From Production Challenges to Logistics Solutions: A Multi-Layered Analysis of Autonomous Vehicle Integration Using the Tesla Manufacturing Case

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Autonomous vehicles (AV), commonly known as self-driving vehicles, are vehicles capable of operating and navigating without human intervention. AVs utilize a wide range of technologies including sensors, cameras, radar, LiDAR (light detection and ranging), GPS, and advanced algorithms to perceive their environment, interpret data, and make decisions to safely navigate to their destination.

Recent advancements in sensing technology, parallelized computing (in the form of high-performance GPUs and ASICs), and artificial intelligence (AI) have fueled investment into AV development by technology and automotive firms. Low level AV technology can be found in most passenger cars today as crucial safety features such as lane keep assist and automatic emergency braking.

However, as the technology keeps advancing, autonomy systems are taking an increasingly greater role as the primary driver of vehicles. Automaker Tesla announced the release of unsupervised full-self driving features as early as 2025 with other technology firms such as Google Waymo and General Motors cruise already offering full self-driving autonomous taxis in select American cities.

AV technology requires vast quantities of real-world data to train algorithms and generate accurate maps of operating environments. A safe, controlled method of data collection involves deploying AVs on frequently repeated routes where environmental unpredictability is minimized. Given these conditions, logistics – specifically in last-mile and long-haul delivery – emerges as a promising area for the initial deployment of high-level AVs.

The logistics sector is a vital component of the global economy, responsible for transporting goods from origin to destination. Long-haul logistics typically involves transporting goods over long distances in large semi-trucks, with over 95% of routes occurring on highways and interstates (U.S. Department of Transportation, 2022). Last-mile delivery completes this process by transporting goods from local hubs directly to customers' doorsteps. Both stages are characterized by predictable, frequently repeated routes, reducing the complexity of navigation and planning for AVs. Additionally, the highway-dominated routes in long-haul logistics mitigate the unpredictability of urban environments, making them especially suitable for AV implementation.

The estimated total addressable market (TAM) for AVs is expected to grow by over 30% from USD 2000 billion in 2023 to over USD 13,000 billion in 2030 (Fortune Business Insights, 2024). To capture market, companies will race to be first to market in any AV medium – including logistics. Furthermore, by deploying to initial AV markets like logistics first, companies can quickly gain a competitive data advantage allowing them to deploy their solutions to other more challenging AV media – such as passenger cars. However, the rush to market, fueled by this AV "hype," risks compromising safety and societal well-being, aggravating road congestion, pollution, and safety issues (McCarroll & Cugurullo, 2022).

Approach to Resolution

This paper employs the Multi-Layered Perspective (MLP) framework, developed by Frank W. Geels, to analyze the complex interactions across different sociotechnical layers involved in technological transitions. By examining Tesla's "production hell" period as a case study, this paper identifies the role of niche innovation, regime practices, and landscape pressures in shaping the adoption of high-level automation in manufacturing. This approach is then applied to the deployment of autonomous vehicles (AVs) in logistics, where a similar interplay among technological innovation, regulatory and industry norms, and societal expectations is emerging.

Central Claim

This paper argues that the adoption of AV technology in logistics requires careful alignment among key actors and MLP layers to prevent issues similar to those encountered in Tesla's automated manufacturing ramp-up. Specifically, it claims that while niche innovations in automation and autonomy can push industries toward rapid adoption, insufficient consultation with relevant actors – such as displaced drivers in logistics – can lead to operational setbacks and social resistance, compromising the intended benefits of AV technology.

Research Approach Overview

To support this claim, the paper first examines Tesla's case, illustrating how pressures from each MLP layer led to over-automation and production challenges. It then applies these insights to the logistics sector, highlighting parallels and potential pitfalls in AV deployment. By mapping MLP interactions in both contexts, the paper provides evidence that overlooking displaced actors and prematurely adopting untested technologies may hinder sustainable AV integration. The analysis concludes with recommendations for stakeholder involvement and incremental testing to align the logistics sector's AV adoption with broader societal and operational goals.

