MITRE | Center for Integrated Transportation

A MULTI-DOMAIN REVIEW OF CHALLENGES AND LESSONS LEARNED FOR SCALING AV OPERATIONS CENTERS

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MITRE Surface Transportation: Automated Vehicle Research Collaborative

About MITRE's Automated Vehicle Research Collaborative

As part of MITRE's Center for Integrated Transportation, the Surface Transportation Program partnered with industry leaders to establish the Automated Vehicle Research Collaborative (AVRC) in June 2024. The AVRC's mission is to complement and expand safety advancements along the path to full-scale AV deployment through partnership and collaboration. Operating in the public interest, the AVRC brings together government, industry, and academia to collaboratively identify and address critical research gaps in the AV ecosystem. By leveraging MITRE's interdisciplinary expertise in transportation safety and autonomy, the AVRC develops independent, data-driven methodologies and evidence-based solutions to enhance safety, mobility, and efficiency across the AV industry. This collaborative approach enables MITRE and its partners to accelerate progress and deliver impactful outcomes for automated vehicle safety and deployment.

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Executive Summary

This report from MITRE's Automated Vehicle Research Collaborative (AVRC) delivers actionable guidance for building, managing, and scaling AV operations centers for SAE J3016 level 3-5 fleets. This report draws on insights from site visits to industry-leading AV operations centers and research conducted across established centers across multiple domains. It provides guidance for launching or improving operations centers, helps organizations adapt to changing needs, and highlights key risks and opportunities in managing and scaling these centers. By highlighting proven practices and strategies, the report empowers AV operators to enhance reliability, safety, and efficiency in fleet operations.

The report highlights seven critical elements of AV operations center functionality and essential features that drive the design of safe, secure, and scalable AV operations centers:

1. **Remote Assistance:** To ensure safe and efficient interactions between AVs and remote assistants, remote assistance must be developed, tested, and operated as a safety-critical operational element until sufficient evidence demonstrates that these processes do not introduce safety risks. Achieving this outcome depends on robust fault monitoring, rapid situational awareness, and clear execution of remote assistant intent. Remote assistance is supported by multiple interaction types (Approval, Input, Request) and allocation models (assignment-based, queue-based), with emphasis on redundancy, connectivity, and clear Standard Operating Procedures (SOPs).
2. **Rider and Customer Support:** Rider and customer support teams play a vital role in ensuring passenger health and safety, freight delivery, coordination, and emergency interactions, all while maintaining a positive customer experience. To achieve these outcomes and effectively execute operationally critical tasks in AV operations centers, teams must be equipped with effective tools, processes, and management to address diverse customer needs. Success in these areas is supported by five key elements: monitoring, comprehensive training, robust communication systems, cross-functional collaboration, and incident management.
3. **Performance Monitoring:** Situational awareness for operators and supervisors—and the ability to implement adaptive operational structures at scale—depends on effective monitoring of AV fleets and operations centers that is robust to system disruptions, degradations, and adversarial threats. Achieving these outcomes requires overcoming challenges with data availability, validation, and utilization, while leveraging a metrics-driven data strategy that enables timely, informed decision-making through access to relevant information from both real-time and post-processed metrics.

The 7 Elements for Designing Safe, Secure, Scalable Operations Centers

1. REMOTE ASSISTANCE
2. RIDER AND CUSTOMER SUPPORT
3. PERFORMANCE MONITORING
4. INCIDENT RESPONSE
5. OPERATIONAL RESILIENCE
6. STAFFING RATIOS
7. ORGANIZATIONAL CULTURE AND MODELS

4. **Incident Response:** An effective incident response capability enables the operations center to address a wide range of incidents, beyond vehicle collisions, while supporting fleet uptime, and driving continuous improvement of safety, efficiency, and usability. Achieving these outcomes depends on integrating performance metrics, reporting requirements, and SOPs—as well as comprehensive training and documentation—into each phase of the incident response process: preparation, detection and analysis, containment, eradication, and recovery, and post-incident activity.
5. **Operational Resilience:** Every operations center should establish continuity of operations (COOP) plans that address hazards, alternate site support, staffing resilience, and cyber resilience for disruptions affecting multiple facilities. A robust COOP plan enables AV operations centers to sustain performance during off-nominal conditions of varying types and severity, safeguarding both service delivery and operational safety. The report introduces and describes the TRUSTS framework, which is designed to ensure organizations effectively anticipate, respond to, and recover from disruptions while maintaining operational performance and safety.
6. **Staffing Ratios:** Organizational resilience and risk mitigation rely on operational ratios that match technical needs and staffing plans, while remaining flexible to adapt to changing conditions. By balancing enterprise, operational, and safety risks, well-defined staffing ratios support acceptable performance limits and help prevent overload. Insights from healthcare and aviation demonstrate that tailoring ratios to operational needs and human factors, whether through bottom-up workload assessments or top-down system-level outcomes, is essential for maintaining adaptability and effective operations. These domains also demonstrate the potential for improved and assured tooling to maintain operational effectiveness while reducing staffing requirements.
7. **Organizational Culture and Models:** Consistent and reliable operations in AV centers require a strong organizational culture and an effective operational model. As operations scale, gaps in culture or structure can create significant risks due to the interplay of technical and organizational challenges. Practices like designating a primary point of contact, aligning shift schedules, and offering breaks or side tasks are essential for fostering shared situational awareness, sustaining staff focus during long shifts, and promoting clear communication in live operations. This report further examines how building a positive culture, adopting safety practices like Just Culture and Safety Management Systems, and choosing the right organizational model—centralized, distributed, or federated—enhance operational reliability and safety.

In addition to the seven core elements, Appendix A proposes ten key metrics for assessing AV operations center performance, including stopped vehicle response time, vehicle recovery events, emergency responder disruptions, remote assist-involved collisions, forced minimal risk maneuvers, avoidance area implementation time and violations, repeated incidents, operations center downtime, and fleet downtime.

This report can serve as a foundational resource for AV stakeholders, providing a holistic framework and actionable insights for designing, scaling, and improving AV operations centers. Although portions of this report are specific to passenger AVs, many of these lessons learned are broadly applicable across AV use cases. By addressing technical, organizational, and human factors challenges, and leveraging cross-domain lessons, organizations can build resilient, safe, and effective operations centers to support the future of automated vehicle fleets.

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1 Introduction

Automated vehicle (AV) operations centers efficiently and safely link vehicle fleets (capacity) with customers (demand), and depend on complex operational processes, accurate and timely data, and sophisticated communications networks. An AV operations center tends to include a facility or set of connected facilities, frontline and supervisory staff, and the equipment required to execute support and communications functions.

To operate and monitor dispersed fleets, organizations should maintain situational awareness over many pieces of the system simultaneously. For AVs, operations centers are essential to ensuring the effectiveness of AV fleet operations. These centers monitor both individual vehicles and the full fleet, remotely assist vehicles, support riders and customers, and respond to incidents. In addition to monitoring service operations, these centers often support research missions such as testing new features, capabilities, and routes.

> **Because AV remote operations centers may be located outside the area where the AVs operate, they complement—but do not replace—local teams needed for recovery, maintenance, stakeholder interactions, and local expertise.**

AV operations centers provide essential organizational functions and are highly complex given the complexity of the capabilities they support. AV operations centers typically require near real-time, two-way communication. They are responsible not only for monitoring the vehicle fleet, but also for providing inputs to individual vehicles via remote assistance, or to the fleet via geofenced avoidance areas and other operational adjustments. Further, in responding to an incident, an AV operations center may be engaging with a range of stakeholders, from other road users to passengers to emergency responders. All these stakeholders may require near-simultaneous communication to mitigate risk after an incident.

Key challenges for AV operations centers include designing facilities, processes, and safety protocols, as well as building teams capable of supporting AV fleets in their current state, while also creating flexibility and extensibility for future iterations of the system. Organizations operating AV fleets must also manage budget, environmental, and regulatory constraints to achieve scalable and efficient growth.

AV operations centers are neither entirely new nor unique as a concept. There are commonalities with operations centers across other domains, including teleoperations within healthcare contexts, dispatch and air traffic control in aviation, and security operations monitoring and response. This report showcases these examples in other domains to highlight similar challenges, lessons learned, and opportunities for organizations operating AV fleets to consider as they continue to refine their own operations center model.

1.1 Scope

This report identifies lessons learned through a multi-domain review of operations centers and their associated processes, as well as site visits to industry-leading AV operations centers. It outlines approaches to assessing an AV operations center to ensure effectiveness for fleet-operated SAE J3016[1] level 3-5 vehicles [1].

[1] The SAE J3016 standard defines six levels of driving automation, ranging from level 0 (no automation) to level 5 (full automation) [1]

Lessons learned are organized along seven focus areas: remote assistance, rider and customer support, performance monitoring, incident response, operational resilience, staffing ratios, and organizational culture and models.

Although portions of this report are specific to passenger AVs, many of the lessons learned should be broadly applicable across AV use cases.

The output of this research workstream serves several purposes. First, these lessons learned can be used by organizations operating AV fleets to inform and improve the effectiveness of their operations centers and support strategies for the development of their organizations over time. Secondly, published information on AV operations centers is limited, yet remote operations are a frequent discussion point among AV stakeholders. The framing and definitions provided in this report are intended to serve as a basis for future discussions and solutions. Third, policies regarding remote operations of AVs are beginning to be proposed and implemented in regulations and are likely to become more frequent in the future. Effective regulations on technical systems, however, require research to understand both how the system currently operates and how regulations can maintain effectiveness as the system evolves. By identifying common approaches for AV operations centers, standards and policies can address regulatory needs in a cohesive and consistent manner.

While this multi-domain review serves as a starting point for research on AV operations centers, there are a significant number of opportunities to extend this work through additional research, experimentation, and new development.

2 Current State of AV Operations Centers

Based on data collection at two AV operations centers and first-hand subject matter expert (SME) experience working within AV operations centers at other companies, the following section represents an assessment of the current state of AV operations centers. Note that the industry has a range of maturity in this space and, as such, this assessment is based on currently available information at the time of authorship.

2.1 Evolution of AV Operations Centers

AV operations are evolving as companies expand to new cities, grow their fleets, carry more riders, and forge new industry partnerships. As operations centers have expanded, they have grown from simple 1:1 teleoperation to complex, 24/7 organizations handling rider and customer support, incident response, security, route planning, real-time decisions, and coordinated leadership. This growth has primarily been an organic expansion of the original facility as new roles and needs have arisen. In some cases, organic growth has transitioned seamlessly into scaled, structured operations, while in other cases, rapid growth has resulted in technical debt that is challenging to address as the organization matures.

AV operations centers have shifted from primarily research and development organizations focused on testing and evaluation to commercial operations teams focused on providing rides to customers, transporting goods along service routes, and establishing business models focused on generating revenue. The transition between these operational modes is not straightforward, especially as the technology is often being developed as revenue models are being introduced. Operations centers may provide support to both testing and commercial operations activities, making it challenging to balance staff and priorities between these two areas.

Further, AV operations centers are not always tightly coordinated with product and engineering teams who may view operations as complementary to a testing function rather than a core capability supporting deployment. Shifting broader organizational mindsets is crucial, as AV operations centers must receive resources and support in order to create safe and effective deployments.

Although AV operations centers are meant to focus on fleet support and efficiency – such as ensuring vehicles complete their routes on time rather than providing safety-critical functions – early implementations may end up impacting safety-critical aspects of vehicle performance. While the safety criticality of operations center functions may decrease as the automated driving system improves, the delineation between a safety-critical and non-safety-critical operations center function is not well-defined. If any element of an AV operations center has a safety impact on vehicle performance, the center must ensure rigorous testing and evaluation, robust integration with safety case elements, comprehensive quality control, and thorough data monitoring.

2.2 Data in AV Operations Centers

In many AV operations centers, data accessibility and availability are major challenges. As processes grow organically, teams may not have adequate opportunities to define a data and metrics strategy required for real-time operational decision making. Examples of data which may be useful to an AV operations center are shown in Table 1.

Data accessibility and availability can be challenging for several reasons. Regarding live operations' data, there are limitations on both vehicle compute capabilities and communication bandwidth. Some metrics require significant computation and may result in large amounts of data, which can be infeasible to evaluate in real-time. Other systems may be designed without defined metrics in mind or without sufficient data accessible to inform evaluation. Often, in practice, remote assistance and rider support tools are created initially to prove out core functionality, with metrics as an afterthought to the primary development.

Once data is retrievable, organizations also have challenges storing, aggregating, analyzing, and visualizing large quantities of operational data to create actionable insights for decision-makers.

Table 1. Examples and Types of Data Relevant to AV Operations Centers

Examples of Data	Types of Data
Real-time event-based data retrieved from the vehicle and displayed in the operations center	▪ Hard braking events ▪ Swerving events ▪ Near misses
Performance data of the remote assistance capability (both the human assistant and the system)	▪ Support time-to-completion ▪ Vehicle response time-to-completion
Incident-related data	▪ Number of events ▪ Number of resolutions ▪ Types of resolutions ▪ Resolution timespans
Data measuring the operational resilience of the facility	▪ Network quality ▪ Queue length

> **Organizations with a comprehensive data strategy establish data governance and use metrics to connect data inputs to decision outputs, helping them determine necessary processing and visualization.**

Access to data impacts operations internally by limiting the available inputs for required decision making, as well as externally in the event regulators request details on operational performance. Further, to the extent the operations center includes any safety-critical functions, those functions must be incorporated within the organization's safety case, with testing and operational data providing evidence for the relevant claims regarding the safety of the system.

2.3 Physical and Organizational Structures of AV Operations Centers

In contrast with long-standing operations centers in other domains, the optimal physical layout for an AV operations center is still evolving. Many facilities face spatial challenges leading to impacts to cross-facility communication and difficulty viewing information simultaneously across operational teams. Several organizations operating AV fleets are exploring new, dedicated facilities which can be designed with effective operations as the primary focus.

Many organizations operating AV fleets utilize a small number of centralized operations facilities at present, with some organizations instead opting for a decentralized model, with a facility adjacent to each deployment. As fleets expand across cities, opening a new facility for each deployment is challenging, yet the optimal balance of centralization versus decentralization has not yet been identified or rigorously researched.

Some organizations operating AV fleets rely on contracting agencies to staff significant portions of their operations center, across both frontline staff and shift-level management. Using contractors is an enabler to scale, as organizations can define requirements in service-level agreements to ensure consistency and reduce overhead. Alternatively, relying on contractors can come with challenges as well, particularly as frequent operational and procedural changes arise with the ongoing maturation of technology and the development of new vehicle systems, tools, and processes.

3 Overview of Core Focus Areas

The following core focus areas outline key aspects of AV operations centers for scaled deployments, including functional roles, support structures, and overarching tenets for implementation. These focus areas do not represent disjointed characteristics but rather encompass a holistic view of an AV operations center. Other focus areas not explicitly discussed in this report, such as vendor integration, coordination with local teams, and alignment across distinct developer and operator organizations, are nonetheless critical but are left as topics for future research.

3.1 Remote Assistance

Remote assistance is any real-time, two-way direct interaction between an AV and remote support personnel, not including remote driving or interactions with vehicle passengers. As such, at no point is the remote assistant (RA) responsible for the execution of the dynamic driving task (DDT) — the real-time functions required to operate a vehicle in on-road traffic — but may provide guidance, inputs, or interventions to the vehicle in a variety of forms [2]. These interactions all require the RA to have sufficient situational awareness of the vehicle's external environment to give effective inputs, and the communication link between the RA and the AV must be sufficiently strong to enable this two-way communication.

3.2 Rider and Customer Support

This function supports the riders in the vehicle in the event of an issue or question. The type of support may take many forms: answering questions about the vehicle, changing the destination, requesting riders use the seatbelt or otherwise engaging with a passenger in violation of the service terms of use, or providing guidance during an unexpected event such as a rider health emergency or an interaction with an emergency responder. Both the rider and rider support personnel can initiate the conversation – the rider via a tablet or hard buttons inside the vehicle, or the operator from their workstation.

Rider and customer support is typically characterized by two-way voice communication with the vehicle interior and, in certain cases, may be responsible for external vehicle communication such as with emergency responders or during unwanted public interactions.

3.3 Performance Monitoring

Performance monitoring incorporates both monitoring of the AV fleet and of the operations center.

