.1
Condition	Normal operating condition
Objective	Detection of parking space availability and contingency plan if it is not available
Operational Events	<ol style="list-style-type: none"> 1) The loading personnel enters “unloading complete” and keys in the depot/ parking garage as the next destination. The truck performs all the post-trip checks. 2) The truck senses parking as the next destination 3) The truck connects to a central server and assess if there are open parking spots. 4) If there are no spots, the truck indicates it to the user and requests for another instruction (e.g a different parking location)
Actors	Truck Unloading personnel Cellular connectivity
Pre conditions	Unloading is finished properly The next stop entered is parking Parking spots are registered on a central server and real time status is updated Parking spot is not available
Post Conditions	The truck requests another input as destination
Sensors	Cellular connectivity
Actuators	
Inputs	Query to get realtime status of available parking spots
Outputs	Route mapping to available parking spot OR Displaying to the user re – unavailability of parking and requesting another input

- c. (Failure) – After unloading the cargo, a new user/ untrained incorrectly directs the truck to a wrong location.

ID	OS-1.1
Condition	Failure operating condition
Objective	Recovering from a misdirection
Operational Events	<ol style="list-style-type: none"> 1) The unloading person enters incorrect destination for the truck (e.g the person types the right address but wrong state) 2) The truck crosschecks the destination entered with historical inputs 3) The truck cross check the distance to destination 4) The truck has ways to detect a potentially incorrect destination 5) The truck prompts user to cross check the input. 6) Depending on the user response (accept/ reject / modify the input) the truck self directs itself to the new destination
Actors	Truck Unloading personnel

Pre conditions	Unloading is finished properly An incorrect next stop is entered
Post Conditions	The truck self directs to the (updated) next destination
Sensors	Touch sensors (for inputting next destination) via touchpad
Actuators	
Inputs	Next destination input from the user
Outputs	Prompt asking user to double check and validate the input destination

4) Directing the vehicle to “car wash”

- a. (Normal) – The user directs the truck to a washing station. The truck aligns itself on the conveyor and transitions into an appropriate mode to enable wash. After wash, the truck gets directed to the appropriate next location (..think about coordination between unloading person, car wash person, truck end locations etc.)

ID	OS-1.1
Condition	Normal operating condition
Objective	After unloading is finished, the truck drives itself to a truck wash station
Operational Events	<ol style="list-style-type: none"> 1) The unloading personnel enters “unloading complete” and keys in waypoints for a truck wash 2) The truck performs all the post-trip checks and routes to the truck wash 3) At the truck wash, the truck aligns itself on the conveyor belt and transitions to “truck wash” mode 4) An agent at the station interacts with the truck via interactive displays to set up the truck for the wash (which type of cleaning, payments etc.). The agent enables the wash 5) After the wash is complete the agent dials in the next destination the truck is supposed to go to 6) The truck exits the “truck wash” mode and self-drives to the next destination
Actors	Truck Wash agent
Pre conditions	Truck is at the wash station Agent is present at the station Truck transitions into a wash mode
Post Conditions	Truck transition out of wash mode Truck know the next destination and begins its trip there
Sensors	Sense alignment on the conveyor belt Sensors to sense user input
Actuators	Actuators to roll the windows up Lock the doors Actuators to realign on the conveyor in case alignment is off Actuator to put the vehicle out of drive (we don’t want the vehicle to creep while under wash)
Inputs	Wash mode trigger Payment
Outputs	Wash receipt

- b. (Degraded) – The user directs the truck to a washing station. The truck does not correctly align itself on the conveyor and/or remains in incorrect shift position to allow seamless translation on the conveyor.

ID	OS-1.1
Condition	Degraded operating condition
Objective	The truck should make sure it has been correctly aligned on the conveyor belt before starting the wash routine
Operational Events	<ol style="list-style-type: none"> 1) The unloading personnel enters “unloading complete” and keys in waypoints for a truck wash 2) The truck performs all the post-trip checks and routes to the truck wash 3) At the truck wash, the truck aligns itself on the conveyor belt and transitions to “truck wash” mode. The alignment is incorrect 4) The truck sense alignment in the wash mode and self aligns itself before allowing access control to the wash agent to begin wash routine 5) The truck displays “alignment in progress” status in order to indicate the wash agent to wait before he enters wash settings and payment options 6) After getting access control, the agent enters all the settings and processes the payment. The agent begins wash. 7) After the wash is complete the agent dials in the next destination the truck is supposed to go to 8) The truck exits the “truck wash” mode and self-drives to the next destination
Actors	Truck Wash agent
Pre conditions	Truck is misaligned on the conveyor belt at the wash station
Post Conditions	Truck has been aligned correctly and gives access control to the agent to begin wash
Sensors	Sense alignment on the conveyor belt Sensors to sense user input
Actuators	Actuators to realign on the conveyor in case alignment is off Actuators to roll the windows up Lock the doors
Inputs	Wash mode trigger Payment
Outputs	Wash receipt Alignment indicators

- c. (Failure) – The user directs the truck to a washing station. The cabin windows and cargo doors remain open and the interior gets damaged due to water and cleaning fluids.