Problem Definition: Understanding the emergence of negative externalities for AVs in logistics

Autonomy currently exists in many forms for road going vehicles. As mentioned earlier, technologies such as lane keep assist, automatic emergency breaking (AEB), auto parking, and highway autopilot can be found in the average economy car. These technologies have been found to greatly improve the safety of vehicles with a 2023 Insurance Institute for Highway Safety (IIHS) showing AEB can result in a 50% reduction in police-reported rear-end crashes (Mueller et. al., 2024). Several regulatory agencies, such as the National Highway Traffic Safety Administration (NHSTA) are requiring certain driver assistance features in every passenger car sold 2029 onwards (National Highway Traffic Safety Administration, 2024). However, it is important to make the distinction between driver assistance autonomy features and full self-driving autonomy where the latter intends to completely replace the human driver.

According to Professor Steven Zoepf, an automotive researcher at Stanford's Mechanical Engineering Lab, current autonomous driving systems can handle approximately 90% of driving scenarios. The last 10% consists of edge case situations – unpredictable or rare driving scenarios that fall outside the standardized patterns these systems are designed to manage (Sacks, 2018). As noted by Kodiak Robotics at CVPR 2023, “For driver assistance, nominal driving matters most. For driverless autonomy, edge case behavior matters most” (The Tenyks, 2023).

These challenging edge cases often involve unique perception difficulties, such as identifying obscure objects or interpreting signals in poor visibility, as well as prediction challenges like anticipating sudden, unusual behavior from other drivers (view Figure 1). Additionally, unique road layouts or unmapped environments further complicate navigation, making these edge cases a primary focus of ongoing research aimed at refining and enhancing autonomous vehicle reliability.

Waymo Perception Edge Case

Figure 1: An edge-case scenario where the reflection of an SUV off an adjacent bus may cause perception difficulties (Adapted from Arnoud, 2018).

The best approach to tackling this final 10% is a subject debate among experts. Some advocate for a camera-only vision approach – a stance upheld by Tesla Motors – over the use of more advanced perception sensors like lidar and radar, and some favor an end-to-end neural network solution instead of a hybrid approach that combines neural and traditional analytical algorithms (Arnoud, 2018).

However, regardless of the approach, solving the last 10% of autonomy is ultimately a data acquisition game. Tuning and training autonomy algorithms to respond effectively to edge case scenarios requires vast amounts of diverse, high-quality data. As shown in Figure 2, the more data is collected, the greater the overlap between potential edge cases and available data, enabling autonomous systems to handle a broader range of rare scenarios. To address scenarios that may never occur naturally, companies turn to simulation to generate synthetic data. However, simulations can't fully capture real-world complexity, so large volumes of real-world data are still essential for validating these models (Li et. al., 2023).

Visualization of the vast expanse of Edge Cases yet to be covered by collected data

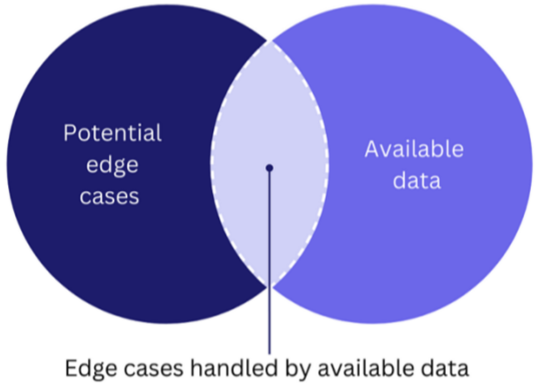

Figure 2: Available data does not cover all the possible edge cases AVs my experience (Adapted from The Tenyks, 2023).

