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Advancing Autonomous Vehicle Regulations in India: A Comparative Analysis and Global Engineering Insights

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Abstract: ***The invention, growth and popularity of autonomous vehicles (AVs) represents evolution of transportation, offering significant potential to enhance road safety, optimize efficiency, and reduce environmental impact. While many developed nations have embraced AV technology through well-defined regulatory frameworks, India's AV sector is still in its nascent stages, with substantial challenges in policy and infrastructure impeding its development. This paper conducts a critical analysis of India's existing regulatory landscape for autonomous vehicles, examining key socio-political, economic, technological, environmental, and legal (PESTEL) factors that influence the feasibility and adoption of AVs. Through a comparative benchmarking study, we evaluate the regulatory frameworks of leading countries—Singapore, the Netherlands, and Norway—each renowned for its progressive AV policies and high readiness for autonomous technology. Using the World Bank Handbook model on Infrastructure Regulatory Systems, this paper identifies key regulatory parameters such as autonomy, transparency, stakeholder representation, and financial independence to assess regulatory effectiveness. The analysis reveals a huge contrast between India's current regulatory readiness and the advanced policies in countries leading the AV space. While these global frameworks prioritize structured testing, licensing, liability guidelines, data protection, and public safety, India lacks a unified approach to address these important aspects. This study proposes a series of actionable recommendations tailored to India's unique context, including the establishment of a dedicated AV regulatory authority, promotion of AV technology through public awareness and educational initiatives, and the formulation of liability and insurance guidelines specific to autonomous operations. Additionally, policy suggestions to strengthen data protection, ensure public safety, and facilitate structured AV testing in designated zones are provided to guide India's AV adoption. This paper aims to bridge the regulatory gap by offering a framework of best practices that combines India's specific needs with international insights, providing policymakers and engineers with strategic guidelines to advance India's preparedness for autonomous transportation and engineering. By adopting these recommendations, India can better harness the potential of AVs to transform its transportation ecosystem, promoting sustainable, safe, smart and efficient mobility solutions for the next decade. This paper aims to bridge the regulatory gap by offering a framework of best practices that combines India's specific needs with international insights, providing policymakers and engineers with strategic guidelines to advance India's preparedness This paper aims to bridge the regulatory gap by offering a framework of best practices that combines India's specific needs with international insights, providing policymakers and engineers with strategic guidelines to advance India's preparedness for autonomous transportation and engineering. By adopting these recommendations, India can better harness the potential of AVs to transform its transportation ecosystem, promoting sustainable, safe, smart and efficient mobility solutions for the next decade.***

Keyword: ***Automobile Industry, Autonomous Vehicles, Framework, Recommendations, Qualitative Analysis tools, AV Technology, Opportunities Surrounding.***

List of Abbreviations

Sr no.	Abbreviation	Full form
1	AV	Autonomous Vehicle
2	EV	Electric Vehicle
3	DAVI	Dutch Autonomous Vehicle Initiative
4	DMV	Department of Motor Vehicle California
5	ATL	Automatic Trailer Loading
6	GM	General Motors
7	CAGR	Compound Annual Growth Rate
8	Bn	Billion
9	RDW	Dutch Vehicle Authority

I. INTRODUCTION

This article revolves around the implementation of autonomous vehicles in India and the laws and benchmarks that need to be framed for their smooth inculcation into the Indian motor fleet. To devise this, we first analyse important information pertaining to autonomous vehicles, their use cases evolution etc. We then move on to the legislation of leading countries pertaining to autonomous vehicles and then draw a set of guidelines for our country. Autonomous vehicles are defined as vehicles that are capable of sensing their environment and functioning without human interference. A human passenger is not required to take control of the vehicle at any point, nor is he required to be inside the vehicle. An AV can drive like a traditional car does and do everything the driver does. The global revenue (market size) of AVs in 2020 was USD 23.33 bn. It shrunk by 3.3% (USD 24.1 bn) compared to 2019 and is expected to grow by 59.33% (USD 37.22 bn) in 2021 and by 80.2% (USD 42 bn) by 2025 [1]. The global AV market shrunk by 3.3% from value in 2019 to value because of the COVID-19 pandemic.

However, all the industries including automobiles are

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expected to recover in 2020 and are expected to grow by 59.33% in
2023. Reduction of road accidents, convenience for the old and disabled and reduced level of pollution levels are the drivers of the AV market.