- **Fleet monitoring** uses dashboards, visualizations, metrics, and data feeds from each vehicle to provide insight into fleet-wide operational status and performance. It typically relies on one-way communication, pulling information from vehicles without direct interaction. In contrast, remote assistance focuses on monitoring and assisting individual vehicles and enables two-way communication for both sending and receiving data. In some cases—such as with certain fleet sizes or depending on the size of the operations center—fleet monitoring and remote assistance may overlap.
- **Operations center monitoring** involves assessing the operation center's effectiveness using data on task execution, incident response metrics, and operational resilience. Depending on the organizational structure, this monitoring may focus on a single operations center or encompass performance data from multiple operations centers simultaneously.

These monitoring functions may be implemented in similar ways within an operations center, particularly regarding how information is displayed, tracked, and used. Although fleet monitoring and operations center monitoring have different goals within an operations center, in both cases, monitoring provides critical data to decision authorities.

3.4 Incident Response

Incident response is the process for identifying an operational incident or risk, rapidly implementing mitigations, diagnosing the root cause, and tracking the issue through to completion. Incidents occur across severity levels depending on the associated risk, which may necessitate a range of incident response protocols to effectively handle all incident types. In many cases, effective incident response requires coordinating with external stakeholders to ensure timely communication, compliance, and resolution.

3.5 Operational Resilience

Operational resilience involves the systems and approaches utilized to maintain operations center functions against disruptions such as natural disasters, communication failures, and cyberattacks. A resilient operations center involves both technical and organizational systems designed to create flexibility and redundancy. Key activities include understanding and documenting the operations center's dependence on external resources and services, collecting and processing data of those resources, creating fallback plans for scenarios where the center is completely compromised, and periodically training personnel to ensure preparedness and effective response during real disruptions.

3.6 Staffing Ratios

An operations center must schedule staff at the necessary ratios to maintain safe operations under a given set of operational conditions. These ratios are likely to vary across conditions depending on the number of remote assistance prompts, incidents, and disruptions. However, ratios must be defined to ensure the operations center remains resilient to fluctuations in demand and responsibility. Additionally, while ratios are designed to scale as the fleet grows, there may be points where operational changes—such as new roles or reorganizations—require adjustments to these ratios.

3.7 Organizational Culture and Models

Appropriate organizational models are key to effective operations in any operations center and include staffing roles, shift schedules, organizational hierarchies, operations center hierarchies, and vendor integration among other key focuses. Different implementations of remote AV operations will require different organizational models. Further, organizational models must be supported by a cohesive and effective organizational culture, including alignment to core values, mechanisms to report issues, and cross-functional communication and collaboration. As such, these structures must be adapted for each organization operating AV fleets.

4 Challenges and Lessons Learned for AV Operations Centers

The following section outlines major challenges in implementing, executing, and scaling each core focus area, and presents lessons learned from a multi-domain review and analysis. These lessons are designed to address specific aspects of each challenge and draw connections between analogous domains and AV operations.

4.1 Remote Assistance

Key Challenge: Both vehicles and remote assistants must be equipped to execute an interaction safely and efficiently while relying on effectively implemented support infrastructure. The balance of these factors creates complex and variable processes which can have critical performance outcomes.

Remote assistance for AV fleet operations presents unique challenges that set it apart from other personnel-operated or autonomous operations. For example, in personnel-operated fleets, such as those between an air traffic control (ATC) tower and an airplane, the pilot is present in the cockpit with full situational awareness of the aircraft, can assume manual control over the platform, and can override autonomous features. In a driverless AV, there is no trained operator inside the vehicle who can take manual control of the platform when there is an issue. Instead, remote operators must rely on the AV's sensor feeds or automated driving system to resolve issues. This unique distinction necessitates the development of new operational models—both for the platform's autonomy and for remote assistant actions—to effectively manage unexpected situations, provide a positive rider experience, and maintain the safety of the surrounding traffic and the environment.

As shown in Figure 1, there are three primary categories of remote assistance which often use different mechanisms to accomplish similar outcomes and may be integrated within a single operations center to enable a range of behaviors.

1. **Approval:** Approval interaction involves the AV proposing a set of options the AV might execute to the RA for selection or confirmation of the most appropriate option. Examples of this include approving a proposed route around a double-parked vehicle, confirming the classification of an object in the road, or selecting the optimal pick-up/drop-off location from the set of suggested proximal locations.
2. **Input:** Input interaction, which puts more responsibility on the RA than the Approval interaction, involves the RA directing the AV to achieve the desired outcome. Examples include drawing or adding waypoints for a suggested route around a double-parked vehicle, providing the identification of an object in the road, or determining and defining the optimal pick-up/drop-off location given the AV's local environment. Despite the increased involvement of the RA, it is still incumbent on the AV to execute the given input safely, or to determine if it is unable to do so.
3. **Request:** Request interactions differ from Approval and Input interactions in that the vehicle is no longer prompting the RA for support, but rather the RA is requesting a change to the vehicle action or mission. These interactions include requesting the vehicle come to a stop by achieving a minimal risk condition (MRC), changing the destination for the current rider based on a rider request, or implementing a geofenced avoidance area.

There are also multiple ways in which RAs may be allocated to a vehicle, which have implications for the broader technical and organizational structures of the operations center.

1. **Assignment-based allocation:** An RA is assigned to a predefined set of vehicles and is responsible for assisting those vehicles for all requests that arise, always maintaining situational awareness for all assigned vehicles.

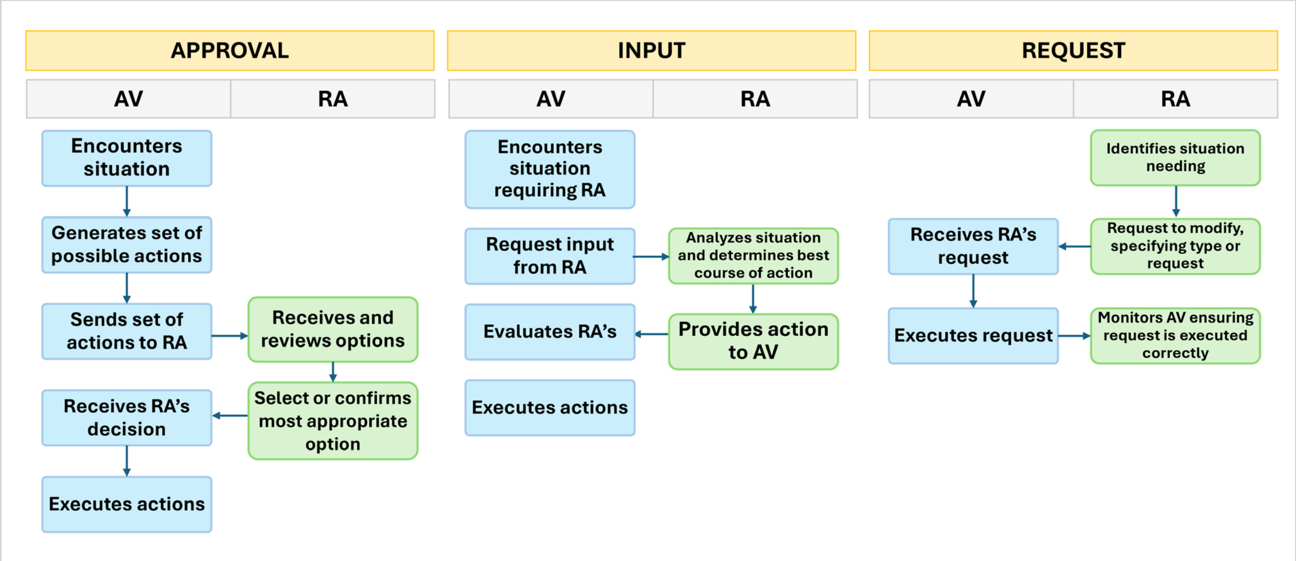

Figure 1: Approval, Input, and Request Interaction Workflows

2. **Queue-based allocation:** RAs are in a queue such that when a prompt arises from an AV for remote assistance, the next available RA is allocated to the incoming vehicle, utilizing sensor feeds to rapidly gain situational awareness and executing the interaction.

Hybrid allocation structures are possible, blending assignment-based and queue-based allocations. For example, a small team may be assigned to a set of vehicles, but a queue is used within this set. Request interactions tend to fall outside the allocation structures and may be handled by a separate team or process responsible for observing the need for support and allocating resources to implement the intervention, since the vehicle is not prompting the intervention.

To date, AV developers have indicated that remote assistance is triggered, provided, and acted upon while the vehicle is at a complete stop. However, there are instances where safe operations of autonomous systems require providing input to the AV while in motion, such as requesting the vehicle to come to a stop by achieving an MRC, or where a sudden stop before prompting remote assistance creates safety risks, such as an autonomous truck requesting RA input while driving at highway speeds. AV stakeholders should have plans in place to ensure continued safe operations of AVs when receiving remote inputs while in motion.

4.1.1 Vehicle Considerations for Remote Assistance

Effective remote assistance begins before an RA intervenes. AVs should be equipped with the necessary autonomy and safety systems to allow RAs sufficient time to respond to the situation.

As shown in Figure 2, an example process could occur as follows:

1. **AV Fault and Support Detection System** – AV identifies a situation or issue that will require a RA's action.
2. **Transition Phase** – AV raises an alert and begins to provide situational awareness to the RA by sending details of the situation.
3. **Intervention and Mitigation** – AV and RA take appropriate actions and steps to minimize safety and mission risks to the AV, passenger, and surrounding environment.
4. **Communication to Passenger** – RA communicates the situation to the passenger and, if needed, coordinates a response action.

STEP 1: AV Fault and Support Detection System

AVs are expected to have comprehensive and reliable fault and support monitoring systems capable of predicting potential incidents and triggering a minimal risk maneuver (MRM) or RA intervention when necessary.

An ideal monitoring system and automated driving system stack has layers of redundancy to ensure that if any part of the system fails, an issue could still be raised to an RA through another pathway. The aviation industry has learned that redundancy is critical to maintain an appropriate level of safety. At a personnel level, in the case of an emergency, one pilot focuses on flying the aircraft as safely as possible or attempts to bring the aircraft to a safe state while the other pilot analyzes and attempts to resolve the underlying issue [3]. Aircraft sensors

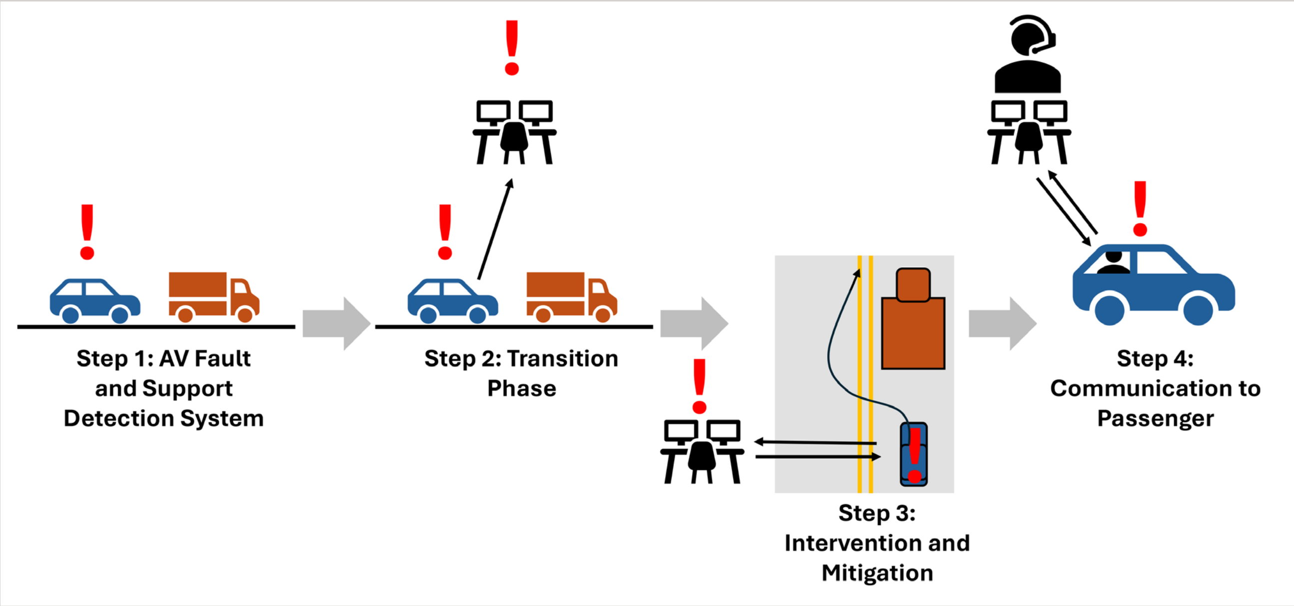

Figure 2: Example Remote Assistance Process

and autopilots are also required to have layers of redundancy to ensure that there is no single point of failure.

Relying on a single sensor can result in dangerous consequences. In 2018 and 2019, Lion Air Flight 610 and Ethiopian Airlines Flight 302 crashed due to several failures, including erroneous data from a single angle of attack (AOA) sensor that caused the maneuvering characteristics augmentation system (MCAS) to improperly activate. Incorrect assumptions regarding the MCAS control system, made during the failure analysis for the risk assessments, also contributed to the accidents [4] [5]. The failure analysis highlighted that using a single sensor for the MCAS system without providing training or guidance would pose a hazardous risk unless it used sensors that "have less than a one-in-10-million chance of failing." This condition is usually fulfilled by taking measurements from two sensors. The investigative report states, "A hazardous failure condition depending on a single sensor should have been avoided in the certification process" [6].

In the AV space, these lessons can be applied by using multi-modal sensor feeds to provide multiple overlapping viewpoints of the environment across a variety of environmental conditions and having several pathways for the monitoring system to raise an alert. From an operations center perspective, RAs or supervisors could periodically check in with each AV and manually observe if the system is functioning as expected. In the aviation industry, pilots are trained to regularly check on the aircraft's status and autopilot to ensure that it is performing as expected according to the flight plan [3].

Loss of Communication

A loss in communication to the AV can cause undesirable consequences, especially if the vehicle inadvertently blocks traffic or operates unsafely without sufficient oversight. It is important to have several contingencies in place to resolve this situation.

Ensuring connectivity and developing both short-term and long-term contingencies to improve connectivity are similarly important in drone as first responder (DFR) technologies. Developers have operationalized several techniques to address connectivity gaps that can also be beneficial for ensuring connectivity during AV operations [7] [8].

First, there should be multiple methods of communication with varying data loads that can be used to reach the vehicle. This layer of redundancy will allow the vehicle to be resilient if one of the lines of communication falters. The vehicle can utilize multiple cellular wireless providers or employ various communication methods, such as cellular or satellite connections. The vehicle can also vary the amount of information that it returns depending on its connectivity status. If the vehicle has low bandwidth and is on a backup layer of communication, the data can be limited to basic telemetry data that allows the vehicle and RA to maintain a safe connection while the vehicle attempts to reestablish a stronger connection.

In the case where the AV has reduced connectivity to the operations center, such that high data volume sensor feeds cannot be shared, the automated driving system should have predetermined contingency actions that it can execute. With limited monitoring, the on-board path planning algorithm could use the connectivity state of the vehicle as an input and reroute itself along a path with stronger connectivity. If the vehicle loses connectivity and encounters an issue that requires RA intervention, standard operating procedures (SOPs) should be in place to dispatch a team to recover the vehicle and implement methods to restore connectivity. Contingency plans should be developed to position rescue crews strategically in key areas, ensuring they can assist the AV if needed.

Currently AV operations are limited to certain routes and geofences that should be regularly monitored for connectivity. As AV organizations begin to grow their operations and include more routes and areas, it will be infeasible to monitor the connectivity of every possible traversable area. One way to address this issue is to record vehicle connectivity and build a database mapping connectivity levels across different areas. Feeding this data into the path planning algorithm enables it to select routes that maximize connectivity and minimize travel through low coverage areas.

System Health Monitoring

AVs should use a parallel monitoring system for less time-sensitive and critical issues, such as anomalies in the automated driving system over a period of time or patterns of discrepancies. In contrast to incidents that require immediate attention, such as navigating around a stopped vehicle or responding to an emergency responder situation, this parallel monitoring system flags issues that could create an unsafe pattern in the long term. For example, if sensor data or accuracy begins to drift but remains within acceptable boundaries, the system can flag an issue and identify that it needs to be recalibrated between destinations.

The operations team can proactively identify and address emerging issues by monitoring vehicle health and autonomy accuracy, allowing them to address issues before they become more severe. This monitoring system may not need to be run entirely on the AV. Telemetry and additional vehicle data could be streamed to the operation center for processing. This would free up computational cycles on the AVs while maintaining overall safety.