ID	OS-1.1
Condition	Failure operating condition
Objective	The truck should detect and act on open doors and windows during a wash routine
Operational Events	<ol style="list-style-type: none"> 1) The truck drives to a wash station, aligns itself correctly, grants access control to the user and enters wash mode 2) The doors and windows of the truck remain open (failure mode in “wash mode”) 3) User attempts to start wash cycle 4) The truck detects “start of wash” and unlocked doors/ open windows and prevents the user from starting the water flow

	<p>5) The truck gives manual control to the agent to close the windows and lock the doors</p> <p>6) The truck only allows user to start wash once door locks and closed windows are detected.</p>
Actors	Truck Wash agent
Pre conditions	Doors are unlocked and windows are not rolled up before in wash mode
Post Conditions	Doors are locked, windows are rolled up and user is allow to proceed to enabling wash
Sensors	Door lock/unlock detection sensor (magnetic/ proximity) Window status sensor (proximity)
Actuators	Motors to roll up the window (in case this also has to be done in an autonomous manner) Actuator to close the doors and lock them
Inputs	Wash mode trigger Payment Manual overrides
Outputs	Wash receipt Indicators that the wash cannot begin due to unlocked doors and unrolled windows Prevention of wash

OS 3 - Off nominal breakdown response

1) Sensor failure

- a. (Normal) – One/ Multiple sensors fail. The truck detects the failure and executes appropriate safety response

ID	OS-1.1
Condition	Normal operating condition
Objective	Appropriate safety response upon detecting sensor failure
Operational Events	<p>1) The truck in enroute and one or more sensor fails (failure can be detected by incorrect/ out of range readings or loss of communication from the sensor)</p> <p>2) The truck detects sensor failure and sets a trouble code</p> <p>3) The truck transitions into the appropriate safe state (the safe state would depend on the severity of the sensor failure)</p> <p>4) The truck notifies the control room about the failure</p> <p>5) The control room takes appropriate action depending on the severity of the failure (these actions could be – sending roadside assistance, teleoperation of the truck, just making a note of the failure for records etc.)</p>
Actors	Truck Control room Roadside assistance
Pre conditions	Failed sensor on the truck Software which categorizes each failure with a severity level and associates a unique safe state for the failure Connectivity to the control room

	Connectivity to roadside assistance units
Post Conditions	Truck transitions to correct safe state and resumes/ halts operation Control room records the failure and initiates proper response
Sensors	Software to detect sensor failure (communication, range, precision, accuracy)
Actuators	Software to transition into proper and unique safe state
Inputs	Sensor readings
Outputs	Query to control room Safe state transition Scheduling of roadside assistance

- b. (Degraded) – The sensor accuracy/ precision and resolution has changed over time and the sensed objects may be error prone. The truck looks for a range/tolerance in the sensed data and makes appropriate decisions

ID	OS-1.1
Condition	Degraded operating condition
Objective	Appropriate safety response upon detecting sensor precision and accuracy deviations
Operational Events	<ol style="list-style-type: none"> 1) The truck is enroute and readings from one or more sensors cannot be trusted 2) The truck software detects these out of tolerance readings 3) The software takes appropriate actions to transition the truck into a mode which is safe for driving 4) The truck notifies control room regarding the situation 5) The control room schedules maintenance for all the sensors at the destination point 6) If the sensor readings for severely out of tolerance, the truck enters limp home mode and quits the trip safely.
Actors	Truck Control room Roadside assistance
Pre conditions	Sensor calibrations are performed and truck is cleared to be driven Out of tolerance sensor on the truck Connectivity to the control room Connectivity to sensor maintenance units
Post Conditions	Truck either continues operation or transitions to correct safe state and resumes/ halts operation depending on the severity of sensor out of tolerance Control room records the failure and initiates proper response
Sensors	Software to detect sensor range/ accuracy/ precision
Actuators	Software to transition into proper and unique safe state
Inputs	Sensor readings
Outputs	Query to control room Safe state transition Scheduling of maintenance

- c. (Degraded) – Dirt/ Dust/ Snow accumulation on the autonomy sensors leading to the truck making suboptimal decisions.

ID	OS-1.1
Condition	Degraded operating condition

Objective	Recovery from sensors with accumulated dust, dirt, snow
Operational Events	<ol style="list-style-type: none"> 1) The truck is enroute and readings from one or more sensors cannot be trusted due to accumulation of dirt, dust or snow 2) The truck either follows degraded operational sequence of sensor out of tolerance OR 3) Actuators on the truck clean the sensor to restore the field of view while the truck is in motion. OR 4) Actuators on the truck clean the sensor and restore the field of view after bringing the truck to a safe stop 5) After restoring the field of view, the truck resumes operation
Actors	Truck
Pre conditions	Cleaned and operational sensors during trip start Dirt, dust or snow accumulation
Post Conditions	Cleaned sensor and resumed trip OR Halted trip and scheduled roadside assistance
Sensors	Software to detect sensor range/ accuracy/ precision
Actuators	High pressure air nozzle Heating coils Wipers
Inputs	Sensor readings
Outputs	Pressurized air flow (to blow off the dirt/ dust) Heat generation to melt the snow Wipers actuation (to eliminate water droplet accumulation)

d. (Failure) – One/ Multiple sensors fail and the truck is not able to execute the safety response.