While lack of knowledge about AV technology, potential loss of employment in the public transport sector and lack of legal & regulatory framework are the inhibitors of the AV market [2].

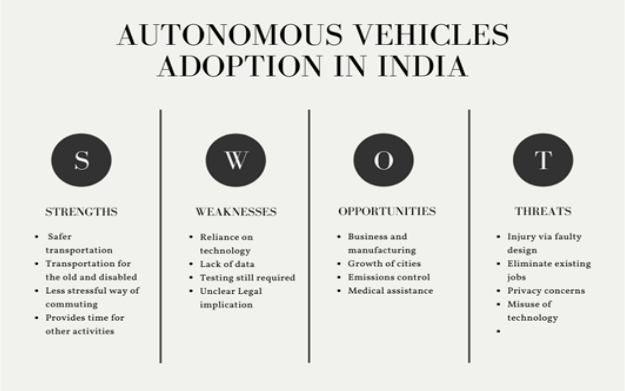
A. Evolution of AV Technology and Recent use Cases

The history of autonomous vehicles (AVs) dates to 1500, when Leonardo Da Vinci designed a self-propelled cart, which many consider the world's first robot. This was followed by the development of the first self-propelled torpedo by Robert Whitehead in 1866, based on Giovanni Luppis' initial design. In 1933, Mechanical Mike Aircraft Autopilot debuted, allowing Wiley Post to become the first person to fly solo around the world. This system used gyroscopes and operated without electricity, relying on compressed air and hydraulic pressure. In 1939, Norman Bel Geddes created the first AV for GM, an electric car guided by radio-controlled electromagnetic waves from magnetized metal spikes in the road. By 1958, GM made this concept a reality, with the car's front end detecting currents from the spikes to steer. During WWII, Ralph Teetor developed cruise control, leading to the 'speedostat' by 1955, which allowed drivers to set and maintain a specific speed. In 1961, James L. Adams invented the 'Stanford Cart' for research on remote vehicle control using video information. Tsukuba Mechanical Engineering introduced lane technology in 1977, creating a car that could track white strips and travel at 50 kph.

In 1980, aerospace engineer Ernst Dickmanns and his team conducted autonomous-driving tests using a Mercedes-Benz van, advancing to autonomous test drives in the 1990s [3]. Rapid development by companies like Tesla, Google, and Waymo occurred in the 2000s. Tesla commercialized Level 2 autonomous technology in 2015 with cars featuring auto-parking and 'autopilot' capabilities. In 2020, Waymo partnered with Jaguar to commercialize Level 3 autonomous cars, planning to roll out 20,000 models of Jaguar's electric SUV with autonomous technology over five years. AVs have expanded beyond consumer attention, integrating into various global industries. The agriculture robotics sector, valued at USD3 billion currently, is projected to grow to USD26 billion by 2026.

In India, Mahindra & Mahindra lead with semi-autonomous and fully autonomous tractors capable of tasks like ploughing and seeding without human intervention. Retail giants like Target are exploring robotic solutions for in-store assistance and product retrieval. AVs have been utilized in warehouses since 2005, with top-tier facilities employing guided carts and automatic trailer loading systems. Initiatives in China and the Netherlands have piloted autonomous shuttles and public vehicles on roads. Waymo plans to deploy 62,000 Chrysler Pacifica minivans in Phoenix for a ride-hailing service, while nuTonomy, now under Delphi, collaborates with Lyft to launch robot taxis in Boston [4].

B. SWOT Analysis of AV Adoption in India



[Fig.1: Autonomous Vehicles SWOT Analysis] [4]