This limitation of autonomous vehicles is evident in the current deployment of autonomy solutions. Autopilot systems like Ford's BlueCruise and General Motors' SuperCruise – designed to go beyond traditional driver assistance by taking full control of the vehicle in certain conditions – are restricted to specific highways that have been pre-mapped to centimeter-level precision using high-resolution sensors. Similarly, autonomous ride-hailing services like Google's Waymo, General Motors' Cruise, and Amazon's Zoox operate only within specific, geolocked areas of cities that are continuously mapped by the companies (Arnoud, 2018). By building high-fidelity maps of the environments in which these systems operate, current AV solutions minimize environmental unpredictability and reduce the likelihood of encountering edge cases.

As mentioned earlier, the logistics sector is considered a prime candidate for the initial deployment of AVs. Long-haul delivery routes in logistics occur over 95% on highways, where the absence of complex intersections and pedestrians, along with smooth road flow, provides a more predictable environment and reduces the likelihood of encountering edge cases (U.S. Department of Transportation, 2022). Last-mile logistics, though taking place in more urban and chaotic settings, often involves frequently repeated routes, allowing for prior mapping that enhances predictability. Consequently, many companies are heavily investing in deploying AV systems in logistics.

A recent market analysis of autonomous vehicles in the last-mile segment of the American logistics system projects the total addressable market (TAM) to grow from around 1.1 billion USD in 2024 to over 7.2 billion USD by 2030 (S&S Insider, 2023). This growth reflects a compound annual growth rate of over 23%, significantly outpacing the standard S&P market growth rate of approximately 10%.

Data acquisition provides a powerful incentive for companies to be first to market with AV solutions in logistics. By deploying AV systems in real-world logistics operations, companies can gather the extensive data needed to refine and enhance their autonomy algorithms for other AV applications as well. This closed-loop software iteration cycle enables continuous improvement in a company's autonomy solutions, creating a compounding advantage that strengthens its AV market position. Consequently, companies that lead in AV logistics deployment gain a significant competitive advantage in the entire AV space.

In response, companies such as Tesla, Rivian, and Kodiak have pioneered the beta testing of AVs in logistics, arguing that the sector can be vastly improved with autonomy by minimizing operational costs, enhancing safety, and overcoming the limitations of human drivers – such as wages and limited working hours. A study examining the impacts of autonomy in logistics further supports these claims, suggesting that AVs could also increase road capacity through efficient platooning and reduce pollution (Medina-Tapia & Robusté, 2018). However, deploying AVs without involving key actors, especially drivers and operators, risks compromising safety and societal well-being, potentially exacerbating problems like road congestion and pollution – issues that AVs are intended to alleviate (McCarroll & Cugurullo, 2022).

Research Approach: Mapping failures of over autonomy in manufacturing to autonomy in logistics using the multilayer perspective

The case study: Tesla Production Hell

In the spring of 2016, Tesla Motors – a relatively small automaker at the time – unveiled the Model 3, a fully electric, mass-market car with a starting price of $35,000. This marked an audacious shift in Tesla's strategy as up until this point, the company had only produced low-volume, high-end electric vehicles like the Model S, Model X, and Roadster. Despite having delivered just 125,000 cars in total since its IPO in 2008, Tesla announced plans to scale Model 3 production to an unprecedented 500,000 vehicles per year by the end of 2017 (Tesla, Inc., 2017). To achieve this ambitious production ramp up, Tesla envisioned an automotive factory of the future with almost every part of the manufacturing assembly line automated (Musk, 2016).

Tesla assumed that high automation in manufacturing would improve assembly line efficiency, as robots excel at performing simple, high-frequency tasks with precision. However, this heavy reliance on automation nearly bankrupted the company, plunging Tesla into a dark chapter now known as "production hell" – a period marked by relentless setbacks, bottlenecks, and intense pressure to meet production goals. Interviews with Tesla leadership revealed that over-automation was to blame. CEO Elon Musk noted, “We had too many robots… we had a complex system of conveyor belts, and we had to get rid of all of it” (King, 2018).

Research Approach Framework

This research aims to follow the multi-layered perspective (MLP) model outlined by Frank W. Geels in “Transformations of Large Technical Systems: A Multilevel Analysis of the Dutch Highway System (1950-2000).” Geels’ work explores how large, complex sociotechnical systems evolve and adapt to new technologies over time. His study uses the Dutch highway system from 1950-2000 as a case study to understand how transformations within these systems occur.