ID	OS-1.1
Condition	Degraded operating condition
Objective	Emergency and contingency operations against sensor failure
Operational Events	<ol style="list-style-type: none"> 1) The truck is enroute one or more sensors fail. 2) The truck is unable to detect sensor failure or is unable to avoid transitioning to a proper safe state and ends up in an accident/incident. 3) The truck logs the entire accident conditions to a detail where the event can be recreated by investigators 4) The truck initiates a 911 e-call 5) The truck establishes connection with the control room and reports the event. 6) The control room schedules emergency roadside assistance
Actors	Truck Control room 911 emergency personnel Other vehicles on the road Roadside assistance
Pre conditions	Sensor failure Truck unable to safely transition to a safe operating condition and this leads to an accident
Post Conditions	Emergency response (cops, fire truck, ambulance) Road side assistance scheduling
Sensors	
Actuators	
Inputs	Sensor readings

Outputs	Query to control room Emergency call to 911 Scheduling of maintenance and roadside assistance

2) Vehicle failure in zero connectivity zone

a. (Degraded)

ID	OS-1.1
Condition	Degraded operating condition
Objective	Truck should be able to establish request roadside assistance after experiencing failure in an area with no connectivity such that it has to come to stop
Operational Events	<ol style="list-style-type: none"> 1) The truck experiences failure while in a zero-connectivity area 2) The failure is severe enough that the truck has to come to stop. 3) The truck uses one of the following to establish connection to the outside world – DSRC (dedicated short range communication) to connect with other vehicles which are being driven on the road, or other trucks from the same fleet which will pass by <ul style="list-style-type: none"> Open wifi hotspots from nearby objects 4) After connection is established, the truck would send an SOS signal (with its GPS latitude, longitude) to a central control room/ location. (A standard would have to be developed to make such SOS signals bounced off other objects to be universal 5) Central control center would then schedule a roadside assistance at that location 6) Truck would store all the data to be retrieved later
Actors	Truck Control room Other vehicles on the road Roadside assistance
Pre conditions	Truck experiences failure such that the truck has to come to a roadside halt Infrastructure exists to bounce “SOS signals” off external access points Truck is experiencing loss of connectivity
Post Conditions	Roadside assistance is scheduled and it arrives at the location of the truck.
Sensors	DSRC Wifi hotspots
Actuators	
Inputs	Open networks
Outputs	Query to control room off other vehicles or open hotspots Scheduling of maintenance and roadside assistance

b. (Normal)

ID	OS-1.1
Condition	Normal operating condition
Objective	Truck established connection and reports failure after recovering from connectivity loss
Operational Events	<ol style="list-style-type: none"> 1) The truck experiences failure while in a zero connectivity area 2) The severity of the failure is such that the truck can remain in motion 3) The truck detects loss of connectivity and enters “lost connectivity data logging mode”. 4) The truck keeps logging data while moving.

	<ul style="list-style-type: none"> 5) Once the connectivity is established, the truck connects to the control room and reports the failure. 6) The control room directs the truck to the nearest maintenance location and schedules maintenance 7) The truck self drives itself to the maintenance location where it is fixed
Actors	Truck Control room
Pre conditions	Truck experiences failure but it can keep moving
Post Conditions	After establishing contact with the control room and getting directions to the next maintenance station, the truck self drives to that station
Sensors	Cellular
Actuators	
Inputs	Commands from control room
Outputs	Commands to control room

c. (Failure)

ID	OS-1.1
Condition	Failure operating condition
Objective	Truck experiences a failure and cannot establish connection at all
Operational Events	<ul style="list-style-type: none"> 1) The truck experiences failure while in a zero connectivity area 2) The severity of the failure is such that the truck cannot remain in motion and has to pull over 3) The infrastructure to bounce SOS signals off other vehicles does not exist 4) Other trucks from the same OEM (or running the same autonomy system, OR from the same fleet) are able to detect this broken down truck. 5) Other trucks ID this truck and report the location to the control room 6) The control room sends roadside assistance to the location
Actors	Truck Control room Other trucks from the same OEM/ autonomy system/ Fleet
Pre conditions	Truck experiences failure and has to pull over. There is no connectivity Trucks from the same fleet or OEM have the ability to id other trucks enroute
Post Conditions	Roadside assistance is dispatched at the location reported by other trucks
Sensors	Cellular QR scanner or infrared (some sensor on the truck that can be used to detect and id the truck)
Actuators	
Inputs	Identification queries form other trucks
Outputs	ID of the truck

3) Flat tire/ tire blowout

- a. (Normal) – The truck detects a flat tire (or a blown tire) and executes the appropriate safety response

ID	OS-1.1
Condition	Normal operating condition

Objective	Truck experiences a flat tire and executes a proper safety response
Operational Events	<ol style="list-style-type: none"> 1) The truck experiences a flat or a tire blowout 2) The software is able to sense the tire pressure/ temperature and detects the flat 3) The truck takes appropriate action and transitions into a safe state 4) The truck reports the incident to the control room 5) Depending on the severity and whether the truck has to pull over, the control room schedules from either a post trip maintenance or road side assistance
Actors	Truck Control room
Pre conditions	Truck has a flat or a tire blowout
Post Conditions	Roadside assistance is dispatched or post trip maintenance is scheduled (depending on the severity of the incident)
Sensors	Tire temperature sensor TPMS Cellular
Actuators	
Inputs	Tire pressure and temperature Command from control room providing information regarding service and next steps the truck should be executing
Outputs	Query to control room reporting the incidence

- b. (Degraded) – The truck detects a tire with low pressure (or a flat tire), but keeps driving as the presence of other tires would not lead to a catastrophic failure