C. Specific Advantages of AVs

Utilizing AI, autonomous vehicles (AVs) are expected to significantly reduce accidents due to their precision and dynamic capabilities. The NHTSA (National Highway Traffic Safety Administration) conducted a crash causation study of accidents between July 3, 2005, and December 31, 2006. According to the investigation, 40.6% of the 5096 accidents were due to lack of attention, such as insufficient surveillance and internal/external distractions. Another 34.1% resulted from judgment errors, such as misjudging other vehicles' speeds and driving excessively fast, and 10.3% were due to execution mistakes. AVs' advanced sensors mitigate these risks. Driver mood, including anger, frustration, and exhaustion, also contributes to accidents, but AVs are unaffected by these emotional states. AVs offer substantial fuel savings through eco-driving practices. Unlike human drivers, who often accelerate and brake non-uniformly, AVs can maintain consistent driving behaviours, reducing energy wastage. Idling during traffic stops and road rage also contributes to fuel inefficiency. Studies indicate eco-driving practices, such as continuous traffic sensing and telematics, can save 10-12% in fuel consumption. Gridlocks, which significantly waste fuel, can be mitigated by AVs communicating to maintain movement. Platooning, which reduces aerodynamic drag by up to 60%, benefits economies reliant on fossil fuels and positively impacts environmental pollution levels in developing cities. AVs also enhance lane capacity. Human-driven highways typically achieve a maximum throughput of about 2,200 vehicles per hour per lane, reflecting only 5% road space utilization. In contrast, AVs utilize road space more efficiently by better anticipating lead vehicle actions and requiring shorter perception and reaction times. This results in smoother braking, shorter vehicle-following gaps, and consistent high-speed travel. Unlike human drivers, AVs maintain performance in narrow lanes due to precise steering. AV technology also smooths traffic flow by mitigating destabilizing shock waves and enabling efficient vehicle platooning. At high market penetration, AVs can achieve advanced platooning, with multiple driverless trucks following a human-driven lead truck, reducing space between vehicles. AVs significantly benefit the elderly and disabled.

An estimated 25.5 million people in the U.S. have disabilities, leading to fewer

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trips outside their homes. According to the U.S. Department of Transportation's 2017 National Household Travel Survey (NHTS), 7 out of 10 respondents cited disabilities as a reason for avoiding travel, with one-third never leaving home due to paralysis. The commercialization of AVs would greatly benefit this demographic, providing easy and convenient transportation options [5].

D. Challenges Surrounding AVs

AVs manufactured in 2020 are expected to cost consumers an additional USD 75,000-100,000 compared to conventional cars, potentially exceeding USD 100,000 due to the complexity of sensor systems. These high costs suggest that AVs will likely find adoption primarily in Mobility as a Service (MaaS) applications such as ridesharing and robot-taxi fleets rather than as personal vehicles. Eliminating driver costs could support this high-price model. The increasing software complexity poses another challenge. Advancing to Level 4 and Level 5 AVs requires sophisticated and expensive sensors, driving consolidation towards powerful clusters of application processors and accelerators in performant multicore Systems on Chips (SoCs). This demands significant changes in software architectures to handle real-time algorithmic processing for interpreting surroundings and making safe decisions. Public acceptance is a critical hurdle; surveys indicate that 73% of Americans fear riding in AVs, and 63% feel less safe sharing the road with them while walking or cycling. Gaining the trust of both passengers and pedestrians is crucial. Safety remains paramount as control shifts from humans to complex computer systems, with any minor error potentially leading to accidents. Moreover, the lack of infrastructure is a significant obstacle.

AVs initially require an ideal driving environment with proper infrastructure and standardized traffic rules, which are often lacking in developing countries like India [6].

II. RESEARCH METHODOLOGY

The author has studied transportation and logistics management for 3 years. This ranges from public transportation to freight management. From the results of the SWOT analysis of AVs in India, it can be concluded that they are a safer, more efficient, cheaper and more advanced mode of transportation and all these strengths will be beneficial to public transportation as well as the freight industry. To ensure the smooth adoption of AVs in India, a framework needs to be drawn according to which AVs will be regulated in India. Following this is the literature review of the topic Some research papers were referred to using Google Scholar to acquire knowledge about the selected topic. The 2020 edition of KPMG's 'Autonomous Vehicle Readiness Index' was referred for the selection of countries for comparison since ranks countries based on 28 different and comprehensive measures. The framework used for policy comparison was adopted from the 'World Bank handbook' as it covers all the important aspects of the process of policymaking. Moving ahead with the qualitative analysis, the first qualitative tool selected for analysis was SWOT as it gives us insights into the Strengths, Weaknesses, Opportunities and Threats of a product/service/industry and is an early indicator of whether the industry will be successful in a particular region or not. The second tool selected for further analysis was PESTEL as it gives a more detailed overview by covering the Political, Economic, Social, Technological, Environmental and Legal Aspects of a country. This helps us figure out the challenges and opportunities of a particular industry in each aspect. Selection of the countries for regulatory analysis. The top 3 countries in the 2020 edition of KPMG's 'Autonomous Vehicle Readiness Index' [7] were chosen for policy comparison as this is one of the most legitimate and comprehensive reports on AVs and provides the most rigorous frameworks needed for their implementation. The comparison of the regulatory framework of Singapore, The Netherlands and Norway (top three countries in KPMG's index) using the World Bank's handbook framework on Infrastructure Regulatory Frameworks is then processed. This framework was chosen because it covers all aspects of a regulatory framework of a company/industry/country using 8 key factors. The key findings from the comparison were analysed and practices relevant to the Indian AV scenario were adopted. After analyzing the results from the regulatory framework analysis and reviewing the scenario in India for AVs, we have listed 6 recommendations and best practices that can be adopted for India's AV regulatory framework.