The primary challenge addressed is the integration of innovative technologies into existing sociotechnical systems. Geels examines how the dynamics between emerging innovations (niches), established practices and regulations (regimes), and broader societal pressures (landscapes) interact to shape the trajectory of these systems. By mapping how these three levels interact, Geels highlights areas of alignment or misalignment that can significantly impact the integration process.

Geels argues that technological transitions are not linear but result from the interplay between these three layers, which can either facilitate or hinder integration. This structured analysis provides insights into how technological transitions can be managed and improved.

A Visual Depiction of the Multi-layered Perspective

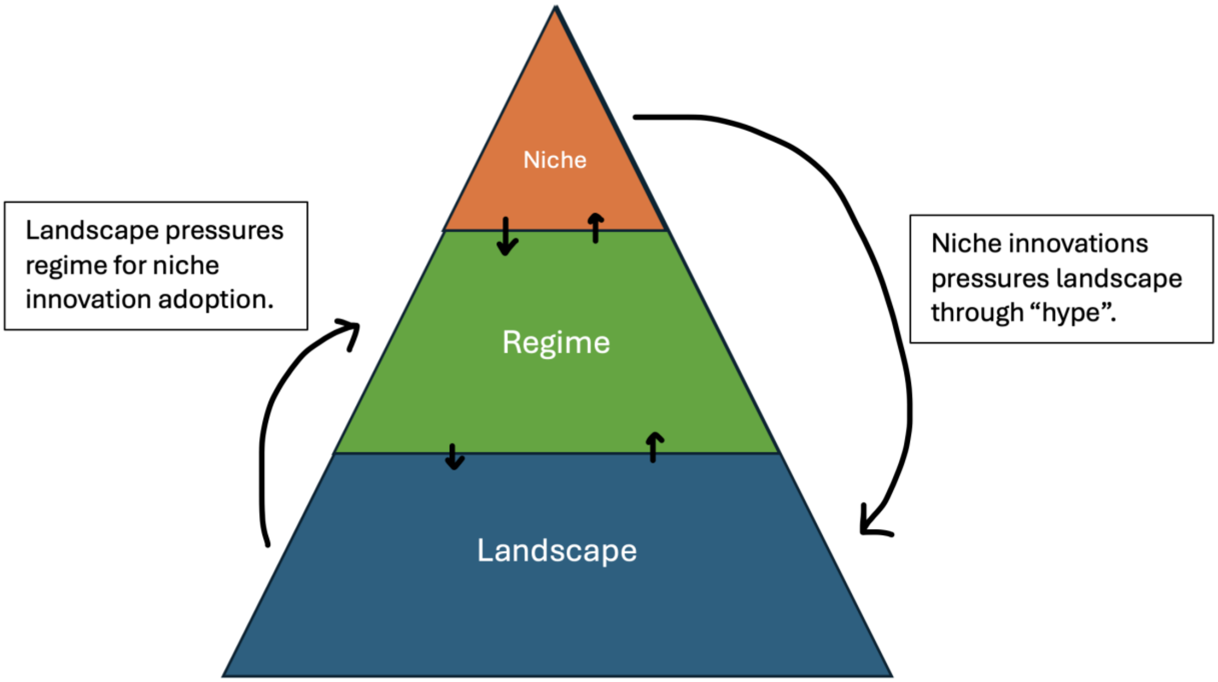

Figure 3: A visual depiction of the 3 layers in the multi-layer perspectives. The black arrows show inter-layer interactions with two possible problematic interactions described in the text boxes.

Research Approach Used

This paper applies the MLP framework to the 2018 Tesla Model 3 "production hell" to examine how an over-reliance on automation led to problematic interactions between the niche, regime, and landscape levels, nearly resulting in Tesla's bankruptcy. After analyzing these misalignments, the paper further applies the MLP framework to autonomous vehicle (AV) deployment in logistics to determine which lessons can be transferred. Geels' approach is promising for this research, as it enables a comprehensive analysis of the interactions between technological innovation and existing systems, making it possible to identify and align key actors and actions needed for effective R&D and deployment of AV systems in logistics.