ID	OS-1.1
Condition	Degraded operating condition
Objective	Truck experiences reduced tire pressure
Operational Events	<ol style="list-style-type: none"> 1) The truck experiences reduced tire pressure 2) The pressure is such that the truck software decides to keep the truck in motion 3) The pressure reduction is reported to control room
Actors	Truck
Pre conditions	Low tire pressure
Post Conditions	Truck keeps moving
Sensors	Tire temperature sensor TPMS
Actuators	
Inputs	Tire pressure and temperature
Outputs	Query to control room reporting realtime tire pressure Affected fuel economy

- c. (Failure) – Tire blows out on highway leading in uncontrolled propulsion

ID	OS-1.1
Condition	Failure operating condition
Objective	Tire blows out on highway leading in uncontrolled propulsion. Contingency plans to mitigate loss

Operational Events	<ol style="list-style-type: none"> 1) The truck experiences a tire blowout 2) The operating conditions are such that the truck further experiences uncontrolled propulsion and there is a hazard of fatal accidents 3) The truck proactively deploys outside airbags to minimize its impact on other roadside units
Actors	Truck
Pre conditions	Tire blowout Truck has airbags/ deployable padding on the outside
Post Conditions	Accident
Sensors	Tire temperature sensor TPMS
Actuators	Airbags
Inputs	Tire pressure and temperature
Outputs	Outside airbags deployed to minimize truck's impact on other roadside units

4) Cargo door unlocks

a. (Normal) –

ID	OS-1.1
Condition	Normal operating condition
Objective	Cargo door unlocks while the truck is in motion
Operational Events	<ol style="list-style-type: none"> 1) The truck is in motion 2) The cargo door unlocks and the door becomes ajar/ open such that there is a risk of cargo getting spilled out 3) The truck detects the door/ lock status 4) The truck actuators forcibly close the door while the truck is in motion 5) The truck actuators lock the door
Actors	Truck
Pre conditions	Truck is in motion
Post Conditions	Truck remains in motion
Sensors	Proximity sensor Magnetic sensor Infrared
Actuators	Plunger Solenoid Linear motors Electromagnet
Inputs	Door status (ajar, open, closed)
Outputs	Actuator command to force the door close and lock the door

b. (Degraded)

ID	OS-1.1
Condition	Degraded operating condition
Objective	Cargo door unlocks and cargo spills out. The truck shall detect the spillage and take appropriate action

Operational Events	<ol style="list-style-type: none"> 1) The truck is in motion 2) The cargo door unlocks the door opens and cargo spills out 3) The truck detects the spillage and comes to a safe stop at the side of the road 4) The truck dispatches drones to lift the cargo and put it back into the truck 5) The truck closes the doors and locks it 6) The truck then continues its trip to a nearest destination where the cargo can be manually secured
Actors	Truck Drones
Pre conditions	Truck is in motion and cargo spills out
Post Conditions	Truck resumes trip after loading the cargo back
Sensors	Proximity sensor Magnetic sensor Infrared Cameras
Actuators	Drones Plunger Solenoid Linear motors Electromagnet
Inputs	Door status (ajar, open, closed) Drone command
Outputs	Drones lifting the cargo and putting it back into the truck Actuators on the truck closing and locking the door

c. (Failure)

ID	OS-1.1
Condition	Failure operating condition
Objective	Cargo door unlocks and cargo spills out and leads to an accident
Operational Events	<ol style="list-style-type: none"> 1) The truck is in motion 2) The cargo door unlocks the door opens and cargo spills out 3) The situation is such that the vehicles behind the truck get hit by the spilled cargo 4) The truck senses this accident, ids the victim vehicles and reports them to the control room 5) The control room dispatches roadside assistance for the truck as well as the hit vehicles 6) The truck initiates a 911 e-call and requests emergency assistance
Actors	Truck Other vehicles
Pre conditions	Truck is in motion and cargo spills out hitting the vehicles behind the truck
Post Conditions	911 arrives, roadside assistance is scheduled
Sensors	Cameras (to id the vehicles) Cellular Radio
Actuators	

Inputs	ID of other vehicles affected
Outputs	911 call Establishing contact to control room Dispatching roadside assistance and emergency help for affected people

5) Fuel leakage

a. (Normal)

ID	OS-1.1
Condition	Normal operating condition
Objective	Truck detects a fuel leak and takes appropriate action
Operational Events	<ol style="list-style-type: none"> 1) There is a fuel leak 2) The truck detects the leak 3) The truck calculates realtime “distance to empty” given the rate of fuel leakage 4) The truck reroutes to the nearest roadside assistance unit and establishes connection with the control room 5) The control room schedules maintenance to fix the leak
Actors	Truck Control room Roadside assistance
Pre conditions	Fuel is leaking out of the tank
Post Conditions	Truck arrives safely at a maintenance facility
Sensors	Fuel sensor Leakage sensor
Actuators	
Inputs	Rate of fuel leak Maps of fuel stations, maintenance depots
Outputs	Rerouting to nearest maintenance depot

b. (Degraded)

ID	OS-1.1
Condition	Degraded operating condition
Objective	Truck detects a fuel leak but get stranded as it cannot reach the nearest maintenance depot in time
Operational Events	<ol style="list-style-type: none"> 1) There is a fuel leak 2) The truck detects the leak 3) The truck calculates realtime “distance to empty” given the rate of fuel leakage. But the leakage rate is so high that the truck computes the probability of reaching the nearest maintenance station is close to zero 4) Given this probability, the truck pulls over by roadside and establishes contact with the control room 5) The control room dispatches roadside assistance to fix the leak and fill the gas tank
Actors	Truck Control room