III. LITERATURE REVIEW

"A multi-criteria decision-making approach to study barriers to the adoption of autonomous vehicles" [8], March 2020, discusses how AV adoption relies heavily on policymakers and government action. They address challenges like infrastructure and public acceptance, using a 5-stage method to identify interlinked barriers and conclude this is the first transportation study integrating Grey-DEMATEL with systems thinking. "Adaptive governance of autonomous vehicles: Accelerating the adoption of disruptive technologies in Singapore" [9], April 2021, examines AV development in Singapore. They highlight safety, liability, and cyber-security risks, concluding that government collaboration with stakeholders and creating a supportive business environment is crucial for success. (Adaptive governance of autonomous vehicles: Accelerating the adoption of disruptive technologies in Singapore., 2021). "Public opinion on about Self-Driving Vehicles in China, Japan, US, UK and Australia" [10] surveys six countries and finds initial positive opinions about AVs, but high safety concerns. Most people want the technology but are unwilling to pay extra, unlike in India. (Schlotte & Sivak, 2014). "Investigating the Importance of Trust on Adopting an Autonomous Vehicle", October 2015, examines AV adoption using the technology acceptance model and trust theory. A survey of 552 drivers assesses AV usefulness and trust. "2020 Autonomous Vehicle Readiness Index" (KPMG), April 2021, assesses 30 countries' preparedness for AVs using 28 measures. India ranks 29th out of 30 countries. (KPMG, 2021). "Autonomous Vehicle Policy Framework: Selected National and Jurisdictional Policy Efforts to Guide Safe AV Development".

(WEF in collaboration with Israel Innovation Authority), November 2020, sets guidelines for evaluating AV regulatory frameworks, applied to Singapore, Norway, and The

Netherlands. (Autonomous Vehicle Policy Framework: Selected National and Jurisdictional Policy Efforts to Guide Safe AV Development., 2020). "Perceptions of autonomous vehicles: Relationship with road users, gender and age" by Lynn M. Hulse, Hui Xie, Edwin R. Galea, February 2018, examines the public perception of AV safety through a survey of 1,000 participants. It finds AVs are seen as riskier for drivers than pedestrians, with young adults and males more accepting. The study concludes it's too early to determine AV safety and social acceptance [11]. "Autonomous vehicles' disengagements: Trends, triggers, and regulatory limitations" by Francesca Favaro, Sky Eurich, Nazanin Nader, January 2018, discusses AV technology disengagements in the US and the regulatory challenges faced by the DMV [12]. “Legal aspects of autonomous vehicle” by Viktoria IIkova, Adrian IIka, 2017, provides information on AV regulation in Europe and the US, addressing benefits, necessary traffic rule changes, and challenges for lawmakers, insurance companies, and carmakers [13]. “Autonomous vehicle- No Driver? No Regulation?” by Shaun Kildare, Joan Claybrook, July 2018, raises concerns about road safety and advocates for immediate federal safeguards for AV testing and deployment. They warn that without common-sense protections, public rejection of AVs could negate safety benefits [14].

A. Research Gap

The Indian Government has taken robust and active steps to change the scenario of the automobile industry with the introduction and commercialization of EVs.

According to the trend observed in the countries which have already adopted EVs, AVs are the next step in evolution. To have a smoother and more successful transition from EVs to AVs than from ICE cars to EVs, India needs to be prepared for them. AVs are much for advanced than conventional human-driven vehicles. They involve a lot of complexities and hence can't be regulated with the same set of rules. Drawing a separate framework containing rules and regulations regarding AV would ensure smooth adoption, from the early stages of testing and licensing to the later stages of commercialization.