Incident Location Database

Incident locations can be used to build a database and train an analytical model to benefit RA operations. Data on frequent incident locations can be used to prompt RAs to monitor the AV more closely as it approaches the location. This would maximize the amount of time available for the RA to gain situational awareness before an incident could occur. By compiling this data in an automated fashion from incidents throughout the day, and augmenting the data with manual reports from the operations center team, the database will become more robust than solely relying on manual incident reporting.

This data can also be used in the AV routing algorithm. When the AV calculates the global path from its current location to the drop off point, it can also identify incidents that are likely to occur along the path and show these to the RA in advance.

This would enable RAs to remain alert during that segment of the drive and to identify the correct SOPs to address any potential incidents. In aviation, although autopilot reduces the burden on pilots to actively fly the aircraft during the entire flight, pilots frequently consider contingency plans for potential incidents that may arise at any moment or in the near future. For example, they may identify alternate areas or airports for emergency landings, anticipate common errors that could occur during takeoff or landing along with the relevant SOPs, and evaluate whether nearby weather could impact the flight. This foresighted flying allows pilots to be prepared and ready to react in the unlikely situation that the incident does occur [3].

Beyond immediate incident assistance, the database could be used to compile a summary and map of the geofenced area that an RA is assigned to monitor for the day. This summary would show the locations of common incidents and could be reviewed at the beginning of the shift to prepare RAs for the types of incidents they are likely to see throughout their shift.

STEP 2: Transition Phase

Once the AV detects an issue and alerts the RA, the AV should begin providing information to assist the RA in determining the correct guidance to resolve the situation.

There has been a considerable amount of research in aviation, SAE J3016 level 1-3 automated driving systems, and other industries to understand how to quickly and successfully transition between autonomous system and human control [9] [10] [11]. Although RAs do not directly teleoperate AVs, lessons from these industries can be leveraged to help RAs gain situational awareness as quickly as possible so that they can suggest actions to the AV to execute safely.

Displayed information

Relevant information should be displayed prominently and organized in a single window in such a way that allows the RAs to quickly gain situational awareness of the vehicle. While more detailed information can be made available in additional windows, tabs, or other menus, the design should ensure that RAs can access information quickly and efficiently, without needing to search through multiple windows or screens [3]. The interface should also clearly state the problem at hand or have clear displays that allow the RA to diagnose the problem within an acceptable timeframe.

In an aircraft cockpit, critical information is displayed and summarized on an instrument called the Primary Flight Display (PFD). The PFD shows information such as the altitude, nose of the plane, and bank attitude and allows pilots to check the status of the aircraft without having to collect information across the cockpit.

The design of the PFD can critically affect an operator's understanding of the state of the aircraft during normal operations and especially during an emergency. In addition to the several autopilot related issues that caused the Lion Air Flight 610 and Ethiopian Air Flight 302 crashes, the final report highlighted that multiple alerts and indicators spread throughout the cockpit, along with a lack of appropriate information, increased the flight crew's workload. This ultimately affected the crew's ability to understand the situation and apply the correct reaction within the necessary timeline to bring the aircraft back to a stable state [6]. For this reason, it is critical that vehicle error messages provide a clear description of the issue and that the display information allows for rapid identification.

In a study evaluating the design of a workplace for remote assistance of AVs and its relationship to performance, situational awareness, and workload, the authors propose a workspace for RA's consisting of seven screens: six standard computer monitors arranged in two rows of three and a touchscreen [12]. As shown in Figure 3, the top row of monitors streams live video from the vehicle. The bottom row includes a details screen, notification screen, and map screen. The details screen exhibits vehicle fleet details, including technical status, position, and schedule, and presents the ability to select various camera configurations. The notification screen displays incoming requests, request status, and a communications bar for initiating voice connection with various people of interest. The map screen displays the AV currently being assisted, nearby AVs, and feature layers such as current road closures and stops, that may be activated as needed. The touchscreen presents a detailed view of the immediate area around the AV and allows operators to interact with the vehicle by conducting remote assistance tasks.

In addition to information about the vehicle, the interface can also be used to provide recommended actions for the RAs. When an error is shown in an aircraft's display, the recommended SOP checklist is also automatically shown to help the pilots resolve the situation [3] [13]. Ideally, RAs should be fully trained to recall the SOPs in real time; however, automatically suggesting a solution adds a layer of redundancy in the event that the RA is unable to remember the correct SOP. Schrank, Walocha, Brandenburg, & Oehl [12] note that when designing a human-machine

Figure 3: Proposed HMI Workspace [12]

interface (HMI) for RAs, it is important to take into account how tasks are structured, along with the associated complexity and workload, in order to determine whether additional tasks can be assigned and, if so, which ones. The authors advised starting RAs with a limited set of tasks and introducing additional tasks incrementally until the optimal task load is established.

> **The situational awareness and workload of RAs play a vital role in maintaining safety in remote assistance tasks.**

Induced cognitive load from a secondary task negatively affects task processing time, as cognitive resources are shared between tasks, causing a depletion of resources from the first task to the second task [12]. However, if RAs frequently alternate between subtasks that require different types of resources, depleted resources may be able to recover (e.g., an operator's visual resource might recover during periods when an operator is performing auditory subtasks) [14]. It was also found that situational awareness declines with a higher cognitive load, even during routine and well-practiced tasks. The study revealed that workload is minimal for less complex tasks but becomes greater as tasks become more complex. It is important to balance this, however, with reduced performance that can result from individuals monitoring systems consistently with limited breaks or deviations. Appropriately designed secondary tasks can maximize operational performance.

It is essential that displays and interfaces are tested with RAs during the design process to understand their cognitive workload and ability to gain situational awareness across a variety of incident levels. RAs may prefer to access information using different methods or have the ability to customize certain features to their needs. Feedback pathways are critical to gather recommendations from RAs.

Look-Ahead Time

Depending on the circumstances and environment around the incident, the AV may be forced to take a sudden MRM, such as pulling over or stopping, in order to safely navigate and arrive at an MRC before a RA can take control of the vehicle. In some cases, this may be the best course of action that yields the safest result.

However, for situations that can support longer reaction times, an ideal workflow could have the monitoring system alert the RA as soon as it predicts an issue will need the RA's input. This additional time allows the RA to gain situational awareness and select the appropriate behavior for the AV to execute safely, without significantly impeding the flow of surrounding traffic or endangering the vehicle [15].

Aniculaesi, Grieser, Rausch, Rehfeldt, & Warnecke [15] present an example of this type of monitoring system. Their system identifies when an AV encounters a new situation that it has not been trained on previously and gradually transfers the decision and control responsibilities to a RA to help with errors or unknown situations. Schwalb [16] proposed a system that can continuously monitor for potential, imminent, and developing hazards and estimate their time to materialization.

A key question arises—how far in advance should the monitoring system alert the RA in order to be effective? Hoffman, Perret & Zeghal [13] examined this question as part of their simulated test to solicit design feedback from pilots on an experimental autopilot interface. The autopilot would detect if the aircraft was on a collision course with another aircraft, alert the pilot both visually and audibly, and display various zones to help the pilot assess the situation and respond accordingly. The simulated scenarios were designed to cover a wide range of complex conflict situations, providing a means to test and explore the limitations of the experiment, pilot, and autopilot.

The authors noted that providing too much look-ahead time could cause "a too high false alarm rate" but too little time could cause "inefficient conflict resolution maneuvers." Based on their preliminary literature review, fast-time simulations over European airspace showed that an 8-minute look-ahead time provided the right efficiency balance. Using this information, the authors ran the simulations with either a 6- or 10-minute look-ahead time.

The results showed that, although both look-ahead times provided a comfortable amount of time for the pilots to resolve all of the scenarios, the pilots preferred the 10-minute look-ahead time. They could spend up to four minutes monitoring the situation to determine if the other aircraft would yield first, yet still have enough time to react if necessary. In contrast, although the pilots could adjust the aircraft's trajectory in less than a minute, they believed the 6-minute look-ahead time was insufficient and would result in overly abrupt maneuvers. However, the authors did note that in denser parts of European airspace, air traffic controllers routinely provide pilots with less than 5 minutes of look-ahead time, with no reports of discomfort or accidents from the pilots [13].

A meta-analysis of driver take-over studies for advanced driver assistance systems focused on a related but distinct problem from remote assistance in AV operations centers [17]. The meta-analysis was focused on take-over times (TOT) for drivers present in the vehicle. TOT is defined as the time from when the vehicle notifies the driver to the moment the driver takes control of the vehicle. They examined possible factors that could affect the driver's ability to gain situational awareness and take action to safely bring the vehicle to an MRC.

Their meta-analysis revealed a wide range of TOTs (0.69-19.79 seconds) with a mean of 2.72 seconds. There were several possible factors that could affect the TOT. The most common factor was the type of non-driving task (NDT) the driver was engaged with before the take-over notification. Using handheld electronic devices strongly increased the mean TOT by an average of 1.33 seconds. For hands-free NDTs, engaging in a visual NDT slightly increased in the mean TOT by 0.29 seconds compared to not engaging in an NDT. The presence of surrounding traffic and the complexity of the situation also had a moderate effect of increasing TOTs – drivers needed this additional time to visually scan the environment and assess the situation before taking control of the vehicle [17].

RAs in an operations center, in contrast, can rely on the AV to bring itself to an MRC while the RA gains situational awareness. However, findings from the meta-analysis highlight interesting patterns that can provide baselines for validation with RAs in AV operations centers in future studies, such as the time taken for RAs to gain situational awareness and take the first action during an intervention under different intervention types and environments.

STEP 3: Intervention and Mitigation

In some scenarios, the safest MRM is to stop in place before proceeding, even at the risk of impeding traffic. For other situations, stopping while at high speeds or while the vehicle is moving are difficult and dangerous. It may be ideal for the vehicle to either pull over or slow down in increments to avoid suddenly stopping and impeding the surrounding traffic. A "soft stop" option would slow the vehicle down while the RA gains situational awareness and formulates the appropriate response to the situation. This incremental decrease in speed would allow the vehicle to slow down in a safe manner and for surrounding traffic to maneuver around the vehicle if needed.

For example, if an AV on the highway detects an unknown object on the road while traveling at a high speed, instead of coming to a complete stop in that lane, the AV could flag an RA and begin to slow down while it waits for guidance. If the vehicle does not receive a command within a safe period of time, it can then pull over and prompt the RA for additional guidance after it has come to a stop.

> **Although driving can present an unlimited number of edge cases, rare scenarios, and unexpected circumstances, there should be a comprehensive examination of possible scenarios and appropriate MRMs from the automated driving system. Similar to creating comprehensive SOPs for RAs, these expected and unexpected scenarios should be extensively mapped out and tested in a robust testing pipeline.**

MRMs and MRCs will be different according to different situations and surrounding environments. Above all, safety of both the AV and other road users should be the top priority, and the MRMs should be comprehensively tested to ensure this outcome. It is important that there is an unambiguous indication when the automated driving system is in control of the vehicle, when the RA can provide guidance, and when the vehicle is acting on that guidance or is unable to safely execute on it. This clear hand-off is essential for the RA to understand when the vehicle is able to receive commands or if their guidance is being accepted by the vehicle.

STEP 4: Communication with Riders

As part of this process, it is also important to consider the rider experience in an intervention or delay. Ideally, every interaction should be seamless enough that passengers are unaware that there was an intervention. If there is a noticeable pause in operations or a startling motion from the AV, it could be beneficial for the rider support team to inform the passenger that the automated driving system or RA is handling the issue. On commercial flights, pilots and flight attendants will make announcements to passengers to inform them of turbulence or other important information. This line of communication can help reassure or prepare anxious passengers in situations where they have little control or understanding [18]. Similarly, having this line of communication in AVs may be beneficial since there is no safety driver physically in the AV to reassure passengers. When the vehicle requires assistance, AVs should use in-vehicle displays to clearly explain what is happening and provide step-by-step guidance through the recovery process, helping passengers build confidence in operational processes.

4.1.2 Operator Considerations for Remote Assistance

Sufficient Understanding of the Automated Driving System

RAs should be thoroughly trained to understand the automated driving system onboard the AVs, enabling them to anticipate potential failures when exposed to certain conditions and recognize system limitations when providing suggestions to the AV. In the aviation space, pilots are trained to understand the complex flight software and autonomy in order to help them manage the aircraft and handle a wide range of situations and problems [3] [18]. For example, if an RA sees that there is a large crowd of people in an area due to an event, they may be able to predict that wireless connectivity over cellular networks could become unreliable and raise this issue to their shift management or security team to create a geofenced avoidance area.

Trained on Geofence Areas

RAs should be trained on, and familiar with, the geofenced areas to which they will be assigned to allow them to learn the area's patterns, nuances, and common problems such as construction areas, traffic patterns, and areas with poor connectivity. This allows RAs to become effective at solving common issues, decreases time needed to gain situational awareness, and helps predict when an intervention may be necessary. In the aviation space, Federal Aviation Administration (FAA) dispatchers are assigned to specific areas and handle flights over specific routes so that they can build familiarity with these areas.

Training and Standard Operating Procedures

Operations centers should have comprehensive SOPs that outline solutions for all reasonably foreseeable issues and scenarios. Comprehensive risk assessments and fault analyses should be done to identify probable failures and develop SOPs to address them. Despite the difficulty in accounting for every unpredictable situation, interventions should succeed when guided by well-defined SOPs. As a safety and redundancy measure, RAs should have access to the SOPs at their stations and a method to navigate to the appropriate sections. Pilots in aircraft have laminated sheets for normal flight procedures or a reference book for technical errors in the cockpit in cases where they are unable to recall the SOP in the moment [3]. There should also be feedback mechanisms for RAs to report ineffective SOPs, propose improvements, or report unusual situations that require new or revised SOPs. This feedback should be incorporated in a timely manner.

> **Frequent updates to software and hardware may make it difficult for RAs to maintain up-to-date knowledge of the full autonomy stack. As a result, it is essential that RAs are continuously trained and have comprehensive SOPs in place to help ensure that they can continue to be effective.**

A certification process for RAs should be created to test candidates on their knowledge and skills. For instance, in airline operations centers (AOCs), airline dispatchers are certified by the FAA [19]. The test has oral and demonstration components for specific areas of operation and tasks. Satisfactory performance is defined by the applicant's ability to perform all the tasks, follow all the procedures, and demonstrate and apply knowledge and skills to specified standards. An unsatisfactory performance is awarded if the applicant does not fulfill the objective performance of any one task.

If possible, AV operations centers should leverage cross training or existing systems to minimize the quantity of assigned new trainings. If an operations center chooses to have more than one center, it is advisable to use consistent systems at each location, rather than custom systems for each facility. In-house custom systems require time for individuals to learn the system and reduces the ability for operation centers to provide coverage for other centers due to these differences.

AV operations centers should design simulated environments to provide RAs opportunities to practice interacting with a vehicle and applying SOPs. For physical mock environments, many AV companies use a private closed course testing space. Closed courses are typically used for testing needs, such as testing and validating new AV software and hardware, as well as testing different scenarios.

AV operations centers can use simulated tools to test basic scenarios that commonly require remote assistance and particular scenarios that may be complex for RAs to learn.

It would be beneficial for organizations to track all instances and operational situations in which remote assistance was used, so that log data can be retrieved and analyzed as needed. An organization may want to simulate specific real-life scenarios that are less common and which RAs felt uncertain in handling. This enables a deeper understanding of the situation and documentation of appropriate handling procedures. Additionally, AV operations centers may also consider training RAs initially in a mock environment and gradually advancing RAs to live operations under close supervision. Similar to the aviation industry, when software or hardware changes are made to the AVs, assessments should be conducted to identify how these changes will affect SOPs and how training programs should be updated or created. RAs should be briefed on these changes and provided trained as needed [6].

4.2 Rider and Customer Support

Key Challenge: The long-term success of AV deployments depends not only on widespread adoption and meaningful rider experiences, but also on the development of rider support roles. These roles introduce unique needs and communication structures that differ from those encountered by traditional customer-facing teams.

4.2.1 Key Elements for Rider and Customer Support

Rider and customer support teams within AV operations centers play a pivotal role in ensuring the success of customer-facing services. They provide real-time assistance, manage rider incidents, facilitate communication, collect rider feedback, and foster trust between riders and AV operations, potentially requiring competency in multiple languages and cultures. Rider support personnel should be able to monitor adherence to in-vehicle safety protocols and proactively contact riders if they are not being observed, such as in cases where seat belts are not being worn. The success of AV operations relies on the interactions of riders with not only the AVs themselves, but also the rider support team. As AV operations expand, rider and customer support will need to adapt to accommodate the evolving landscape.