	Roadside assistance
Pre conditions	Fuel is leaking out of the tank at a rate such that the truck cannot make it to the nearest maintenance stop
Post Conditions	Roadside assistance arrives at the truck location to address the leak
Sensors	Fuel sensor Leakage sensor Cellular
Actuators	
Inputs	Rate of fuel leak Maps of fuel stations, maintenance depots
Outputs	Pulling over Connection to control room and request for roadside assistance

c. (Failure)

ID	OS-1.1
Condition	Failure operating condition
Objective	Leakage sensor fails and truck is unable to detect a leak. The system should be able to get to safe stop in case fuel finishes without notice
Operational Events	<ol style="list-style-type: none"> 1) Fuel tank is empty (due to a leak) without any prior indication while the truck is cruising on a highway 2) Before the fuel tank reaches a critical level, the truck takes action and enters a limited operation mode and pulls over 3) The truck establishes contact with the control room and requests roadside assistance
Actors	Truck Control room Roadside assistance
Pre conditions	Fuel tank is empty
Post Conditions	Roadside assistance arrives at the truck location to address the issue
Sensors	Fuel level sensor Cellular
Actuators	
Inputs	Realtime fuel level
Outputs	Pulling over Connection to control room and request for roadside assistance

Appendix B – Functional Decomposition

Driving

F1.1.1	Detection of low hanging bridges
F1.1.2	Detection of "Passenger Cars Only" routes and Parkways
F1.1.3	Driving on/off weigh scales
F1.1.4	Avioding routes with low hanging bridges
F1.1.5	Avioding "Passenger Cars Only" routes and parkways
F1.1.6	Routing through or avioding weigh station detours
F1.1.7	Autonomy sensor pre trip conditioning (checking for functionality, range, accuracy, preciscion)
F1.1.8	Calibrating autonomy sensors
F1.1.9	Acting on flat tire conditions (limp mode?)
F1.1.10	Taking preventive actions to aviod tire blowouts
F1.1.11	Action on brake failure
F1.1.12	Rrealtime rerouting to avoid trip delays
F1.1.13	Driving in wet/ slippery conditions
F1.1.14	Detecting autonomy sensor sense issues (due to accumulation of dirt, snow, water/ dust on sensors)
F1.1.15	Real time sensor out of calibration detection and response
F1.1.16	Ability to enter/exit a truck platoon
F1.1.17	Ability to recover from sense issues (on the fly and offline)
F1.1.18	Fallback functions to eliminate possibility of system malfunction if one truck in a platoon malfunctions
F1.1.19	Recovering from getting stuck in snow
F1.1.20	Detection of tire temperatures
F1.1.21	Detection of tire flats
F1.1.22	Detection of brake wear / Brake failure / Brake pressure reduction
F1.1.23	Detection of protestors and hijackers
F1.1.24	Preventing drive in overloaded conditions
F1.1.25	Detection and action on reducing fuel levels (may need real time rerouting to nearest fuel stations)
F1.1.26	Detection and action on 12V battery health during the trip
F1.1.27	Preventing drive when loading/ unloading is in process
F1.1.28	Commencing emergency response under low fuel levels if a fuel station is not within the range's reach
F1.1.29	Detecting potential trip delays

F1.1.30	Avioding protestors, hijackers
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Non-Driving

	Function
F1.2.31	Deciding to route via a particular weigh station based on recommendations from DOT
F1.2.32	Deciding whether to route through weigh scales or not
F1.2.33	Calculating optimal route via these refuelling stops
F1.2.34	Ability to connect to DOT servers
F1.2.35	Receiving data from DOT servers
F1.2.36	Ability to sense feedback from control room to begin, end or resume a trip
F1.2.37	Ability to update over the air
F1.2.38	Ability for human agents to deduct charges
F1.2.39	Ability to sense inputs from human agents to begin, end or resume a trip
F1.2.40	Detection of start of / end of loading/ unloading
F1.2.41	Displaying necessary permits at the weigh station
F1.2.42	Displaying necessary data coming from the control room to the human agent
F1.2.43	Ability to display necessary documents at border crossings
F1.2.44	Preventing filling of incorrect fuel
F1.2.45	Recording data in a blackbox
F1.2.46	Integration with weigh station status indicators (open/closed)
F1.2.47	Integration with weigh station "EZ Pass" scan sensors
F1.2.48	Ability to detect refueling is complete, payment is processed and truck is good to resume the trip
F1.2.49	Weight sensing (cargo, total)
F1.2.50	Detection of unwanted inventory
F1.2.51	Detection of leaks (fluid, pressure, gas, hazardous materials)
F1.2.52	Detecting and acting on cargo spillage
F1.2.53	Ability to complete the trip when reaching destination at odd hours (when facility is closed, unmanned to receive shipments etc)
F1.2.54	Detecting and acting on unintended door unlocking (cargo and cabin)
F1.2.55	Readjusting strap tensions periodically
F1.2.56	Detecting and acting on overloading conditions (static)
F1.2.57	Image sensing and processing in cargo area (for unwanted cargo, material, personnel)
F1.2.58	Ability to aviod getting the truck hijacked
F1.2.59	Mapping fuel stations
F1.2.60	Calculating refuelling stops
F1.2.61	Certifying truck for starting the trip