The Research Approach as a list of Sequential Steps

1.	Fit the Tesla “production hell” case study to the MLP framework by identifying the 3-layers (niche, regime, and landscape).
2.	Identify the interactions between the 3-layers in the Tesla manufacturing scenario utilizing the MLP.
3.	Identify problematic inter and intra layer interactions which in the Tesla manufacturing MLP analysis.
4.	Fit the current AV in Logistics field to the MLP framework by identifying the 3-layers (niche, regime, and landscape).
5.	Map MLP interactions between the Tesla manufacturing scenario and AVs in logistics keeping not of similar problematic interactions.
6.	Identify key actors which should be involved with the deployment of AVs in logistics to avoid MLP layer misalignments.

Table 1: Identifies the sequential research approach this study utilizes.

Results: Insights and Lessons for Autonomous Vehicle Deployment in Logistics

Fitting the Tesla "Production Hell" Manufacturing Period to the Multi-Layered Perspective

The Tesla Model 3 was widely anticipated as a groundbreaking car, embodying not only advanced electric vehicle (EV) technology but also the promise of full autonomy, with the hardware to enable self-driving capabilities in future software updates. This vision, combined with new electric permanent magnet motors and an innovative battery architecture delivering over 300 miles on a single charge, solidified societal expectations for the Model 3 to become the car of the future (Musk, 2016). Positioned at an accessible $35,000 price point, these expectations from the public, media, and Tesla itself created a strong landscape-level pressure. Furthermore, Tesla's mission to "accelerate the transition to sustainable energy" aligned with this, raising the stakes for the Model 3's success as a mass-market EV.

In the regime layer, Tesla's ambitious choice of a fully automated factory, following Elon Musk's vision of a high-speed, robot-dominated "alien dreadnaught," reflects a significant departure from established automotive manufacturing norms. Aiming to scale production by over 3000% in one year, Tesla sought to redefine mass production through automation, an approach that would bring unforeseen obstacles. Musk later admitted, "the problem with cars is production; it's 99 percent of the difficulty" (Weber, 2023).

At the niche level, high-speed automation technology, enhanced by machine learning (ML) algorithms, was central to Tesla's manufacturing strategy. While machines excel at high-precision, repetitive tasks, Tesla pushed the frontier by applying ML techniques to allow robots to perform more adaptive roles, handling tasks like part identification and assembly in real time. For instance, instead of simply instructing a robot to tighten a bolt in a fixed position, attempt to leverage ML-driven vision systems that could locate and identify bolts autonomously. This shift from fixed automation to adaptive, ML-enhanced automation represented a novel development in the manufacturing niche, though one that ultimately exposed the limitations of the technology under the intense pressures of mass production.

The Multi-layer Perspective breakdown for Tesla Model 3 Manufacturing

MLP Layer	**Tesla Manufacturing Case**
Niche	Automation in manufacturing, novel improvements in machine learning.
Regime	Automotive manufacturing with an excessively ambitious production ramp requirement.
Landscape	The Tesla Model 3 was expected to be the most technologically advanced car on the market.

Table 2: A multi-layer perspective analysis of the Tesla's "production hell" period. Shows the identification of the three major layers – niche, regime, and landscape.

<u>Result 1: Niche innovations can induce "hype" in the landscape pressuring regime adoption</u>

A major driving force for the adoption and development of novel autonomy for Tesla's Model 3 factory was the existence of niche innovations – robotics and AI – theoretically capable of replacing assembly line workers. As mentioned above, the general assumption that the Model 3 will be the most advanced automobile pressured Tesla, the regime, to create the most advanced factory to produce it (Weber, 2023). This pressured Tesla's manufacturing landscape to rapidly embrace autonomy, leading to the creation and deployment of several novel innovations despite their untested reliability at scale.