Unlike traditional, personnel-operated rider services such as taxis, AV rider support teams require distinct operational and structural approaches. These teams are more closely aligned to customer success (CS) or customer experience (CX) functions, as their primary focus is on delivering maximum value to riders and fostering long-term relationships between the organization and its customers.

Companies within different industries, like aviation, have set high standards for their customer experience by utilizing customer-centric approaches driven by their CX teams. This may include enhancing technology within the aircraft to be more user-friendly, accessible, or up to date; changing the layout of customer seating on the aircraft based on customer feedback; or enhancing the flight experience by creating memorable moments during the pre-flight announcements and safety briefing. Companies have differentiated themselves within the aviation industry as leaders in customer experience by continuously innovating and responding to customer feedback. In the automotive industry, companies have leveraged feedback and consumer data to enhance customer-facing tools and processes, like creating mobile or web apps designed to streamline the process of filing accident reports [20]. The AV industry can leverage these examples to learn ways of utilizing their rider support teams to their full capacities and leveraging the data they provide to adopt new tools, capabilities, and offerings for both customers and employees.

For rider and customer support teams to effectively manage operations and enhance rider experience, it is critical to consider and integrate several key elements:

1. Monitoring
2. Comprehensive Training
3. Robust Communication Systems
4. Cross-Functional Collaboration
5. Incident Management

Monitoring

It is important for rider support teams to monitor and understand what is happening inside and around the AV. AV operations centers must have seamless, real-time visibility into the vehicle's position, estimated time of arrival, and the surrounding external environment via live camera feeds and other relevant sensor data.

> **In emergency situations, immediate access to real-time data is critical, enabling rider support teams to relay precise information to emergency responders, including exact vehicle location, number of passengers, and other relevant information. It also empowers rider support personnel to proactively identify rider health emergencies, allowing operators to quickly intervene and provide effective support.**

Beyond emergency response, access to real-time data helps deliver high-quality rider experiences. Rider support teams can proactively assist and address rider concerns and issues. Key safety measures, such as identifying and monitoring seat belt use, can be actively enforced. Rider support personnel can track pick-up and drop-off locations, address environmental factors (i.e., route changes, weather disruptions, or unexpected traffic delays), and manage unwanted external interactions. Rider support teams can coordinate closely with RAs to convey accurate information directly to the rider.

Comprehensive and Cross-Functional Training

Comprehensive training and development opportunities are crucial to the success of rider support teams, hinging on their ability to innovate, adapt to evolving environments and customer needs, and deliver effective support. Traditionally, training methods such as workshops, instructor-led sessions (ILS), shadowing, and on-the-job training have been used. Over the past several years, training has evolved and new methods have emerged that include immersive technologies like virtual reality (VR), gaming, and e-learning/mobile platforms that have allowed for more specialized training opportunities for staff.

For AV operations centers, rider support teams require training on the technology used to support their role, an understanding of the AVs and their technology, navigating emergency and/or escalated situations, and customer service skills and best practices. Similar to CS/CX teams, rider support teams will require effective training on operational protocols – especially those surrounding escalation scenarios. Investing in a mix of traditional and emerging training methods can help rider support teams in their everyday role as they interact with riders and use the skills learned to anticipate rider needs, positively influence the customer journey, and ultimately be leveraged to further aid AV operations.

Rider support teams should be trained in providing personalized responses, including addressing customer diversity in a manner that resonates with their unique needs and preferences. For example, rider support teams should train for engaging with riders who may be visually or hearing impaired. Additionally, rider support personnel could receive training from mental health first responder personnel on navigating emergency and escalated situations with passengers who may have mental health difficulties and/or physical disabilities.

Training goes beyond simply focusing on interactions with riders. Integrating comprehensive and cross-functional training into the foundation of rider and customer support teams foster a supportive environment that encourages greater innovation, proactivity and forward-thinking among team members. These benefits help address customer challenges and needs, while also increasing employee engagement and trust—factors that can lead to higher retention rates and improved collaboration. These are all benefits that help to ensure success as companies begin to scale.

Types of Training

As outlined in Table 2, a variety of training types and methods can be utilized to develop and strengthen skills and capabilities.

Immersive training methods like simulations, gamification, and dry runs create high engagement and experiential learning environments for employees. These methods are particularly useful for rider support training, allowing teams to simulate routine, unique, and emergency scenarios. AV operations centers could use desktop game engine-based simulations, where avatar-based training scenarios are delivered through personal computers in a similar format to video games [21]. A key benefit to this type of training method is allowing staff to navigate real-world environments, perform tasks, and receive feedback in real-time. Rider support teams can foster highly engaging learning environments by proactively training and using data and feedback to customize simulations and update training programs. For AV operations centers, utilizing tools such as desktop game engine-based simulations offers scalable solutions with lower costs and hardware requirements compared to other immersive technologies. These training methods also provide realistic, operationally representative environments, allowing rider support staff to train under realistic operational ratios and anticipated request volumes.

Non-immersive training methods, such as workshops, ILT, and mentoring, focus on structured and passive information delivery. While they involve less interactivity, they are more flexible, cost-effective, and well-suited at delivering foundational knowledge that does not require experiential learning or practice. AV operations centers may use e-learning materials housed within an internal platform to administer self-paced training courses on CX best practices to keep employees' skills and knowledge up to date. Rider support teams could leverage workshops in a cross-functional way by including teams and management from across the operations center that rider support may typically interact with. Workshops not only allow for interactivity through group discussions, but they also build rapport and strengthen connections across teams.

Table 2. Types of Training

Immersive Training Methods	Non-immersive Training Methods
Tabletop Exercises (TTXs)	Instructor Led Training (ILT)
Virtual Reality	E-Learning
Simulations	On-the-Job Training (OJT)
Dry runs/Role Playing	Mentoring and Coaching
Gamification	Workshops

When planning employee training, it is important to consider the most effective methods for learning. Utilizing solely one training approach may not be sufficient in creating a comprehensive and accessible learning environment for staff. The Center for Creative Leadership's learning and development model, shown in Figure 4, highlights that 10% of learning should be formal (e.g., educational courses), 20% should be social learning (e.g., coaching, mentoring), and 70% should be experiential (e.g., simulations) [22]. AV operations centers may want to consider these factors when outlining their training approach and analyzing the current state of their training to identify the gaps and ways to enhance training for staff. This model also provides guidance for AV operations centers to create a training approach that blends immersive and non-immersive training methods, thereby creating robust and accessible training opportunities and learning environments for employees.

Robust Communication Systems

AVs are typically equipped with in-app and in-car tools that enable riders to communicate with rider support, whether for simple inquiries about the vehicle or more complex situations such as emergencies. Whether simple or complex, it is crucial that rider support teams have a robust communication system that allows them to navigate any scenario with both the rider and internal AV operations teams that may be needed in various instances.

In-app and in-car tools, such as buttons or screens within the vehicle or app, enable riders to quickly obtain assistance and receive information from support teams, as illustrated on the display shown in Figure 5 [23]. For many rides, communication via in-app and in-car systems often consist of automated messages (e.g., "the ride is about to begin, please buckle your seat belt") that are not sent directly by rider support teams. AV operations centers may want

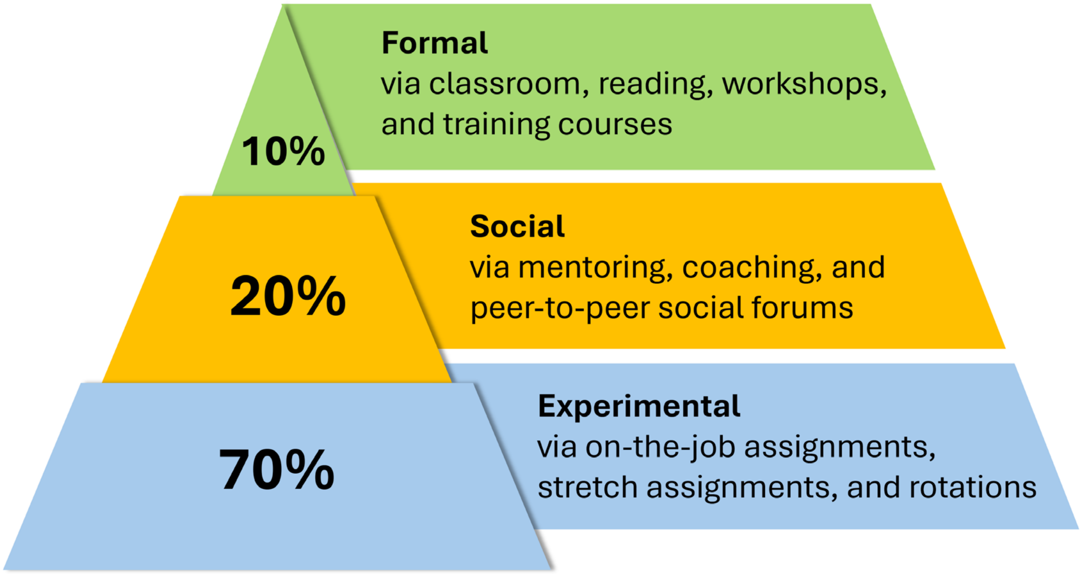

Figure 4: Learning and Development Model

Figure 5: Waymo In-Vehicle Display [23]

to consider alternative and redundant methods. For example, if the on-screen instructions malfunction and the rider does not receive important instructions at the start of the ride, the support team must intervene to provide necessary guidance and ensure the ride proceeds safely.

> **To support a seamless and safe rider experience, AV operations centers should regularly test all communication systems for reliability, ensure that redundant communication methods exist and are accessible to all riders, and develop protocols for escalating issues when automated communication systems fail.**

Cross-functional Collaboration

AV operations centers comprise several teams which all impact the rider experience. It is essential that rider support teams understand the key teams within AV operations centers and which teams they may need to collaborate with to create channels of effective and continuous communication. Rider support teams must work closely with RAs, remote monitors, and supervisors to resolve issues efficiently. Leveraging tools and resources like shared dashboards, consistent escalation protocols, and cross-operations center coordination meetings contribute to successful AV operations.

One approach could include implementing shared dashboards that provide each team with real-time visibility on both RA and rider support. This could enable seamless communication and coordination. For example, if there is an issue with the vehicle, the rider support team can proactively reach out to the rider and provide necessary information. Utilizing shared dashboards for real-time information sharing can strengthen collaboration and consistency amongst teams, enabling more effective responses to rider needs and incidents while potentially reducing response times for both.

Cross-functional collaboration extends beyond managing real-time situations; it also establishes pathways within operations centers for teams to interact, stay informed, and exchange information and feedback with one another. Additionally, cross-functional collaboration helps to prevent or mitigate team silos, which can lead to disconnects that impact both rider experience and safety. Within the operations center, it also reduces the risk of harmful cultural dynamics, such as an "us vs. them" mentality among teams. To achieve this, management teams could establish recurring meetings with key teams that rider support needs to engage with. Meeting discussions can revolve around past events and observations and upcoming milestones. These meetings can provide space to innovate and collaborate around larger goals and potential improvement opportunities.

Given the importance of collaboration, AV operations centers should ensure that their physical layout and facility design support and encourage effective coordination across roles. This could involve having rider support and remote assistance teams sit near or next to one another. Some companies strategically design their layout so that CS representatives are seated near the sales team responsible for their assigned region, so that CS representatives can easily turn around or walk around to communicate in person. This may help establish a culture that encourages regular interaction with rider support and promotes the development of strong rapport.

Operations center leadership could benefit from establishing all-hands meetings. These not only provide the opportunity for the entire organization to understand each team's recent outcomes, but it allows employees to understand how they all fit together as one large entity and reminds them of the larger organizational mission. By creating these opportunities for cross-functional collaboration, AV operations centers can set themselves up for success in the present state and firmly establish the foundations needed as they begin to scale.

Incident Management

Incident management is another important element for rider support teams, requiring well-defined processes and robust tools to monitor, track, and address incidents. AV operations centers should consider the flow of information and how it is shared across teams to ensure relevant teams stay informed and efficiently resolve issues. A notable complexity is the variety of ways riders may request support or report incidents. For example, a rider may use the app instead of the in-vehicle communication system to contact rider support. Many CX teams employ an omni-channel approach, allowing customers to interact with a company through multiple channels such as email, phone, social media, and in-person. For AV operations, this could also include communication through the AV itself. Since there are multiple avenues for information to flow, it is important for AV operations centers to clearly define which individual(s) or team(s) is responsible for receiving, routing, and ultimately resolving incidents and requests.

For rider support, another essential aspect of incident management involves collecting customer feedback and identifying potential opportunities for improvement. Establishing a feedback collection and analysis process should be a key focus for AV operations centers to analyze trends, assess strengths, and pinpoint areas for improvement in their rider experience.

4.3 Performance Monitoring

Key Challenge: Understanding and assessing system performance relies on a range of metrics, tools, and analyses, applied at every level—from individual vehicles to the entire fleet and across the operations center.

4.3.1 Key Elements of a Metrics Program

Measuring performance allows decision makers to determine whether the operations center is delivering on its mission or if adjustments—whether short-term or long-term—are needed to achieve the desired outcomes. In *MITRE's 11 Strategies of a World-Class Cybersecurity Operations Center,* only half of the security operations centers (SOCs) polled had implemented a formal metrics program [24]. For AV operations centers, metrics programs should be developed during initial planning and setup phases, and regularly reevaluated as the center grows and evolves, and as new roles and functions are introduced.

Five elements of a metrics program, shown for a SOC in Figure 6, ensure that the program is aligned with both business and operational needs: objectives, data sources and collection, data synthesis, reporting, and decision-making and action [24].

Safety and performance objectives should be the key driver for operations center metrics. Metrics should be tuned to ensure that relevant outcomes are assessed, measured, and tracked in order to provide evidence of performance relative to objectives set out by program leadership.

Figure 6: Elements of a SOC Metrics Program [24]

Data sources and collection methods are critical to ensure that outcomes can be assessed and measured in a timely and accurate manner. If data is not available to support metrics relevant to objectives, it will be impossible to understand operations center performance in those areas. As such, the metrics program should be implemented jointly with a data strategy that identifies where required data will come from and how it will be stored and analyzed.

Relevant data may take different forms. Some data may be directly derived from fleet operations, RA performance, or incident response metrics. Other data may include qualitative after-action reviews of daily operations or responses to specific incidents. These are similar to a combat assessment in military operations, which evaluates the effectiveness of mission execution. The combat assessment provides qualitative and quantitative data on battle damage and munitions effects and provides recommendations for the next operational steps.

Valuable data can also be generated from operational exercises, TTXs, wargaming, and simulation experiments (SIMEXs) to analyze tools, processes, and organizations in particular settings that may occur less frequently or less consistently in real operations.

Data synthesis refers to the methods used to process collected data. Where possible, repeatable and automated processes should be used instead of relying on ad hoc or one-time analyses. When defining the data synthesis strategy, it is important to recognize the various synthesis models that may be implemented. For example, data may be processed in batches on regular cadences, other data may be aggregated and analyzed in real-time as it is received, and data may also be synthesized on-demand when queried. Aligning data, metrics, and objectives to the appropriate synthesis approach may be based on a variety of factors including data type and analysis complexity, reporting requirements and cadences, and data availability.

Reporting defines how the operations center structures its metrics output to the intended audiences and how the objective of each metric is described. As mentioned above, reporting requirements will impact the data synthesis approach and may vary depending on the intended audience. On-site operations center leadership is likely to need near real-time access to certain metrics to support real-time decision making. In contrast, senior leadership may only request to review aggregate metrics over longer periods, such as days, weeks, or months. It is also important to tailor data presentation to each audience: on-site visualizations can support rapid, real-time decision making and may require display of a broad range of metrics, while periodic reports for senior leaders should highlight key aggregated metrics in charts that make it easy to identify important trends.

> **Metrics become meaningful when they are used to inform decisions and actions that produce outcomes. Resources should only be allocated to collecting and analyzing metrics that are actively used to guide decisions.**

For an AV fleet, operations center performance metrics support both real-time adjustments to operations and longer-term changes to the broader organization. For example, in a queue-based remote assistance structure, a significant increase in queue length—captured and reported in near real-time—enables on-site management to respond promptly. They might quickly add RAs, reduce the number of vehicles on the road, or adjust the prioritization of remote support prompts to ensure that the highest-risk requests are addressed first. In another case, data on network latency at the operations center can help identify continuity-of-operations risks and determine whether functions should be distributed across multiple facilities or transferred to a backup facility. Appendix A presents a set of candidate metrics for high-level assessment of operations center performance.