IV. ANALYSIS FOR REGULATION OF AVS

A. Importance of AV Regulation

Regulation is needed to protect the legitimate interests of businesses as well as the public. A strong regulatory framework not only keeps the specified industry relevant and helps gain the confidence of people towards it but also protects consumers, promotes the effective functioning of the industry and keeps the safety of other important factors such as the environment in check. According to a report published by Grand View Research in 2020, AVs have a global market demand of approximately 6.7 thousand units and are likely to grow at a CAGR of 67.3% from 2021-2030. They have high growth potential and are acting as a catalyst in the technological development of the world. But their adoption plan highlights four hurdles. Firstly, there is a lack of legal uniformity that could hurt customer receptiveness and make them sceptical about this technology. This in turn, could lead to sub-par adoption of this technology which would hurt the market share and growth of the industry Secondly the saving benefits of AVs can be lost due to a lack of knowledge about the technology on the consumer's end can lead to wastage of potential of AVs such as traffic reduction, improved fuel economy and reduced number of accidents. Thirdly, there could be concerns about Data Protection as AVs function on real-time data such as satellite navigation and personal information such as the location of the driver. Improper regulation can lead to theft, modification and destruction of such sensitive data. And lastly are the concerns surrounding safety, If proper tests and trials are not conducted according to a set of rules and regulations, faulty AVs could end up on public roads which could lead to traffic violations and accidents. Considering the importance of AVs in technological development, their market share, CAGR rate and the above-mentioned factors, we conclude that regulating AVs is important.

B. PESTEL Analysis of AVs in India

PESTEL is a qualitative analysis tool that is used to identify external macro forces facing an organization or industry. The letters stand for political, economic, social, technological, environmental and legal. Before framing any framework, situational analysis is very important. PESTEL enables us to conduct situational analysis comprehensively and efficiently. It helps successfully monitor and respond to changes in the macro forces to have a robust framework at every stage [15].

[Fig.2: Different Elements of PESTEL][15]

C. PESTEL Analysis: INDIA

Political factors-India has a federal government structure in which decisions on some subjects are taken by the Union government and some are taken by the state government. The Union lists comprise subjects such as citizenship, Armed forces and foreign affairs. The State lists comprise police, public health and water. Currently, the Union government is formed by Bhartiya Janta Party and Shri Narendra Modi is our Prime Minister. The automotive and vehicle regulations in India are governed by the Ministry of Road Transport and Highways (MoRT&H) which is the nodal ministry for the regulation of the automotive sector in India.

The Ministry has been active in promoting innovations in automotive technology like EVs (electric vehicles). FAME-I(Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India) was launched under the

National Mission on Electric Mobility in 2011/
National Electric Mobility Mission Plan 2020, unveiled in 2013 [16]. The scheme aims to encourage the progressive induction of reliable, affordable and efficient electric and hybrid vehicles (xEV). The First Phase of the scheme was initially approved for a period of 2 years, commencing from 1st April 2015. The Scheme has been extended from time to time, with the last extension allowed for a period up to 31st March 2019. It is under the framework of the Demand Incentive Disbursement Mechanism. The incentive amount has been determined for each category of vehicles like Mild Hybrid, Strong Hybrid, Plug-in Hybrid and Pure Electric technologies and battery specification. It is implemented and monitored by the National Automotive Board under D/o Heavy Industry. It is one of the DBT schemes categorized under in-kind mode. In February 2021, the Delhi government started the process to set up 100 vehicle battery charging points across the state to push the adoption of electric vehicles. Although there have been discussions regarding AVs, nothing concrete has been announced till now [17].

Table 1: Political Challenges and Opportunities Surrounding Avs

Challenges	Opportunities
In 2019, Union Road Transport and Highways Minister Shri Nitin Gadkari announced that the government wouldn't take any initiatives regarding AVs in India as the government would not promote any technology which would lead to a decrease in the rate of employment.	India is short of around 25 lakh drivers in the public transport industry. The introduction of AVs in India would fill this gap rapidly and it would boost the nation's GDP and economy.
On December 30, 2020, the Union Road Transport and Highways minister announced that autonomous giant Tesla will enter India as an automobile company.	Taking inspiration from Tesla, many budding engineers working in the field of technology and AI could invent Indigenous AVs
India has been struggling with the COVID-19 pandemic since 2020 which has shifted its funds and focus from the technology and automobile sector.	AVs can be a significant factor in reducing COVID-19 transmission as these vehicles can be used to haul medicines, supplies and patients from one place to another without any human contact. An example of this can be seen in testing at a hospital in Bangalore.