<u>Result 2: Consultation of pertinent actors and displaced actors is important</u>

In an interview, Elon Musk highlights a task from the Model 3 production line that illustrates the difficulties robots face with tasks humans find straightforward. This task involves reaching into the partially assembled vehicle to connect two dangling wires above the center console near the rearview mirror – a trivial action for any human. However, for a robot, this process requires a series of precise steps: awkwardly maneuvering through a narrow opening in the partially built car, accurately locating and identifying the ends of the two wires, securely gripping them, correctly orienting each wire, and completing the connection reliably. Musk notes that after many failed attempts and production bottlenecks, autonomy was entirely abandoned for this task.

Effective collaboration between experienced assembly line workers and the engineers developing automation could have surfaced potential issues in the autonomous wire connection solution before significant resources were invested. Specifically, by reviewing the robots' intended steps for connecting the wires, assembly line workers might have identified key challenges early on. For instance, they could have pointed out that the robots were too bulky to operate with the necessary dexterity within the vehicle's limited space or that the wires may not always be easily visible, leading to inefficiencies or errors.

Tesla's initial over-reliance on automation during the Model 3 production led to significant challenges, prompting the company to revert to traditional manufacturing processes in certain areas. Musk acknowledged that "excessive automation at Tesla was a mistake" and that "humans are underrated" (Wong, 2018). However, this experience did not diminish Tesla's commitment to automation. The company continues to operate some of the most automated manufacturing plants globally, contributing to its position as the only profitable electric vehicle manufacturer, largely due to its innovative production techniques (Weber, 2023).

Fitting autonomous vehicles in logistics to the Multi-Layered Perspective

Applying the Multi-Level Perspective (MLP) to autonomous vehicles (AVs) in logistics reveals a dynamic interplay across its three layers. At the niche level, companies are actively developing and testing AV technologies through pilot programs, focusing on innovations like self-driving trucks and delivery robots. For instance, Aurora Innovation and Kodiak Robotics have launched fully autonomous trucks in Texas, aiming to transform freight transportation (Sacks, 2024). The regime encompasses established logistics practices, regulatory frameworks, and industry stakeholders such as trucking companies and supply chain managers. These entities are beginning to integrate AV technologies to enhance efficiency and fleet safety. The landscape includes broader societal factors, including sustainability goals, economic trends, and public acceptance of AV technology. The push for greener logistics solutions and the potential for cost reductions are driving interest in AVs, while public trust and regulatory readiness continue to shape their adoption trajectory. This MLP layer mapping is summarized in table 3.

The Multi-layer Perspective breakdown for Autonomous Vehicles for road Logistics

MLP Layer	**AVs in Logistics long haul and last mile delivery**
Niche	Development of AV technology for road vehicles.
Regime	Regulatory bodies, infrastructure and automotive industry players, and logistics practices for long haul and last mile delivery.
Landscape	Sustainability goals, economic trends, and the public acceptance of AV technology.

Table 3: A multi-layer perspective analysis of AVs in logistics. Shows the identification of the three major layers – niche, regime, and landscape.

Mapping MLP interactions between the Tesla manufacturing case and AVs in logistics long haul and last mile delivery

A notable parallel exists between the Multi-Level Perspective (MLP) interactions in Tesla’s manufacturing challenges and the adoption of autonomous vehicles (AVs) in logistics. In

Tesla's case, societal expectations for the Model 3 to be the most technologically advanced vehicle, combined with the hype surrounding novel automation technologies, exerted pressure on the manufacturing regime to adopt these innovations rapidly. This led to significant production challenges, as the manufacturing processes were not fully prepared for such advanced automation.

Similarly, in the logistics sector, there is a growing emphasis on sustainability and environmental responsibility, driven by societal concerns and regulatory goals. Innovations in AV technology, such as synchronized platooning – where vehicles travel in convoys to enhance fleet efficiency – and reduced vehicle traffic, align with these landscape pressures. However, this alignment may pressure the logistics industry to prematurely integrate AV technologies into long-haul and last-mile delivery operations. Without thorough testing and validation, such premature adoption could lead to operational inefficiencies and safety concerns.