It is important to view these elements as a data strategy within a metrics program that should be assessed, designed, and developed in advance of fleet operations. Although this program should contain feedback loops that enable iterative improvements based on findings from fleet operations, failing to instantiate an initial implementation of a metrics program before fleet operations begin creates both organizational and operational risk.

4.3.2 Real-Time Metrics

For AVs, log data is offloaded from vehicles regularly during operations, typically over wired fiber internet connections when the vehicle has returned to its depot. This data tends to be rich representations of the driving situations encountered by the vehicle, including raw sensor data, perception outputs, vehicle decision-making logs, fault monitoring, and more. Log data feeds back into operations and development processes through complex analyses of driving performance and safety risks, re-simulation of encountered driving scenarios, retraining machine learning models, and validation of simulation environments. AVs can generate terabytes of data in several hours of operations.

Real-time operational insights, however, require live data reporting from the AV, which is generally transmitted over low-bandwidth cellular networks. As a result, it is not practical to transmit the entire driving log over these networks; only select, high-priority data should be identified and prioritized for real-time transmission.

Autonomy best practices from military applications suggest that, at a minimum, each vehicle should be transmitting basic telemetry data including location, speed, and direction of travel so that the position and trajectory of each vehicle is known at all times. Other key parameters include vehicle charge or fuel levels, whether the vehicle has a passenger, and basic vehicle health.

To support remote assistance functions, vehicles must be capable of transmitting sensor data with low latency, allowing RAs to maintain appropriate situational awareness. This requires imagery from around the vehicle at sufficient frequency for an operator to understand the situation. Frequency could change depending on vehicle status, where a lower frames per second (FPS) rate is used when the vehicle is nominal or operational, and a higher FPS is used when the RA needs to handle an issue.

This latency should be extensively tested to understand the time difference between when a command is issued, when the vehicle receives it, and when the vehicle acts on it. It is important to understand the delay, as delayed responses from the vehicles begin to erode public trust in an AV's abilities to react in a timely manner to a situation. This delay may also cause unsafe situations – for example, if a vehicle is blocking traffic and has called on an RA to resolve the situation, a large latency issue may result in an RA command being executed after the scene has shifted, reducing the safety alignment between the command and environment. For the RA, if there is a large latency between the time when the data is received and the state of the world around the vehicle, the operator may choose an incorrect action to take based on outdated information.

Communication latency is a key factor for AV operations centers. Fleet monitoring (one-way communication) tends to have less strict constraints on latency. Fleet data updating once per second or once every 10 seconds may be sufficient for tracking location and vehicle health. Remote assistance (two-way communication) may need more rigorous latency requirements to ensure RAs are receiving timely data and their input is reaching the vehicle in a timely manner. Actions based on out-of-date data from either the operations center or the vehicle can create risks to safe operations.

Regarding operations center performance, metrics that support live decision-making should be prioritized for real-time assessment. These are likely to include the number of remote assistant prompts, the number of incidents, the identification of any cyberattacks or risks, experienced network latency, ridership and to/from which locations, and the presence of, or need for, geofenced avoidance zones. Each implementation of an AV operations center will utilize different performance metrics for their facilities based on their objectives, the issues they seek to identify, and the levers available to mitigate those issues.

4.3.3 Post-processed Metrics

Many metrics are not used to inform real-time decision making but rather are used on longer time scales to monitor performance or ensure compliance. Within the broader metrics program, the intended audience and desired outcomes will determine the cadence for post-processing vehicle data and reporting metrics.

With operationalizing any artificial intelligence (AI) enabled system, it is critical to monitor metrics and performance with respect to system changes and new software releases. For an AI model, retraining can produce entirely new emergent behaviors that are inconsistent with those observed prior. This means that aggregating data over model releases may produce skewed results. This can be true for software releases generally, depending on the scope of the software release.

In this way, metrics can support evaluation of performance changes at each release. For example, if a new remote assistance interface is released, aggregating performance on the former interface with performance on the new interface will not appropriately describe the effectiveness of remote assistance. Identifying the interface release as a change point, however, can demonstrate whether any performance metrics have changed from the former interface to the updated interface. This can show whether the issues were adequately addressed with the new release or if new issues were introduced.

It is also worth noting that some metrics may typically be computed through post-processing vehicle log data, but they may be valuable data for real-time fleet monitoring. As an example, AV operations centers may track metrics regarding unexpected vehicle behaviors such as swerving and hard braking. Although these metrics are often computed through offline processing of vehicle log data, operations center staff may recognize that they can be valuable to identify whether operational mitigations must be rapidly implemented due to unexpected vehicle behaviors. Even though indicators of event occurrence are not typically high-bandwidth data to transmit, transitioning these metrics from post-processing to real-time onboard processing will require new approaches to computing, storing, and aggregating the metrics.

4.3.4 Optimizing Data Visualizations for Situational Awareness

It is important to consider the HMI for remote monitoring and how data is represented on the screen to support operator situational awareness and workload. Maintaining situational awareness is pertinent for operators to make informed decisions. Many operations centers have large, shared displays towards the front of the room and have multiple small monitors at each operator workstation. These large displays help maintain shared situational awareness and present important information and metrics related to the operations center itself or elements the operation center is monitoring. For AV operations centers, shared screens could present locations of all vehicles, weather in operational areas, communication network strength, vehicle safety risk levels, or global security events. Displaying information relevant to all teams—rather than just one team—supports effective situational awareness across the entire operations center.

For individual workspace monitoring, operator interfaces should avoid displaying unfiltered data. When faced with excess raw information, operators may either overlook important details or arbitrarily select data to focus on. Instead, operators should be presented with curated data views that can be thoroughly assessed throughout the duration of their shift [24].

4.4 Incident Response

Key Challenge: Response to AV incidents must be timely, coordinated, and provide effective short-term and long-term mitigations.

4.4.1 Establishing an Incident Response Process

Similar to operations centers in other domains, AV operations centers face a range of vulnerabilities and unexpected events (e.g., crashes, system failures, medical emergencies, road closures, severe weather). They must be equipped with the right resources and procedures to effectively handle incidents. The National Institute of Standards and Technology (NIST) outlines several phases in the incident response process for handling computer security incidents, as shown in Figure 7 [25]. AV operations centers can follow a similar process, adapting the following phases to flow best inside their organizations.

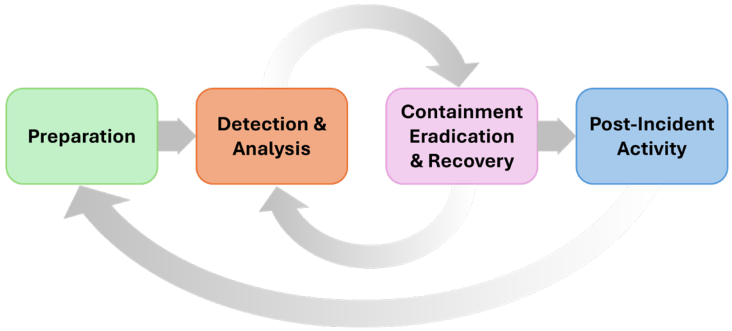

Figure 7: Incident Response Life Cycle [25]

1. **Preparation**
   This phase involves establishing response capabilities to prepare the organization and train incident response teams. Conducting risk assessments is a critical component in safeguarding against incidents. Risk assessments enable operation centers to define relevant risks, evaluate risk impact and likelihood, and develop procedures accordingly. Risk assessment results should be communicated and shared across the organization. Using the results from risk assessments, an organization can create an incident response policy which defines incident types, establishes the organizational structure for incident response, defines roles and responsibilities, and outlines the incident response process. Based on this policy, organizations can develop an incident response plan, establish a roadmap for the capability – including goals, metrics, and requirements for incident response personnel – and define the frequency of personnel training. Incident response procedures should be guided by the established policy and plan, and procedures should be clearly documented in SOPs and/or playbooks.

   Since AV operations centers may have to engage with multiple third parties, it is critical to thoroughly and effectively communicate with outside parties before, during, and after an incident. Centers should consider meeting periodically with emergency responders and other public safety officials to discuss how different teams should coordinate and respond to incidents. To facilitate timely external communication during rapid response incidents, AV operations should maintain an up-to-date external contact list and establish clear information-sharing protocols.

2. **Detection and Analysis**
   This phase involves detecting and assessing potential incidents through automated systems and manual processes. One of the most challenging aspects of incident response is accurately identifying and evaluating potential incidents. This is driven by three main factors: (1) incidents may be detected through a wide variety of sources, (2) volume of potential signs is often high, and (3) proper analysis requires specialized technical expertise. Signs of an incident are classified into two categories: precursors and indicators. A precursor is evidence suggesting that an incident may occur in the future, while an indicator is evidence that an incident has occurred or may be occurring.

   To ensure efficient incident detection and analysis, AV operations centers should assemble teams of highly skilled and specialized staff who can effectively analyze precursors and indicators and respond appropriately. Once an incident is detected, the incident response team(s) should quickly conduct an initial analysis to deduce the scope, the incident root cause, and how the incident unfolded. Maintaining a record of all details regarding an incident is recommended. Incidents should be prioritized in this stage, and not necessarily handled on a first-come, first-served basis. Factors to consider when prioritizing incidents include the functional impact, information impact, and recoverability. After an incident is analyzed and prioritized, the incident response team(s) must notify the appropriate individuals who need to be involved.

3. **Containment, Eradication, and Recovery**
   This phase involves containing incidents from causing further impact, often by implementing operational mitigations, eliminating components of the threats, and removing the root cause to restore services to normal

operations. It is important to emphasize developing clear strategies and procedures in the preparation phase, as containment strategies will vary between incidents and having well-defined plans can make decision-making much easier. After an incident has been contained, eradication may be required to fully remove any remaining components associated with the incident. In some cases, eradication is not necessary or may be integrated into recovery. During recovery, normal operations are restored and verified to ensure operations are functioning as expected. To ensure remediation steps are prioritized, eradication and recovery should be carried out using a phased approach. For example, in the case of large-scale incidents, recovery may span several months. Earlier phases should focus on implementing quick changes to increase overall security, while later phases should focus on longer-term changes and refinement.

4. **Post-Incident Activity**
   The final phase involves lessons-learned discussions to improve incident handling operations. Post-incident reviews (PIRs), also known as hot-washes or after-action reviews (AARs), are informative processes to analyze actions and review lessons learned [24]. These reviews are conducted after major incidents, but can be done after smaller incidents, if teams have the availability and resources. PIRs can be valuable in creating discussions around enhancing security measures and improving incident handling procedures. Teams can discuss what worked well and what did not work well, if the right people were involved, and if the necessary resources were available. The outcomes of these reviews can be translated into reports, which are essential for updating training and existing processes. In addition to PIR reports, creating follow-up reports for each incident (major or small) can be highly beneficial for future reference, as these materials serve as resources for addressing similar incidents. Conducting post-mortem analyses are helpful in revealing any missing steps or inaccuracies in incident handling procedures.

For AV operations centers, the key focus of these phases is on establishing and following processes for foreseeable incidents, rather than relying on experienced staff to develop a pathway in real-time.

> **Although AV operations are growing, and it may be challenging to document every instantiation of each incident type, implementing a rigorous post-incident process and ensuring lessons learned are tracked and materials are updated will help mature incident response processes over time.**

4.4.2 Incident Response Team Structures and Models

As incident response team structure and staffing models can differ across organizations, AV operations centers should establish the structures that best align with their organization. For instance, in the Incident Command System (ICS), an established and widely used management framework in public health and disaster response settings, there is a hierarchical structure with an incident commander (IC) at the top, along with a public information officer, safety officer, and liaison officer under the IC. Four sections exist underneath with a section chief in each: operation section chief, planning section chief, logistics section chief, and financial administration section chief [26] [27].

NIST summarizes three team structure models and three staffing models commonly used for SOCs, as shown in Table 3 and Table 4 [25].

Table 3. Incident Response Team Structures

Incident Response Team Structure	Description	Ideal For
Central incident response team	A single team responsible for handling all incidents across an organization	Small organizations or centralized organizational structures
Distributed incident response team	Multiple response teams, each managing a particular segment of an organization *Note: Even with separate teams, the incident response process should remain consistent across all teams*	Large or geographically dispersed organizations
Coordination incident response team	A single team that strictly provides advice to other departmental teams *Note: This team only assists others without having authority over other teams*	Organizations needing advisory support

Table 4. Incident Response Staffing Models

Incident Response Staffing Models	Description	Ideal For
Employee operated	An organization executes all of its incident response tasks	Organizations with a sufficient quantity of qualified staff
Partially outsourced	Portions of incident work are outsourced For example, an organization may handle basic incident response tasks internally while relying on contractors for more serious incidents. Alternatively, an organization could outsource 24/7 monitoring of certain services, with external providers responsible for identifying and analyzing suspicious activity and reporting detected incidents to the organization's response team.	Organizations needing external support for specific tasks
Fully outsourced	All incident work is outsourced to external contractors *Note: It is assumed that the organization will have employees supervising the contractors' work*	Organizations who lack available and qualified employees but need a full-time and onsite incident response team

As an example of incident response team models, Real Time Crime Centers (RTCCs) are units monitoring and analyzing crime in real time to support law enforcement. RTCCs can be embedded or external to a police department's Crime Analysis Division (CAD). For RTCCs embedded within a CAD, some incidents may be easier to resolve because the RTCC and the CAD can work together seamlessly. Additionally, these two units would likely share the same chain of command, helping streamline task allocation. Because external RTCCs are distinct from CADs, it is important to clearly delineate their respective roles, responsibilities, and expectations to avoid redundant efforts [28].

Similarly, roles and responsibilities during incident response are especially important for AV operations centers that may have several stakeholders involved in fleet operations. For example, the operations center may be fully or partially staffed by contractors, often from several agencies, and the local site teams required for vehicle recovery may be outsourced as well. Further, the organization operating the fleet may be separate from the autonomous vehicle developer, such as in cases where an existing rideshare service is integrating an autonomous fleet, or a freight logistics company is using autonomous trucks. Defining responsibilities for incident response across these organizations and creating a cohesive incident response team capable of managing incidents across stakeholders are both key to effectively and rapidly reducing risk, implementing mitigations, and creating short-term and long-term solutions.

4.4.3 Measuring Incident Resolution Success

PIRs should produce a set of objective and subjective data for each incident which can be used to measure the success of the incident response team(s). Operations centers should focus on collecting data that is actionable over data that is simply available. Some candidate metrics include [25]:

1. Total number of incidents handled
2. Time per incident (e.g., to identify, to implement initial mitigations, to implement long-term mitigations, to update incident response processes with lessons learned)
3. Objective assessment of each incident based on initial and residual risk levels and fleet-wide impact
4. Subjective assessment of each incident based on defined performance criteria

In the same way that fleet performance is regularly monitored, incident response performance metrics should be consistently maintained and evaluated to ensure the defined processes are effective and adequate staff are available to support incident management. At scale, the volume of incidents is likely to increase initially, but may decrease as the technology improves. Metrics programs can support incident response teams in understanding these changes. Metrics also enable informed decision-making from leadership regarding staffing levels or approaches to triaging incidents to ensure high-severity incidents are addressed, even as the incident volume increases.

4.4.4 Incident Awareness

Incidents may be initially reported via phone calls from riders or the public, rider support, vehicle alerts, or other sources. To ensure efficient handling, establishing a triage team to receive, organize, and direct these reports to the appropriate teams and individuals is recommended. A triage team provides a clearly defined point of contact for the incident response team(s). For example, in SOCs, tier 1 analysts are responsible for the triage of all incident reports and typically handle low-severity incidents. Tier 1 analysts may escalate high-severity incidents to tier 2 or tier 3 analysts.

For AV operations, this would mean positioning a team within or near the operations center to conduct real-time triaging of all incidents and reported issues, much like tier 1 analysts in a SOC. While an effective safety culture should empower any team member to raise an issue to their leadership, the tier 1 analyst team provides the first line of escalation in assessing the incident severity, fleet risk, and resolution pathway.