Economic factors. In 2019, India was the world's fifth-largest automobile market, with approximately 3.81 million units sold in the passenger and commercial vehicle segments. India is also a significant automobile exporter, with strong growth prospects. In 2020, automobile exports reached 4.77 million vehicles, with a CAGR of 6.94% from FY16-20. Hatchbacks and compact sedans are the most popular passenger cars among Indians. EV sales (excluding autorickshaws) grew by 20% to 1.56 lakh units in 2020. According to NITI Aayog and Rocky Mountain Institute (RMI), India's EV finance industry could reach USD 50 billion by 2030. To meet growing demand, automakers have been actively investing in the industry. The sector attracted USD 24.62 billion in FDI between April 2000 and September 2020 (Indian automotive report 2020, 2021). Achieving India's EV ambitions will require a cumulative investment of USD 180 billion in vehicle production and charging infrastructure by 2030. Companies like Fiat Chrysler and Lamborghini announced plans in January 2021 to expand their local product lines and increase sales post-COVID-19. Additionally, AV giant Tesla established an R&D centre in Bengaluru and registered its subsidiary as 'Tesla India Motors and Energy Private Limited.' Investments in EV technology is expected to be followed by investments in the AV sector.

Table 2: Economic Challenges and Opportunities Surrounding AVs

Challenges	Opportunities
The unemployment rate is at an all-time high of 5.3%. The introduction of AVs would lead to an increase in this percentage, thus having a negative impact on the economy.	With AV-centric companies like Tesla and Waymo entering the market, the FDI would substantially grow thus boosting the economy.

Social factors- As of March 2021, India's population stands at 1.391 billion, with significant cultural and economic fragmentation due to its diverse geography. Currently, 34.5% of the population is urban, 28% live below the poverty line (BPL), and nearly 55% are middle-class. The working class constitutes 39.1% of the total population (as per the 2011 census) [18]. The Indian automobile industry leads in inclusive growth, community development, and social projects. According to a 2019 Statista survey, 30 out of every 1,000 people in India own a car, a figure that is slowly increasing. The hatchback segment is the most popular, making up 49.17% of the market in 2019, due to its affordability, low maintenance, fuel efficiency, and compact size. Electric vehicles (EVs) account for 0.48% of total cars, likely due to the nascent technology, limited models, and fewer recharge stations. While the percentage of autonomous vehicles (AVs) in India is currently very small, this is expected to change with Tesla's debut in 2021. A 2014 University of Michigan survey on autonomous cars included participants from six countries, including India. The analysis of responses highlights both social challenges and opportunities for AVs in India.

Table 3: Social Challenges and Opportunities Surrounding Avs

Challenges	Opportunities
AVs in India are still in the prototype stage and most people haven't seen them functioning in public. The government as well as automobile manufacturers have to active steps to educate people about this technology.	According to the survey, 73% of Indians in the survey have previously heard about AVs through the internet and social media and 50% have a very positive outlook towards them. This tells us that Indians are interested in knowing about AVs so it would be easy to promote this technology.
The majority of respondents expressed high levels of concern about driving in self-driving vehicles, safety issues related to equipment failures or system failure, and self-driving vehicles not performing as well as human drivers.	It has been proven that AVs would reduce 95% traffic violations and accidents as there will be no scope for human error.
It has been suggested that to implement AV technology, it would take an extra sum of USD 75,000.	According to the survey, 75% of Indians are willing to pay USD1,600 to enable this technology in their cars. By producing these cars domestically, a break-even point can be reached.

Technological factors- India is a leader in the global IT market, driven by its dedication to unmatched technology. Ranked 48th out of 63 countries in digital readiness by the Institute of Management, the IT/business process management (IT-BPM) sector contributed 8% to the GDP in FY 2020, amounting to USD 175
billion, employing over 4 million people. India is the largest offshore destination for IT companies, accounting for over 30% of the global outsourced BPM market. AI, a key component in AV technology, held a 2.1% market share in India's automobile industry in 2020, amounting to USD 1.339 billion. The IT services sector held the largest market share at 40%, while the cross-sector industry had the lowest.