F1.2.62	Action on leaks
F1.2.63	Eliminating of HVAC, cabin lighting when in autonomous mode
F1.2.64	Ability to reforecast a contingency in such a situations to avoid reaching at odd hours
F1.2.65	Ability to recover from wrong update
F1.2.66	Auto checking functionality of driving and non driving functions post update
F1.2.67	Preventing in-trip updating
F1.2.68	Pre trip checking routines (check for tires, fluids, corelate loaded inventory with manifest, vehicle faults etc)
F1.2.69	Post trip checking routines
F1.2.70	Periodic checks for all failure conditions as preventive maintainence (brake wear, tire pressure, strap tension, temperatures, pressures etc)
F1.2.71	Ability to aviod getting the truck vandalized (smashed windows, stolen cargo, trashed cabin, knifed tires, destroying autonomy sensors etc)
F1.2.72	Detecting low/ zero connectivity areas

Truck-to-Control Room

F1.3.73	Connecting with control room when requested by human agent (could be agent at weigh station, toll booth, cop etc)
F1.3.74	Ability to contact a human agent if the autonomy functions fail to transmit data
F1.3.75	Connecting to control room when refuelling station is not manned (and truck is waiting to get refueled)
F1.3.76	Requesting human assistance for refuelling
F1.3.77	Transmission of weight data (cargo, total) to control room
F1.3.78	Transmission of in vehicle inventory data to control room
F1.3.79	Transmitting pre/post trip check data to control room
F1.3.80	Transmitting sensor conditioning/ calibration data to control room
F1.3.81	Requesting roadside assistance when needed
F1.3.82	Transmitting failure conditions to control room (leaks, tire blowouts, brake failures, engine overheating etc)
F1.3.83	Reporting enroute incidences (bad weather, protests, hijackers, road blocks, accidents) to aviod other trucks taking that route of possible
F1.3.84	Transmitting data about potential trip delays
F1.3.85	Receiving alternate route information to avoid potential trip delays
F1.3.86	Communicating this contingency (reaching facility during odd hours)with the ahead of time control room
F1.3.87	Reporting OTA update status and issues
F1.3.88	Ability for human agent to send data/ requests from the truck to the control room
F1.3.89	Fallback process to recover from connectivity losses during truck-human interaction events

F1.3.90	Data logging (enough detailed data to recreate incidents)
F1.3.91	Payment processing
F1.3.92	Reporting accidents and incidents when in zero connectivity area
F1.3.93	Ability to estimate whereabouts of the truck in lost connectivity cases
F1.3.94	Acting on feedback from control room for roadside assistance (could be a "repair mode" that the truck can transition into to allow third parties to service the vehicle on road)
F1.3.95	Ability to recover from an accident in a zero connectivity area (continue driving, request road side assistance etc)

Control Room-to-Truck

F1.4.96	Sending data requested by the human agent
F1.4.97	Contacting human services to assist with refueling at an unmanned fuel station
F1.4.98	Providing feedback to the truck on the refueling status
F1.4.99	Providing feedback on roadside assistance
F1.4.100	Conveying alternate route information to the truck
F1.4.101	Ability to update the truck remotely upon request
F1.4.102	Detection and action on cargo/ inventory receiving data which raises concerns (unwanted cargo, missing inventory)
F1.4.103	Fallback process to recover from connectivity losses during truck-human interaction events
F1.4.104	Logging all the incoming data
F1.4.105	Reforecasting alternate routes to avoid potential trip delays
F1.4.106	Ability to dispatch roadside assistance if needed in lost connectivity cases
F1.4.107	Adding/Deleting/Changing Waypoints
F1.4.108	Overriding Waypoints
F1.4.109	Fall back to contact the human agent if data transmission fails
F1.4.110	Payment receipt notifications

Truck-to-Human

F1.5.112	Loading cargo manifest into truck software
F1.5.113	Ability for truck to execute the summoned actions
F1.5.114	Ability for human agent to "clear" the truck for continuation of the trip
F1.5.115	Ability to indicate start of / end of loading/unloading
F1.5.116	Allowing humans to perform roadside service
F1.5.117	Recovering from potential vandalization of the truck enroute
F1.5.118	Interfacing with DOT agent at weigh station
F1.5.119	Ability for DOT agent at the weigh station to request data from the truck

F1.5.120	Ability for DOT agent at the weigh station summon next actions (actions like clearing the truck for rest of the trip, requesting more data, contacting authorities for weight violations etc)
F1.5.121	Ability to interface with human agent at "cash only" toll stations
F1.5.122	Ability to check tires, truck fluids, cargo, strap tensions at refueling stops
F1.5.123	Ability to interact with road side assistance personnel
F1.5.124	Ability for human agent to "clear" the vehicle to resume trip after roadside service
F1.5.125	Interaction with border crossing agents
F1.5.126	Ability for human agent to deduct relevant toll charges
F1.5.127	Ability to enable human agent communicate to the control room while onsite
F1.5.128	Ability to detect refueling is complete, payment is processed and truck is good to resume the trip
F1.5.129	Ability to receive shipments (checking for cargo, appropriate paperwork, instructing the truck towards next destination)
F1.5.130	Fall back functions if toll charge deduction fails
F1.5.131	Manual Override for steering
F1.5.132	Manual override for acceleration, Brake
F1.5.133	Manual override for all non driving functions (cabin controls, door locks, windows, wipers etc)