4.4.5 Incident Response Decision Making Pathways

Many incident response teams have an established IC or a similar role, e.g., AOCs have an Aircraft Commander (AC). In this role, the IC is responsible for managing incidents and holds the authority to direct and approve actions concerning the incident. In addition, the IC is responsible for contacting the appropriate internal individuals and outside parties.

In the ICS approach, the IC is required to orchestrate all response activities and will communicate with and subdivide tasks between each section chief, who will then divide those tasks among their section [26]. The Hospital Incident Command System (HICS) is a management system providing operational coordination for hospitals in response to health outbreaks [27] [29]. The organizational structure typically consists of an IC and a deputy IC.

While all staff should have pathways to raise issues that they identify, the responsible authority for the operations center (i.e., operations center manager), or broader operations center shift leadership team, are likely to hold decision-making authority for immediate mitigations. These mitigations should balance risk reduction with other key performance metrics, such as fleet uptime or ridership. Larger decisions, such as pausing or grounding the fleet over longer durations, may require additional approvals from organizational leadership.

4.4.6 Incident Response Training

TTXs can be an effective method to train staff to respond to emergency situations and operate in time-constrained environments. Human-in-the-loop (HITL) evaluations are a helpful way to test a system and the usability of the system. TTXs are primarily effective for qualitative metrics rather than quantitative metrics. Workshops, games, and seminars are other discussion-based exercises to help operators prepare for managing incidents [30]. Similar to training RAs in a simulated environment, these exercises can train staff on emerging incidents or uncommon documented incidents so that AV operations centers can appropriately establish or update incident operating procedures. Providing a diverse range of training scenarios is essential to ensure operators are prepared for a full range of situations they may encounter. AV operations centers can determine the timing of training exercises, choosing to schedule them at regular intervals throughout the year or in response to specific events and emerging challenges.

In SOCs, training is continuous to ensure that operators stay up to date with evolving vulnerabilities and technologies. To maintain their certifications, operators are required to take a certain number of classes each year. However, when individuals are away at training, others need to cover their responsibilities. The redistribution of workload can significantly increase responsibilities for those filling in, sometimes for extended periods, which may negatively affect operator performance. To mitigate this issue, organizations can use short-term assignments to support operational gaps [31].

AV operations centers should also offer training to prepare staff for incident response during overload situations, such as when multiple incidents occur simultaneously. While simple training scenarios can ensure that staff understand processes, and that those processes are nominally effective, the occurrence of these events during live operations may have additional complexities that create emergent challenges. Often, the confluence of multiple incidents may require different risk mitigations compared to addressing each incident individually.

4.4.7 Incident Response Documentation

SOPs and playbooks are vital for incident response training and serve as key reference documentation for staff. These are typically established during the preparation phase in the incident response process and are updated regularly. SOPs and playbooks for AV operations centers should establish clear expectations for all staff and help ensure consistency in managing incidents. The general information outlined in these documents should include the scope and circumstances under which it should be used, intended audience, roles and responsibilities, incident categories, detailed procedures and protocols, and version history. AV operations centers should treat these materials as living documents and ensure they are readily accessible to all staff. The cadence for updating or publishing new SOPs and playbooks varies by organization. For SOCs, the general guideline is if a specific type of incident is handled by the SOC at least once a month, on average, there should be an approved SOP on file for addressing that incident [24]. Typically, in a tiered SOC structure, the most senior tier (i.e., tier 3 analysts) develops the playbooks for lower tiers to use. Tier 1 and tier 2 analysts can then provide feedback to tier 3 analysts to update the playbooks appropriately [32].

Incident handling checklists can be another valuable resource to assist operators in navigating incidents. These checklists outline the key steps to be taken, though the specific actions may vary based on the type and nature of each incident. It is important to note that these checklists only serve as a general guide to the major steps that should be performed and do not mandate the exact order of steps to be followed [25]. Checklists may offer a more concise format that makes them easily referenceable for AV operations center staff compared to SOPs and playbooks. By outlining essential procedures, checklists can eliminate the need to navigate through lengthy documents, enabling quicker decision-making and execution. This is particularly helpful in high-pressure environments. It is important to note that checklists are intended to supplement SOPs and playbooks, not replace them.

4.5 Operational Resilience

Key Challenge: Building resilience in AV operations requires developing strategies and procedures that address a wide range of potential disruptions.

4.5.1 Continuity of Operations

To support operational resilience, operations centers initiate continuity of operations (COOP) processes to ensure that primary functions continue to be performed in the case of a widespread emergency or outage. A salient component of COOP is utilizing existing operating facilities as alternate sites for fallback. For instance, the Federal Emergency Management Agency (FEMA) recommends that if an emergency operations center (EOC) cannot support an effort, they should identify an alternate EOC with equal capabilities to the primary EOC [30]. Some questions to consider when creating an alternate site [24]:

- How long can the primary site be down for? How quickly must an alternate site be brought to full capability?
- What scenarios is the alternate site intended to address? How realistic are these scenarios and how often do they occur?
- Does the organization need to build a new alternate center, or can an existing facility be used?

A COOP plan is a vital document operations centers should create to outline how its organization will maintain essential functions during a disruption. The content of a COOP plan may vary among organizations based on size, organizational structure, available resources, and other factors. FEMA has a COOP plan template that can be used to guide the creation of the document [33]. Document purpose and scope, conditions under which the plan should be activated, and roles and responsibilities are among the content that should be written into the plan.

FEMA outlines four phases of COOP activation that should be captured in the plan document:

1. **Readiness and Preparedness**
   The Readiness and Preparedness phase should include all continuity readiness and preparedness activities. To enable an operations center to relocate to an alternate site swiftly and seamlessly, the center should adequately prepare secondary sites with relocation plans.
2. **Activation and Relocation**
   Relocation plans should be noted in this phase with a process for attaining operational capability at alternate sites with minimal disruption to operations. Non-relocation guidance and procedures should also be mentioned.
3. **Continuity Operations**
   Continuity Operations involves all procedures, including arrival procedures and operational procedures, to continue primary functions.
4. **Reconstitution**
   The process of returning to normal operations should be outlined in this phase. This process should only be initiated once it is determined that normal business operations can resume.

If relocation of staff from the affected center to the COOP site is not feasible, voice loops could be utilized. Voice loops is an auditory system that allows communication and shared situational awareness among geographically dispersed staff. The voice loop system is commonly used in space shuttle mission control, air traffic management, and aircraft operations. With voice loops, staff can be on multiple voice loop channels [34]. As shown in Figure 8, the Flight Director loop is for communications between the flight director and primary controllers in the front room. All controllers can monitor the Flight Director loop, but only the flight director and front room controllers are allowed direct communication. Front room controllers and support staff communicate through the Front-to-Back loop. Conference loops are used only in the event of a failure situation and can aid in quick coordination across subsystem controllers.

For AV operations, an RA monitoring three vehicles would be on at least three separate channels, one related to each vehicle. A rider support team member would have separate channels for each vehicle they are supporting. A centralized operations center channel would be an effective way to share valuable or urgent information across multiple dispersed centers. Additionally, a channel for each functional team could be helpful for staff to communicate among their specialized team.

Training operators on specific geofences has benefits but can be a limiting factor when relocating staff from one site to another. It can make it difficult for operators to set up in a different facility and area because they must learn the new area and new systems if these differ between facilities. This can introduce inconsistencies in service quality and make it difficult for operators to adapt when relocation is required during a widespread disruption. There are solutions to expedite transitions to the new areas. Local operational trends can be automatically updated and summarized using incident logs and historical data. Operators could learn the intricacies of the geofenced areas from a well-designed interactive map. Regardless of whether such a system exists or not, it is important for experienced local staff to brief incoming team members.

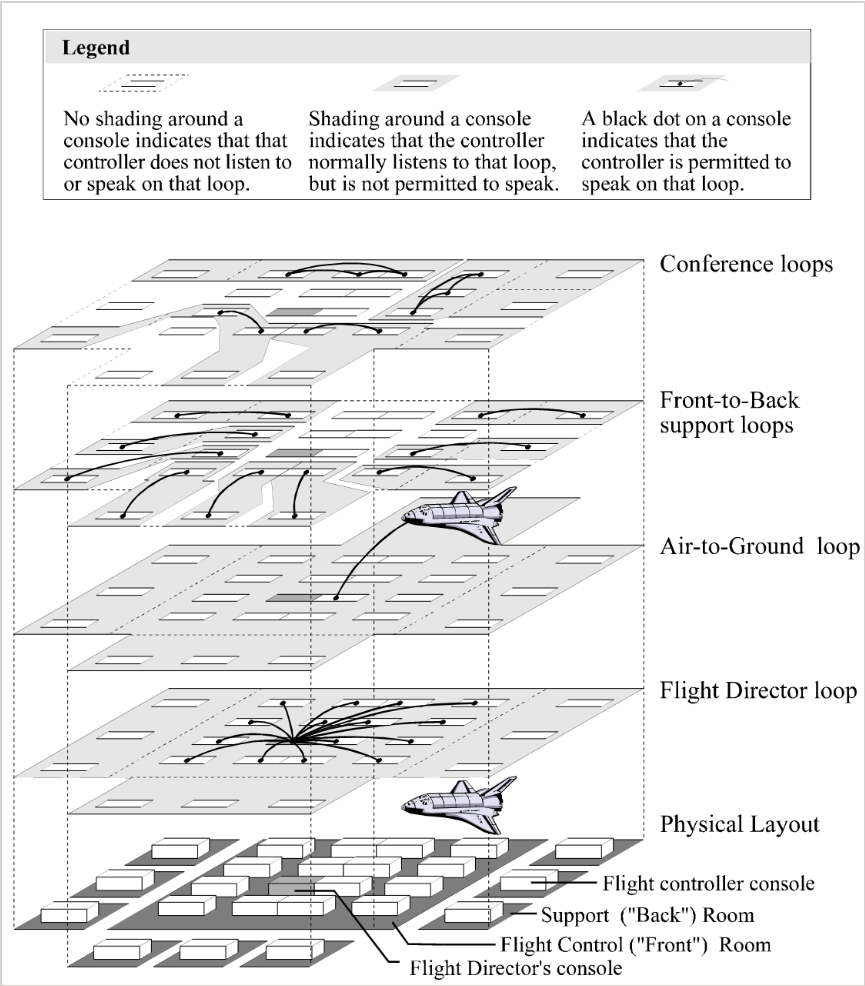

Figure 8 Voice Loop Structure in Space Shuttle Mission Control [34]

Organizational Resilience Framework

Researchers at MITRE developed the Transform with Resilience during Upgrades to Socio-Technical Systems (TRUSTS) framework [35]. This framework was created from insights, research, theories, and principles about resilient sociotechnical systems and their ability to respond and overcome challenges. TRUSTS is intended to assist in managing high-consequence work systems by maintaining a balance between organizational control, resilience and efficiency, and frontline operations.

Within this framework, work units are teams, departments, groups, or other subsets of a work system. A work system refers to the enterprise of all work units. Agents are personnel and technologies that make and execute choices. TRUSTS consists of five resilience factors shown in Figure 9.

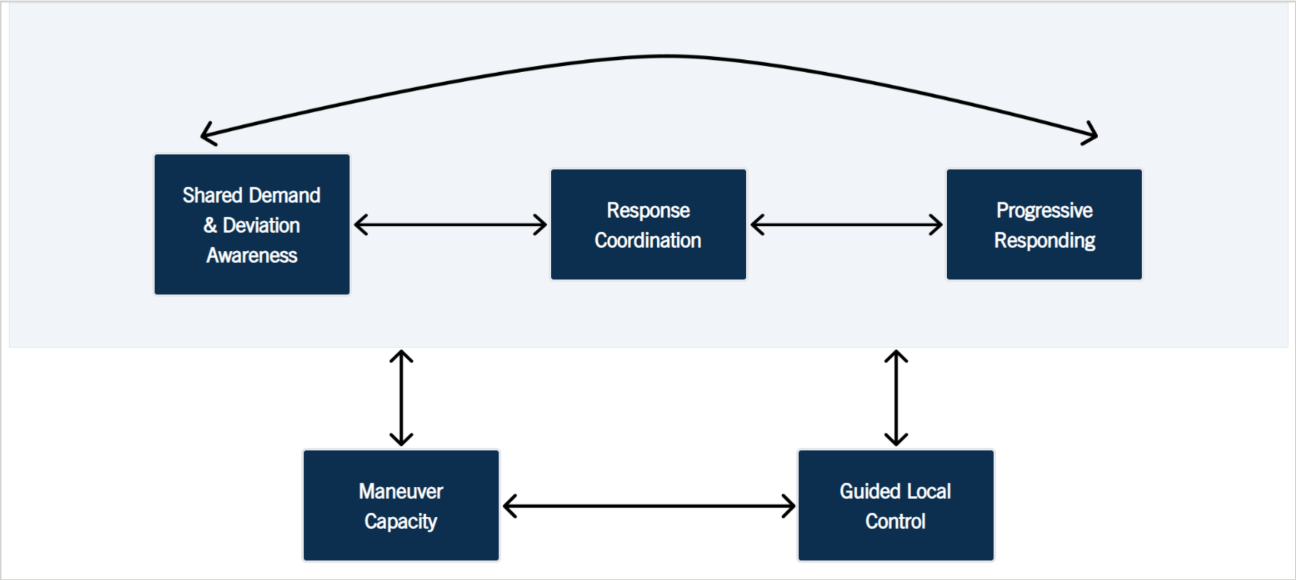

Figure 9: TRUSTS Five Resilience Factors [35]

1. **Shared Demand and Deviation Awareness:** All work units and agents recognize, process, and communicate new demands and deviations from standard business operations. Four sub-factors:
    1. *Detect and Share New Demands:* all work units are aware when things have changed
    2. *Detect and Share At-Risk Functions:* all work units and agents communicate when they are overwhelmed or nearing the point of becoming overwhelmed
    3. *Detect and Share Plan Deviations:* all work units are able to recognize when there is a deviation from what is expected or planned
    4. *Detect and Share Resource Deviations:* all work units are aware of changes that unexpectedly impact the availability of or access to essential resources.
2. **Response Coordination:** All work units coordinate and cooperate to avoid breakdowns in coordination and employ resources and capabilities. Five sub-factors:
    1. *Coordinate Resource Use:* means exist to ensure resources are available, adaptable, and accessible
    2. *Use Monitoring to Synchronize:* all work units and agents should know the workload of others and provide support responsively
    3. *Adapt Direct Communications to Conditions:* work units coordinate vertically and horizontally during challenging conditions
    4. *Use Work Practice Agreements to Synchronize:* all work units and agents know their expected roles and responsibilities under different conditions
    5. *Set Adaptive Permissions:* software permissions support the flexible use of personnel and resources during a challenging situation
3. **Progressive Responding:** In dynamic work systems and environments, a quickly initiated and progressively adapted response is the most effective response. Four sub-factors:

1. *Anticipate and Prepare:* work units monitor trends and patterns to anticipate and prepare for problems early
2. *Modify the Response:* work units fine-tune, adapt, switch, or replan the current response plan as the situation becomes better understood
3. *Reduce Uncertainty:* work units reduce uncertainty by probing and shaping the situation
4. *Monitor for Misalignment:* work units monitor any deviations from plans and look for opportunities to enhance planned actions.

4. **Maneuver Capacity:** A work system and its work units have the capacity to respond to a variety of conditions. Two sub-factors:
    1. *Respond Flexibly:* new processes can be created, as needed, in the case where something is not available or working appropriately
    2. *Diversity of Means:* a diversity in resources, tools, and other means are available to work units.
5. **Guided Local Control:** Frontline work units respond directly and rapidly to the situations they face. Three sub-factors:
    1. *Frontline Authority:* frontline work units and agents use leadership guidance to make and enact decisions within their area of responsibility
    2. *Backline Support:* backline work units focus on the big picture, incoming demands and opportunities, and distribution of resources in order to allow frontline units to focus on time-critical demands
    3. *Loose Organizational Guidance:* leadership provides guidance with the expectation frontline work units will follow loosely and improvise in a given situation.

The way an organization is structured impacts its ability to build resilience and respond effectively to disruptions. By leveraging the TRUSTS framework, organizations can foster efficient communication and collaboration among staff. The TRUSTS framework focuses primarily on organizational resilience, which is a key component of continuity of operations.