Another parallel concerns the potential oversight of displaced actors. In Tesla's manufacturing scenario, insufficient consultation with assembly line workers during the automation process led to production bottlenecks and inefficiencies. Similarly, in logistics, vehicle drivers are primary stakeholders who may be displaced by AV technologies. Actively involving these drivers in the design, development, and deployment of AV systems is crucial. Their practical Insights can help identify potential challenges and ensure smoother integration of autonomous technologies. Neglecting their input could result in unforeseen operational issues, mirroring the challenges faced by Tesla.

An overview of the mapping between the Tesla Manufacturing MLP and the AVs in Logistics MLP

Result	Tesla Manufacturing Case	AVs in Logistics Case
Result 1: Niche innovations can induce “hype” in the landscape, pressuring regime adoption	Landscape pressures, including societal expectations for the Model 3 as the “car of the future” and the appeal of novel automation, pushed Tesla’s manufacturing regime to adopt ambitious automation.	Sustainability and environmental concerns in the logistics landscape, alongside AV innovations (like platooning), may pressure logistics operations to adopt AV prematurely.
Result 2: Consultation of pertinent actors and displaced actors is important	Limited consultation with assembly line workers led to automation-related bottlenecks in Tesla’s production. Engaging workers might have highlighted practical issues earlier.	Vehicle drivers are key stakeholders potentially displaced by AVs in logistics. Their insights on practical challenges could aid in smoother integration of AV technologies.

Table 4: A summary of the mapping between the Tesla manufacturing MLP interactions and the AVs in logistics MLP interactions.

Conclusion

This paper argues that autonomous vehicle (AV) adoption in logistics demands an integrative approach across niche innovations, regime practices, and landscape pressures to prevent pitfalls similar to those in Tesla's over-automated manufacturing experience. In both cases, niche innovations – whether in robotics or autonomous driving – create momentum within their industries. However, a lack of coordination with key stakeholders, such as displaced drivers in logistics, may create barriers, introducing risks to operational continuity and eroding public acceptance. The central claim is that comprehensive alignment among pertinent actors across the Multi-Layered Perspective (MLP) framework is essential to achieve successful and responsible deployment of AV technology in logistics.

The implications of this research emphasize the need for AV technology in logistics to proceed with structured testing, transparent communication, and collaboration with relevant actors. Proactive engagement with stakeholders, particularly vehicle operators and regulatory bodies, is crucial to preemptively address potential challenges, ensuring smoother implementation and minimizing disruptions. Moreover, involving displaced actors like drivers may help address critical operational and safety issues that could otherwise go unnoticed, facilitating a balanced integration of AVs into logistics. For instance, drivers' insights into practical driving challenges can enhance the adaptability and reliability of AV systems. By transferring lessons from Tesla's experience, logistics companies can develop AV strategies that support efficiency and innovation while maintaining workforce and public trust.

Practically, this research suggests that a phased AV deployment approach in logistics could allow companies to manage risks effectively while achieving early benefits in efficiency and environmental sustainability. Initial AV applications could focus on highly controlled, repetitive routes, such as highway-based long-haul transportation, before scaling to more complex urban environments. Furthermore, AV technologies like synchronized platooning could improve traffic flow and fuel economy, directly addressing sustainability goals. This phased integration would provide logistics companies with valuable data and insights while allowing gradual regulatory adjustments, easing the transition for all stakeholders.

However, a significant limitation in applying AV technology to logistics is the issue of public safety, as these vehicles will operate on public roads shared with unconsenting individuals. Unlike Tesla's manufacturing setup, logistics AVs introduce a broader arena of actors – the public – whose concerns over safety, privacy, and environmental impact must be addressed. Any AV deployment in logistics, therefore, requires not only technical reliability but also a strong emphasis on public communication, education, and regulatory oversight. The logistics sector must balance the potential benefits of AVs with the responsibility to protect public well-being, particularly as it encounters scenarios that test AV technology in diverse, real-world conditions.

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