Human-to-Human

F1.6.134	Linking cargo manifest to DOT servers
F1.6.135	Contacting human agents enroute in case autonomy functions on the truck or between truck and control room fail
F1.6.136	AT lifecycle management
F1.6.137	Requesting refueling assistance for an unmanned fuel station
F1.6.138	Training for receiving shipments/ unloading/ loading / certifying the truck to start/end the trip
F1.6.139	Service training for autonomous truck servicing and maintainence (functionality checks of HW/ SW, range/precision checks)
F1.6.140	Scheduled maintainence programs
F1.6.141	Predictive maintainence programs
F1.6.142	Certification programs to certify technicians for AT servicing
F1.6.143	Preventive maintainence infrastructure
F1.6.144	Keeping refuelling stops manned
F1.6.145	Planning for providing human assistance at destination points during odd hours when needed

F1.6.146	Process to check for cross compatibility of hardware/software during replacement of parts
F1.6.147	Accident investigation teams/ accident management programs
F1.6.148	Autonomy product teams to spec out features that a fleet would need OEMs to incorporate
F1.6.149	Vehicle leasing/ purchasing teams with renewed skills to acquire Ats
F1.6.150	Citizen education teams
F1.6.151	Relationships with upfitters/ body builders
F1.6.152	Data Engineering/ Data science teams
F1.6.153	Health and safety management of operators
F1.6.154	Providing human capital for refuelling
F1.6.155	Providing human capital for road side assistance
F1.6.156	Providing human capital for loading/unloading activities
F1.6.157	Internal data science/ engineering teams to analyze truck data for process/cost/route optimizations
F1.6.158	Definition and standards for allowed hardware and sw functionality tolerance
F1.6.159	Insurance planning to protect against autonomy system failures
F1.6.160	Insurance planning to protect against vandalism
F1.6.161	Fleet representation body in new regulation creation. Government – OEM – Stack providers
F1.6.162	Analysis of trip delays and optimizations in the fleet to avoid future occurrences
F1.6.163	OTA update management (training personnel, proper processes to schedule updates, associated paperwork)
F1.6.164	Payroll, contracts of all the external human assistance needs
F1.6.165	Data gathering and analysis tools and processes to eliminate ambiguity in examining accidents
F1.6.166	Recovering from potential vandalization of the truck enroute

Appendix C – Formal Decomposition

Displays
Screen
Tablets
Lights / LEDs
LCD
Audio feedback
Control room displays
Real time vehicle maps

Controls
Buttons
Sliders
Payment portal
Keyboard
Voice based actuators
Biometric controls (access control)
Joystick
Haptic inputs
Control room command input media

Autonomy hardware
Lidar
Radar
Sonar
Cameras
IR Sensors

General hardware (off and on vehicle)
Servers
Server cooling system

Data storage rooms
Bluetooth modems
NFC
Printer (to print receipts, permits etc if needed)
Document Scanner
Fuel door access control hardware
On board data storage (HDD/SSD/SD Card etc)
QR/ Barcode scanner
Strap adjustment actuators
Control room hardware (computers etc)
Alarms
Reflectors/ Blinkers

Sensors
Weight
Gas
Pressure
Leakage
Temperature
Proximity (door status)
Hall effect
Camera/ Image sensor
Infrared
Hazardous material sensors
TPMS
Voltage sense (12V battery conditioning)

Human
technicians
service/maintenance managers
engineers
data scientists
hourly workers (loading/unlading, refueling etc)
control room operators
emergency response personnel

security guards
incident investigators
product managers
upfitters
regulators
certification personnel

Cellular
Modem (3G, 4G, 5G)
Sim Card
Cellular Towers
Cables
Data Plans
In vehicle telemetry
Hotspots
Wifi

Autonomy software
Perception
State Estimation
Route planning
Route optimization
Vehicle navigation
Fuel/ Weigh station mapping
Route Reforecasting
Summon mode
Remote control mode
Limp home mode

General Software
Fault handling state machine
V2V connectivity
Sensor conditioning/calibration

Pre/post trip check routines	
State machines to interact with human inputs	
Access control software	
Control room connectivity	
Requesting roadside assistance	
Cabin controls	
Platoon entry/exit modes	
Detection of weather conditions, roadblocks	
E-call	
Safety "pull over" mode	
Weigh station mode	
Border crossing mode	
Cash Toll Station mode	
Car wash mode	

Appendix D – Survey Data

Total readiness

TR-ROI		1	2	3	4
1		0.015	0.028	0.033	0.043
2		0.023	0.045	0.054	0.068
3		0.029	0.056	0.067	0.086
4		0.036	0.070	0.083	0.106
5		0.019	0.037	0.044	0.057

TR-SR		1	2	3	4
1		0.007	0.013	0.041	0.058
2		0.011	0.021	0.066	0.094
3		0.013	0.026	0.082	0.117
4		0.017	0.032	0.101	0.145
5		0.009	0.017	0.054	0.078

SR (y)-ROI (x)		1	2	3	4
1		0.007	0.013	0.016	0.020
2		0.013	0.026	0.030	0.039
3		0.042	0.081	0.097	0.124
4		0.060	0.116	0.138	0.177