> **Defining how teams within an AV operations center can support operational resilience, especially during disruptions and higher-than-expected load, is important to ensure that the AV fleet remains operational during a range of conditions and events.**

4.5.2 Cyber Resilience in Operations Centers

There is a wealth of literature available on cybersecurity best practices that can be utilized to help AV operations centers build resiliency against cyberattacks. The National Highway Traffic Safety Administration (NHTSA) published a comprehensive report reviewing cybersecurity best practices for automotive cybersecurity [36]. Additionally, *MITRE's 11 Strategies of a World-Class Cybersecurity Operations Center* provides valuable insights into the organization and functionality of efficient SOCs [24].

An effective strategy SOCs use is setting up hardware and software (HW/SW) stacks at different facilities with the same function but with intentionally different configurations. This can make it more difficult for an adversary to compromise an organization's entire HW/SW infrastructure, as the diversity in design creates an additional layer of defense. AV operations centers may consider outsourcing a dedicated cybersecurity team to support proactive and reactive actions regarding cyber risks. If outsourcing a dedicated cybersecurity team is not feasible, an effective alternative would be to appoint a cybersecurity or IT lead within the operations center to develop and implement a security strategy and counsel on processes related to privacy and security.

Implementing regular cybersecurity training is an effective defense against cyber breaches [37]. All staff should be expected to periodically refresh their understanding of cybersecurity practices, ensuring they remain prepared to respond to breaches. Training material should be included in playbooks. Similar to developing a COOP plan and incident response procedures, operation centers should also create a cyber breach response plan. The response plan should clearly outline roles and responsibilities of personnel involved and procedures to detect and mitigate damage.

By leveraging established security best practices and investing in strong cybersecurity defenses, AV operations centers can ensure they remain resilient against cyberattacks and prepared to address evolving cyber threats.

4.6 Staffing Ratios

Key Challenge: Balancing staffing ratios with operational requirements, along with developing staffing plans and schedules, may result in conflicting priorities.

4.6.1 Evaluating Ratios Based on Operational Needs

The optimal operator to vehicle ratio for AV operations centers is not a one-size-fits-all solution. Each AV operations center should define and test the ratios that are effective for their organizational goals and operational needs. While the ratio of RAs to vehicles is often the most discussed, operations centers must define staffing ratios across all roles in order to effectively scale.

This can include defining the minimum and maximum vehicles a single operator can effectively oversee. A study investigating if a single human can supervise a swarm of 100 heterogeneous robots evaluated ratios with a bottom-up approach, using a multi-dimensional workload perspective. The authors noted that overall workload can be broken down into several components: cognitive, physical, visual, auditory, and speech [38]. By breaking down workload across these criteria and assessing the proportion of time when overload conditions are observed, decision makers can determine whether the vehicle-to-operator ratio must be reduced in order to reduce overload conditions to within an acceptable range. The determination of this acceptable range must be based on analysis of the resultant risks from operations within overload conditions. This granular approach gives insights into the limits of human performance, making for an effective bottom-up approach to evaluating operator ratios.

Conversely, a top-down approach involves evaluating the entire operational capabilities of a system across all phases of operation. For example, the FAA's commercial unmanned aircraft systems (UAS) airworthiness criteria require commercial UAS operators to test the entire flight envelope and address 13 different categories, including flight distance, flight duration, route complexity, weather, and aircraft-to-pilot ratio [39]. Under the top-down approach, operational ratio limits are not defined by the regulator, and the operator is not responsible for detailing how their ratio is formulated. Rather, the operator must demonstrate they can effectively operate their system at their proposed ratio across the operational envelope. Provided that no failures occur during these airworthiness tests, the entity is permitted to operate at the ratio they have defined. Operators may also use this approach directly to define their operational ratios. By incrementally increasing the vehicle-to-operator ratio until failures are observed, the operational ratio can be established near this performance threshold, without relying on the testing and instrumentation required by the bottom-up approach.

Lessons learned can be drawn from the healthcare domain, as nurse-to-patient ratios have been evaluated and assessed in many peer-reviewed publications. In a healthcare study investigating cost effectiveness of various nurse-to-patient staffing ratios (between 1:8 and 1:4), the authors found that the lowest ratio (1:8) resulted in the highest patient mortality, but least cost. As the number of patients per nurse decreased, mortality improved, but costs increased [40].

Similarly, the authors of another paper found an association between nurse workload and patient survival. The authors evaluated the workload of nurses for all patients in the intensive care unit (ICU). The Therapeutic Intervention Scoring System-76 (TISS-76) is used to measure nursing workload. The findings suggest that survival rates significantly drop when the workload was above 52 TISS points. A score of <40 TISS points was associated with increased survival [41]. Applicable to the AV operations, these findings suggest that, as the number of vehicles per operator increases, quality of service may decrease, and that the bottom-up approach (workload-based) may provide surrogate measures for the top-down approach (outcome-based).

4.6.2 Impact of Remote Support Structures on Evaluating Ratios

Assignment-based and queue-based ratios each influence staffing ratios in different ways. Assignment-based structures require more staff relative to the number of vehicles as compared to queue-based structures. An assignment-based model requires operators to monitor and/or assist a dedicated number of vehicles. Since operators are allocated to specific vehicles, the number of staff tends to be higher because operators can only oversee a limited number of vehicles in parallel before reaching a high workload. However, during periods of low demand, this approach may result in inefficiencies due to reduced operator vigilance and engagement. As AV fleets scale, this model may be less favorable because the number of operators required increases proportionally, limiting scalability. With a queue-based model, operators can support a larger fleet because they only engage when intervention is needed, thus allowing for a lower number of operators relative to the fleet. This model supports a quick-paced environment and can support AV fleet scaling, although it provides less active vehicle oversight.

4.6.3 Dynamic Adjustment of Ratios

AV operations centers can embrace a flexible staffing model and optimize the use of floating staff to quickly adjust to increased demands or incidents. University of California Los Angeles (UCLA) Health developed a nursing system float team (NSFT) to meet increasing demands and expansion [31]. Staff in the NSFT are allocated to specialty divisions based on experience and competency, but the NSFT also cross-trains staff to expand departmental coverage. For AV operations, floating staff can be allocated to each functional team in the operations center (e.g., remote assistance, remote monitoring, rider support) and, as operations scale, potentially cross-train staff to cover other teams. With floating staff, staffing ratios may not necessarily need to be adjusted to support increased demand, as staffing redundancy is built in through the floater system.

4.7 Organizational Culture and Models

Key Challenge: Traditional organizational culture and models must be adapted to support new technology-driven roles and workflows, which can create dynamic and evolving roles and responsibilities. Maintaining a strong safety culture is particularly difficult because oversight relies on remote, technology-mediated supervision, making it harder to ensure accountability and consistent safety practices.

4.7.1 Organizational Culture

Figure 10: Elements of organizational culture

Organizational culture refers to the set of values, beliefs, attitudes, systems, and rules that shape and guide employee behavior within an organization [42]. An organization's culture influences every aspect of its operations and serves as a foundational element in driving a company's success, as shown in Figure 10. However, culture has often been relegated to a "soft" element of organizational success, leading many organizations to overlook the intention needed to shape it. In recent years, industries have increasingly recognized the competitive advantage that an effective culture can provide.

Organizational culture is crucial for a company's success as it shapes employee behavior, drives engagement, and influences overall performance. A strong, positive culture fosters a sense of belonging, purpose, and psychological safety, leading to higher employee motivation, productivity, and retention.

It also impacts recruitment, brand reputation, and the ability to innovate. Everything within an organization from its leadership to communications and the layout of the office space contributes to an organization's culture.

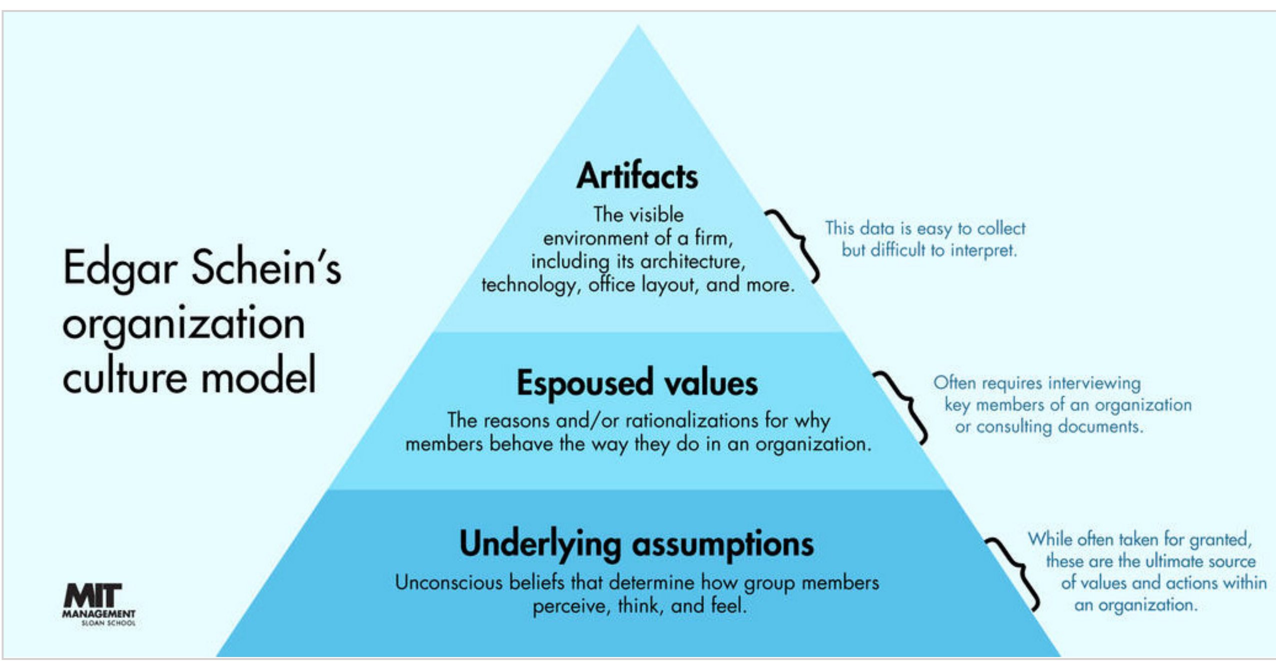

Figure 11: Edgar Schein's Organization Culture Model [43]

Outlined in Figure 11, an organization's culture is made up of three core areas: artifacts, espoused values, and shared and underlying assumptions. Leaders within organizations often focus on artifacts (e.g., mission statements, written documents, etc.) and espoused values as the primary drivers of culture. However, it is the shared and underlying assumptions that form the core of an organization's culture. These ingrained beliefs and behaviors, which guide how people act, ultimately shape an organization's identity.

Artifacts

Artifacts are pieces of data that can be easily observed or collected but may be challenging to interpret. For example, the layout of an organization is easily observable, yet the decisions behind its design can reveal insights about the organization's culture and priorities. The layout of an AV operations center should encourage and foster shared situational awareness and cross-functional collaboration. If the operations center floor is arranged so that some employees cannot see large, shared displays intended to provide common situational awareness, this creates not only a physical barrier but also inadvertently suggests that shared awareness is of lesser importance. While an open layout is supposed to support collaboration and contribute to a better work environment for staff, removing physical walls to create an "open space" is not sufficient to ensure those outcomes. A well-designed operations center should enable clear lines of sight among team members to facilitate seamless collaboration and communication, as well as between staff and supervisors to support effective, transparent decision-making. Implementing a floor plan does not guarantee desired outcomes; it must be accompanied by appropriate organizational values and culture and should be continuously monitored and adjusted based on feedback, performance metrics, and evolving organizational needs – especially as the organization and its facilities scale.

Espoused vs. Enacted Values

Distinguishing between espoused and enacted values often requires interviewing key organizational members (such as leadership, staff, stakeholders/customers) and/or reviewing documents to identify both the values the organization claims to uphold (espoused values) and those reflected in actual actions and behaviors (enacted values). An organization may state that it values collaboration, teamwork, and innovation and therefore will implement an open workspace. However, if teams remain siloed, cross-functional collaboration is limited, or there is little interaction between leadership and staff, the enacted values will overshadow the espoused values, ultimately defining the organization's culture. Understanding the gap between espoused and enacted values is not only a quality metric to understanding culture, but it also helps identify areas for improvement.

Ideally, espoused and enacted values should align, creating a foundation of trust within the organization. Alignment positively impacts external stakeholders, increasing the organization's reputation. When there is misalignment, it can have serious impacts on employee engagement, morale, and the company's reputation. For AV operations, the additional complexity of maintaining public trust in their technology means the organizational culture impacts employees, riders, and the public at large.

As an AV operations center is shaping its culture, it should consider:

- What are the core values of our organization?
- In what ways will we create a positive work environment and experience for our staff?
- How do we meaningfully recognize, express appreciation for, and celebrate our staff?
- What implicit messages is our operations center subconsciously conveying to staff?
- What methods, mechanisms, or tools do we currently have in place – or could we develop – to assess our organizational culture?

Shared and Underlying Assumptions

The shared and underlying assumptions within an organization ultimately shape its values and drive its actions. While individuals within an organization have their own set of beliefs, values, and assumptions, an organization's underlying assumptions – such as how employees are motivated and managed, how interactions occur among staff and with customers, and how leaders view the organization – strongly influence the unconscious beliefs that shape how employees perceive, think, and feel at work [43]. For example, while many organizations espouse the value of collaboration, underlying beliefs may contradict this value. If employees believe that remaining quiet and focusing solely on their individual desktop screens is expected, it can present a challenge and reinforce negative behaviors.

Basic assumptions about relationships within an organization often become evident in the frequency and inclusiveness of meetings. For example, the absence of cross-functional meetings or an excessive number of meetings that disrupt productivity can signal or reinforce beliefs about whose contributions are most valued within the organization. While the "rule" may never be spoken aloud, the impact of the enacted value over the espoused value of collaboration, can lead to assumptions and behaviors that manifest in competitiveness, reluctance to challenge leadership, or feelings of discouragement.

> **As AV operations centers align teams with distinct roles, often merging full-time and part-time employees from several vendor agencies, organizations must ensure that staff operate with a shared understanding of their role and expectations.**

Misaligned assumptions may result in communication and coordination challenges that manifest during high-pressure operational events, or dissatisfaction resulting in reduced role performance and emergent safety, operational, or enterprise risks. Dedicating the time and resources to examine and strengthen the values and elements that influence organizational assumptions enables operations centers to build a positive culture.

Creating an Organizational Culture

Organizations prioritize culture because they recognize its significant influence on their overall success. AV operations centers will need to carefully consider the ways in which they cultivate their culture. Considerations for creating a healthy organizational culture include:

- **Consistent Communication and Transparency:** Establish consistent forms of communication (e.g., all hands meetings, 1:1's, team meetings, etc.) that connect employees to their work and the larger mission of the organization in meaningful ways. Additionally, provide two-way communication pathways (e.g., feedback channels through managers or anonymous platforms). Along with consistent communication, being transparent in decision-making processes and company performance can foster trust and a sense of authenticity.
- **Prioritize Employee Engagement:** Highlight employee well-being as a priority through words and actions such as flexible work schedules, meaningful rewards and recognition, and avenues for social connections.
- **Prioritize Development and Growth:** Be intentional about the types of training provided for employees. Set clear development pathways that are visible and provide various development opportunities. Foster an environment of acceptance and learning from mistakes.

- **Model Desired Behaviors and Values:** Communicate core values and establish ways for employees to see leadership model desired behaviors and values.
- **Celebrate:** Foster positive reinforcement in simple ways, like a "kudos" board, and larger, periodic acknowledgements.

Lastly, important for any safety-critical operation, a key best practice is the creation of safety culture. A key component of safety culture that several industries, especially the transportation industry, have adopted is Just Culture. Just Culture refers to "a system of shared accountability in which organizations are accountable for the systems they have designed and for responding to the behaviors of their employees in a fair and just manner." Just Culture ensures there is non-punitive action (and in some cases rewards) for employees that report safety concerns. The result is multifaceted: employees feel safe enough to report safety concerns—both internal and external—even when the concerns challenge the organization's espoused culture. Additionally, because Just Culture prioritizes learning, employees are encouraged to continually develop, and system improvements are made to prevent future errors [44]. Together, these efforts result in a safer rider experience and enhanced public trust in both the organization and the broader AV industry.

> **As an AV operations center scales, an established safety culture helps ensure that safety is maintained as the organization grows.**

AV operations centers should embrace Just Culture and implement elements like voluntary non-punitive safety reporting procedures and integrate within organizational safety management systems (SMS) [45]. Within the transportation industry, organizations are implementing Just Culture programs that investigate incidents with processes focused on accountability, learning over blame, and considering systemic contributions of reported incidents. Programs include an inquiry panel that reviews reported incidents to ensure fairness during the investigation and determination process. By applying Just Culture principles, determinations emphasize assigning accountability—whether to the employee or the system—promoting learning through coaching or counseling and implementing corrective actions such as system improvements or updates. By utilizing Just Culture principles, organizations continue to align themselves with best practices for building healthy and positive work cultures.

Feedback and Continuous Improvement

Cultivating a healthy organizational culture requires purposeful action, along with ongoing, meaningful reflection. Organizations committed to building a strong culture routinely evaluate their strengths and gaps, identify areas for improvement, and use these findings to implement meaningful changes. Questions such as, but not limited to:

- How do we show our organizational values? How are they reflected day-to-day?
- How can we create an environment where employees feel comfortable sharing their ideas, concerns, and/or challenges?
- In what ways are leadership modeling our desired values and behaviors? Where are areas for improvement?
- How do we foster an environment where different perspectives are welcomed and celebrated?
- What disconnects, if any, are there between the culture employees experience and our espoused values?
- What mechanisms are in place to address challenges, resolve conflict, and/or address undesired behaviors that undermine our values?

- How do we react to and address positive feedback? Constructive criticism?
- What policies will we/do we have in place to promote a healthy work-life balance?
- How do we recognize employees and their achievements in meaningful ways?
- What aspects of the culture we aspire to have are most important?

For instance, the United States Government uses the Federal Employee Viewpoint Survey (FEVS) to analyze organizational culture. FEVS is administered to agencies as a way of gauging and understanding employees' perceptions of the climate of an organization. The questions asked and the results obtained can be used to gain insights into the organizational culture.

These considerations are all broadly applicable for AV operations centers. Although the scope of operations may be different from other environments, with scaled implementations, AV operations centers encounter many similar challenges regarding coordinating and maintaining performance of a large, diverse set of staff. As AV operations centers evolve and operational processes, tools, and software rapidly change, it is critical to establish effective communication methods across the organization—including with product, engineering, leadership, and other key teams—to facilitate efficient collaboration and avoid creating barriers to performance.

It is important for operations centers to proactively consider critical questions from the outset and continue to revisit them as the organization evolves.

4.7.2 Shift Schedules

Operations centers are tasked with defining a shift schedule model, and their operating hours. AV operations centers may require more flexible schedules to meet demands. For SOCs, there are multiple options to determine shift staffing [24]. Table 5 outlines SOC shift staffing models and considerations for implementation for AV operations centers.

As outlined in Table 5, the "follow the sun" model is an effective solution for operations centers seeking 24x7 coverage without requiring employees to work overnight shifts. Using this model, teams located in different time zones handle operations during their local business hours. For example, a team in California could start at 9am PST and a team in London could start at 9am BST. This approach staggers shift start times across time zones, allowing the operations center to provide 24x7 support without requiring staff to work overnight.

Determining shift staffing and schedules for AV operations centers requires consideration of operational needs, fleet size, and activity level. Some questions to consider if moving to 24x7 operations:

- What is the size of the fleet, and does it require after-hour monitoring? Are there specific routes where AVs primarily operate during off-peak hours?
- If an AV experiences an issue after hours, are adequate resources – such as vehicle recovery teams, maintenance teams, etc. – readily available to provide immediate support?
- What is the current staff size? Are there enough staff to support 24x7 operations?

Traditional 9-5 operations may work for smaller fleets, but as AV fleets scale, more flexible staffing times are needed to support the dynamic and safety-critical nature of AV operations.

Table 5. SOC Shift Staffing Models and Considerations for AV Operations Centers

Shift Staffing Models	Implementation in SOCs	Considerations for AV Operations Centers
Critical 24x7 capabilities	Staff only critical portions (i.e., event monitoring and detection) of SOCs 24x7, while leaving other portions on-call	Identify most critical AV operations functions to staff 24x7
Extended weekdays	Remain on a weekday schedule, but extend hours to 12 hours a day so there are analysts on shift during high-activity time	Align extended hours during peak AV fleet activity
Weekend shifts	Add a shift during the weekends, consisting of two or three analysts	Adjust staffing based on AV fleet activity and demand on weekends
Staff 24x7 but concentrate resources during business hours	Maintain minimum coverage at night, while having majority of analysts during normal business hours	Ensure 24x7 capabilities, but boost staff presence during main business hours
Outsource to a coordinating or sister SOC	Hand off operations to coordinating or sister SOCs to access primary SOC systems and data feeds	Use regional AV operations centers
Contract with a SOC managed service provider	Hand off functions during off hours or contract to provide 24x7 capabilities	Contract with an AV operations service provider to manage day-to-day functions
Follow the sun	Staggers shifts with multiple geographically dispersed locations	Requires multiple AV operations centers nationally and globally

4.7.3. Transfer of Situational Awareness between Shifts

To support situational awareness transfers across shifts, having a shift manager on site can be helpful in maintaining and tracking important information from each shift in a centralized log. The log can contain times, events, operators involved, tasks that need further attention, and other details, and can be handed off from the outgoing team to the incoming team. The centralized log, along with a debrief from the outgoing team, is effective to ensure continuity of operations and maintain accountability. Shared digital platforms, such as dashboards, databases, or collaborative communication tools, enable transparent, real-time, and easily accessible information sharing. Relying on multiple communication channels or platforms can fragment information and increase the risk of miscommunication. Consolidating information into one centralized log ensures all staff have easy access to the same accurate and up to date information.

Another consideration is an overlap period between shifts to allow outgoing teams and incoming teams to interact directly. This can facilitate a smoother transfer of situational awareness and reduces the risk of misinterpretations. In space shuttle mission control, shift changes/handovers are scheduled for one hour in which the outgoing controller updates the incoming controller physically at their assigned workstation [46]. To check the understanding from the handover briefings, and to coordinate activities that need to be conducted during the new shift, the incoming back room controllers will brief the incoming front room controllers, which is done through voice loops so other controllers can listen in. At the same time, the front room controllers give the incoming flight director a high-level update via voice loop. These handovers flow bottom-up. For AV operations centers, handover briefings could include updates about vehicle behavior, weather, road conditions, and software issues. Since there is rarely downtime in AV operations, floaters could be utilized during the hour of handovers for primary staff.

4.7.4. Organizational Models

For AV operations centers, the most effective organizational model will depend on factors such as fleet size, corporate structure, and specific use cases. In one model, operations centers may consist of a central location (i.e., a headquarters) and multiple hubs situated in different regions. This approach enables nationwide operations while maintaining the cross-functional collaboration necessary for effective scaling. Questions for AV organizations to consider when planning a hub approach include:

- What is the functional role of the hub locations and who should they serve?
- Do AV functional teams (e.g., remote assistance, rider support, etc.) need to be within or adjacent to the area of the fleet's operations, or can they be geographically dispersed? And for what reasons?

The organizational models for SOCs are shown in [24].

Effectively establishing an operations center organization relies on several coordinated factors, from a strong organizational culture that promotes safety and the processes in support of this culture, to the technical implementation of staffing plans, shift schedules, and team and facility hierarchies. The interplay of these factors with core operational functions and processes is increasingly important as operations center organizations scale.

Table 6. SOC Organizational Structures

Organization Model	Description
National	Shares situational awareness of incidents and events across multiple large constituencies.
Hierarchical	The central organization plays an active role in providing security operation services to lower-level SOCs and coordinating a broader range of responsibilities.
Coordinating	One SOC oversees and manages duties of other SOCs beneath it. Does not direct day-to-day duties of SOCs but focuses on incident management and situational awareness.
Federated	Multiple SOCs operate independently and are responsible for their specific portion of the constituency but share a primary organization.
Centralized	This is the most common model. Resources are consolidated under one authority in a centralized location. Personnel have dedicated roles.
Distributed	Division of resources enclosed in various sections of the organization. Allows for specialization in different areas.
Additional Duty	No formal organization, therefore, SOC responsibilities are part of other job duties.
Ad Hoc Response	No standing incident response team with little to no procedures for handling incidents. Commonly used for smaller organizations.
Managed Operations	Provides third-party security operations to external organizations.

5 Conclusion

Although AV operations centers have unique complexities, processes, and structures, lessons from other domains can inform the pathways to scale. As the AV industry expands, operations centers—which often begin as small-scale facilities with limited capabilities—are incorporating new functions, additional responsibilities, and larger fleets. Many of the challenges observed in current AV operations centers are closely tied to this growth. The lessons learned highlighted in this report offer potential solutions that organizations can tailor to their specific operations center implementation.

The work completed to date reveals several priority issues that AV operations centers must address in the near-term:

- Human factors experimentation can assess the likelihood and risk of overload conditions for remote assistants, rider support personnel, and shift-level management under different vehicle communication and organizational structures to understand the safety impacts of these events.
- Ensuring that operations centers are resilient to cyberattacks is critical for safety and security, as these facilities provide entry points to vehicle control, rider information, and data feeds. Deeper analysis of threats and mitigations will support enhanced and continuously improving security protocols.
- Establishing a common framework for assessing AV operations center performance can create a common language for discussing incidents and effective practices. Understanding the effectiveness of these centers is important for achieving scaled AV operations.
- Identifying the opportunities and risks associated with macro-level organizational structures for AV operations centers will enable stakeholders to implement and assess these centers more effectively. Centralized facilities, regional hubs, and local centers all have differing implications for vehicle interactions, incident response, operational resilience, and fleet-wide monitoring. Research into the implications of these structures can identify potentially unforeseen risks at scale.

Further exploration of these research areas, along with integration of lessons learned from mature operations center implementations, can ensure safe, efficient, and secure AV deployments.

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Appendix A: Approaches to Assessing and Monitoring AV Operations Centers

Although many metrics are used to monitor AV operations centers, their complexity and close integration with both the vehicle fleet and the broader organization call for a focused approach. To this end, a set of ten metrics are proposed to effectively capture the performance of the operations center and its interactions with the fleet, without being specific to a certain operations center implementation. Although these metrics are designed for operational performance monitoring, certain metrics may also be adapted to use in pre-operations testing and evaluation. These metrics should be normalized by vehicle miles traveled (VMT), fleet size, number of operators, or similar factors and should maintain awareness of software updates to both the AV and the operations center in order to identify unexpected regressions. Note that these metrics are relevant to several of the core focus areas outlined in this report and address both on-vehicle and off-vehicle events.

1. **Stopped Vehicle Response Time:** This metric includes all unplanned vehicle stoppages in the roadway, not including stops for pick-up/drop-off, stoplights, or traffic congestion, and measures the duration until the vehicle either moves again or is recovered. An alternative version of this metric is defined as "unplanned stoppages longer than two minutes," however, presenting descriptive statistics about the distribution of response times can provide more insight while removing a static threshold. Although vehicle stoppages are a normal element of driving, and often a safety measure when a failure occurs, a high volume of prolonged stoppages in the roadway can be disruptive and may indicate persistent issues with the AV or an inability to navigate complex driving situations. An effective operations center should have remote mechanisms for reducing the frequency of these stoppages.
2. **Vehicle Recovery Events (VREs):** Occur any time a local team must be dispatched to an AV's location to address an issue or tow a vehicle. These represent the tail of prolonged stoppages wherein the vehicle is unable to continue operating on its own or with remote support. As with prolonged stoppages, VREs are expected in any on-road fleet operations. However, a high volume of VREs poses issues for local traffic and results in significant costs for fleet operators. An operations center's role is in identifying the issue, dispatching a local recovery team, and triaging the issue to implement mitigations.
3. **Emergency Responder Disruptions:** This metric includes any interaction in which an emergency responder must change their path or adjust their onsite response to an emergency to accommodate an AV. While it is important to track all instances of this occurrence, an operations center must maintain a record of those instances where remote operations were involved. This involvement may include a remote assistant on standby as the encounter unfolds, providing or approving vehicle route decisions, or interfacing with emergency responders and riders via in-vehicle communications.
4. **Remote Assist-involved Collisions**: Similarly, all collisions are expected to be monitored, but for an operations center it is particularly important to note the collisions in which a remote assistant was involved immediately prior to the collision occurring.
5. **Forced Minimal Risk Maneuvers:** If a remote operations facility is able to remotely request an AV to execute a minimal risk maneuver, instances of this request should be tracked, as these are often a result of the AV executing an unsafe or unexpected behavior, or experiencing a fault, prior to the request.

6. **Avoidance Area Implementation Time:** From notification of need, the time it takes for an avoidance area to be implemented and pushed to the AV fleet.
7. **Avoidance Area Violations:** Instances of an AV entering an avoidance area that has been implemented. Of particular note are instances when an AV is within an avoidance area at the time of implementation, or an AV is on an immediate path to enter an avoidance area.
8. **Repeated Incidents from Identified Issue:** Although many metrics can be used to evaluate an incident response process at the top level, one outcome of effective incident response is to avoid future unmitigated incidents from an issue that has been previously identified. Tracking the occurrence of these repeated incidents is a key metric to assess the effectiveness of incident response processes.
9. **Operations Center Downtime:** Hours or days of downtime for the operations center functions. With redundant operations center facilities, an individual facility may be down without any loss of operations center functionality. Thus, the focus of this metric is on continuity of operations, rather than any individual facility. This provides an assessment of the operational resilience for the operations center.
10. **Fleet Downtime:** Hours or days of downtime for the AV fleet. While causes of fleet downtime may be unrelated to operations center effectiveness, operations center functions, such as incident response and remote monitoring, should support fleet uptime.

Aligning AV stakeholders on a set of relevant top-line metrics for operations centers is a critical step toward developing safe and effective AV operations centers in support of widespread AV fleets. The metrics and discussion presented above serve as a starting point toward this alignment, and a foundation for a broader, common framework for assessing AV operations center performance.

Remote Assistance Triggers or Interventions have been proposed as an alternative metric for disengagements, which has become deprecated because it does not extend to operations without a safety operator in the vehicle and is inconsistently applied across AV fleets.

Remote Assistance Triggers or Interventions are not recommended metrics in this report for a similar reason. In most cases, since the vehicle remains responsible for safety outcomes at all times, remote assistance interventions are in place for risk mitigation while maintaining efficient operations. As such, depending on acceptable risk tolerances for vehicle decision-making, two fleets of identical vehicles could have different implementations such that one prompts for remote assistance support significantly more often than the other.

For example, a common remote assistance trigger occurs in situations where another vehicle is blocking a two-lane road and the AV must cross a double-yellow lane marking in order to proceed. The remote assistant is providing permission for the AV to proceed. Without the remote assistant, the AV would typically remain stopped until the blocking vehicle clears. A fleet operator may have extensively tested their vehicle's ability to identify a safe and appropriate path around a blocked vehicle and opt to remove the request for remote assistance in this case, such that the vehicle executes this behavior fully autonomously.

Although the scenario may occur an equal number of times, with the same safe outcome under each occurrence, there would be a drastic difference in the quantity of remote assistance triggers and interventions. The difference in these numbers provides no indication of vehicle or system performance, but only the differing risk tolerances between the fleet operators. An operator whose fleet experiences more remote assistance triggers may be operating a safer system than one with fewer triggers.

Appendix B: Acronyms

AAR	after-action review
AC	aircraft commander
AI	artificial intelligence
AOA	angle of attack
AOC	airline operations center
ATC	air traffic control
AV	automated vehicle
CAD	crime analysis division
COOP	continuity of operations
CS	customer success
CX	customer experience
DDT	dynamic driving task
DFR	drone as first responder
EOC	emergency operations center
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FEVS	Federal Employee Viewpoint Survey
FPS	frames per second
HICS	Hospital Incident Command System
HITL	human-in-the-loop
HMI	human-machine interface
HW/SW	hardware/software
IC	incident commander
ICS	incident command system
ICU	intensive care unit
ILS	instructor-led sessions
MCAS	Maneuvering Characteristics Augmentation System
AVRC	AV Research Collaborative
MRC	minimal risk condition
MRM	minimal risk maneuver
NDT	non-driving task
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NSFT	nursing system float team
PFD	primary flight display
PIR	post-incident review
RA	remote assistant
RTCC	Real Time Crime Center
SIMEX	simulation experiment
SME	subject matter expert
SOC	security operations center
SOP	standard operating procedure
TOT	take-over-time
TRUSTS	Transform with Resilience during Upgrades to Socio-Technical Systems
TTX	tabletop exercise
UAS	unmanned aircraft system
VMT	vehicle miles traveled
VR	virtual reality
VRE	vehicle recovery event

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