Refueling

TR-ROI		1	2	3	4
1		0.046	0.071	0.043	0.037
2		0.064	0.098	0.060	0.051
3		0.064	0.098	0.060	0.051
4		0.060	0.093	0.056	0.048
5		0.000	0.000	0.000	0.000

TR-SR		1	2	3	4
1		0.015	0.027	0.078	0.078
2		0.021	0.037	0.107	0.107
3		0.021	0.037	0.107	0.107
4		0.020	0.035	0.101	0.101
5		0.000	0.000	0.000	0.000

SR (y)-ROI (x)	1	2	3	4
1	0.018	0.027	0.017	0.014
2	0.032	0.049	0.030	0.026
3	0.092	0.142	0.086	0.074
4	0.092	0.142	0.086	0.074

Pre trip checks

TR-ROI	1	2	3	4
1	0.021	0.032	0.044	0.025
2	0.021	0.032	0.044	0.025
3	0.055	0.085	0.114	0.065
4	0.044	0.068	0.093	0.052
5	0.031	0.048	0.065	0.037

TR-SR	1	2	3	4
1	0.009	0.017	0.042	0.053
2	0.009	0.017	0.042	0.053
3	0.024	0.043	0.111	0.140
4	0.020	0.035	0.090	0.113
5	0.014	0.025	0.063	0.080

SR (y)-ROI (x)	1	2	3	4
1	0.013	0.020	0.027	0.015
2	0.023	0.036	0.049	0.028
3	0.060	0.093	0.125	0.071
4	0.076	0.117	0.158	0.089

Vandalism

	1	2	3	4
1	0.014	0.045	0.033	0.059
2	0.018	0.058	0.043	0.785
3	0.018	0.058	0.043	0.784
4	0.021	0.067	0.050	0.089
5	0.021	0.067	0.050	0.089

TR-SR	1	2	3	4
1	0.005	0.021	0.051	0.076
2	0.006	0.027	0.066	0.098
3	0.006	0.027	0.066	0.098

4	0.007	0.031	0.076	0.114
5	0.007	0.031	0.076	0.114

	1	2	3	4
1	0.003	0.009	0.007	0.012
2	0.013	0.040	0.030	0.053
3	0.031	0.099	0.073	0.130
4	0.047	0.148	0.109	0.195

Fault Handling

TR-ROI

	1	2	3	4
1	0.005	0.017	0.021	0.033
2	0.017	0.060	0.077	0.119
3	0.016	0.056	0.072	0.113
4	0.011	0.040	0.051	0.080
5	0.013	0.046	0.060	0.093

TR-SR

	1	2	3	4
1	0.003	0.014	0.020	0.039
2	0.012	0.050	0.070	0.140
3	0.012	0.047	0.066	0.133
4	0.008	0.033	0.047	0.094
5	0.010	0.039	0.055	0.109

	1	2	3	4
1	0.003	0.010	0.013	0.020
2	0.011	0.040	0.051	0.080
3	0.016	0.056	0.072	0.113
4	0.032	0.113	0.145	0.225

Weigh stations

TR-ROI

	1	2	3	4
1	0.021	0.045	0.045	0.040
2	0.019	0.040	0.040	0.036
3	0.019	0.040	0.040	0.036
4	0.053	0.112	0.112	0.101
5	0.028	0.058	0.058	0.052

TR-SR

	1	2	3	4
1	0.007	0.009	0.041	0.094

2	0.006	0.008	0.037	0.085
3	0.006	0.008	0.037	0.085
4	0.017	0.023	0.103	0.235
5	0.009	0.012	0.054	0.122

SR (y)-ROI
(x)

	1	2	3	4
1	0.006	0.013	0.013	0.012
2	0.009	0.018	0.018	0.016
3	0.038	0.081	0.081	0.072
4	0.087	0.184	0.184	0.165

Loading unloading

TR-ROI

	1	2	3	4
1	0.001	0.005	0.008	0.017
2	0.007	0.024	0.038	0.083
3	0.010	0.033	0.053	0.116
4	0.020	0.066	0.106	0.232
5	0.009	0.028	0.045	0.099

TR-SR

	1	2	3	4
1	0.000	0.002	0.002	0.016
2	0.002	0.011	0.011	0.080
3	0.003	0.016	0.016	0.112
4	0.006	0.032	0.032	0.225
5	0.003	0.014	0.014	0.096

SR (y)-ROI
(x)

	1	2	3	4
1	0.001	0.002	0.004	0.008
2	0.004	0.012	0.019	0.041
3	0.018	0.059	0.095	0.207
4	0.025	0.083	0.133	0.290

Truck Platooning

TR-ROI

	1	2	3	4
1	0.012	0.007	0.036	0.051
2	0.020	0.011	0.063	0.088
3	0.030	0.017	0.094	0.132

4	0.036	0.021	0.115	0.161
5	0.012	0.007	0.036	0.051

TR-SR		1	2	3	4
1	0.011	0.003	0.045	0.047	
2	0.019	0.006	0.077	0.080	
3	0.029	0.008	0.116	0.120	
4	0.035	0.010	0.141	0.146	
5	0.011	0.003	0.045	0.047	

SR (y)-ROI (x)		1	2	3	4
1	0.012	0.007	0.036	0.051	
2	0.003	0.002	0.010	0.015	
3	0.046	0.027	0.146	0.205	
4	0.048	0.027	0.151	0.213	