The Ministry of Electronics and Information Technology, governing technological regulations, launched the TIDE 2.0 (Technology Incubation and Development of Entrepreneurs) scheme under the 'Digital India Initiative' in 2019 to promote tech entrepreneurship. The government is also boosting AI, IoT, big data, cybersecurity, machine learning, and robotics with an increased outlay of USD 477 million. India's flagship digital initiative aims to enhance internet accessibility, promoting e-governance, e-banking, e-education, and e-health. In the 2019 Union Budget, Finance Minister Nirmala Sitharaman announced industry-relevant skill training for 10 million youth in AI, Big Data, and robotics.

Table 4: Technological Challenges and Opportunities Surrounding Avs

Challenges	Opportunities
The technology required for the smooth functioning of AVs needs to be more advanced than even the latest jet fighter software. The software stack would be very complex to make as it would be working on real-time data and would be required to adopt changes happening in the environment.	Since India is one of the leading countries in the IT sector, a common and unified platform can be built with easily upgradable and portable software stacks.
As India is still in its early stages of EV adoption, innovations in the field of AV can be considered less fruitful.	AVs are not just limited to passenger cars but have a wider spectrum. It can boost the agriculture sector (one of the biggest contributors to India's GDP) with AI-enabled tractors and harvesters as demonstrated by Mahindra& Mahindra and Escorts. It will also boost smooth, safe and easy public transportation as seen in the case of Novus-Drive.
As India is already lagging behind many countries in AV technology, it would take groundbreaking innovations to keep up with them.	India is one of the leading manufacturers of semiconductors, amounting to USD21 bn and has some of the most advanced examples. Since AVs rely on semiconductors for all their electric functions, it can give us a head start.

Environmental Factors- The Ministry of Environment, Climate Change, and Forest, headed by Union Minister Shri Prakash Javadekar, oversees environmental decisions in India. The country, with its diverse geographical features, is also one of the most polluted, housing 22 of the top 30 most polluted cities globally, including Delhi, Mumbai, and Kolkata [19]. This has prompted the government to launch initiatives like the National Clean Air Programme (NCAP) under the Central Sector "Control of Pollution" Scheme, aiming for a 20-30% reduction in PM10 and PM2.5 concentrations by 2024, using 2017 as the base year. The automobile sector contributes 14% to India's overall air pollution, with diesel vehicles accounting for 61%. This high percentage is due to the large number of vehicles, higher-than-normal emissions, and traffic congestion. The government responded by implementing BS-6 engine norms in April 2020, reducing emissions by 25%. Additionally, the government announced in 2017 that all petrol and diesel vehicles will be banned by 2030, promoting EVs instead. AVs, mostly electric and 10-12% more efficient than human-driven vehicles, are also considered a viable option to reduce air pollution and increase lane capacity, thus alleviating traffic congestion.

Table 5: Environmental Challenges and Opportunities Surrounding AVs

Challenges	Opportunities
Although there are standardized traffic rules in regulations in India, most people don't follow them which can cause confusion for AVs and can lead to accidents or worse deaths.	By thoroughly testing them in an environment which is modified according to the Indian traffic scenario, AVs can adopt the traffic system in India.
Due to heavy precipitation and snow in India, LiDAR (Light Imaging Detection and Ranging), the primary sensor used in AVs to draw an image of the road would not work efficiently.	There has been rapid evolution in the LiDAR industry in the past 15 years and companies like Velodyne and Luminar are working towards making a powerful, robust, and adaptive system.
At present, most electric AVs are prototypes and only ICE AVs are mainstream. Introducing them would lead to further degradation of the environment.	ICE AVs are proven to **be 10-12%** more efficient than human-driven cars. This results in less carbon footprint and would also save money spent on fuel.

Legal factors- India operates under a federal law system that blends parliamentary legislation, court laws, customary practices, and religious laws. The Indian Judicial System evolves through decisions, orders, and judgments by judges, with the Supreme Court serving as the final legal authority. Legislation in India involves members of the Lok Sabha and Rajya Sabha introducing bills in Parliament, which must pass both houses and receive presidential approval to become law. As of January 2017, India has 1,248 laws. The principal legislation governing the automotive sector is the Motor Vehicles Act of 1988 [20].

The Ministry of Road Transport and Highways oversees this sector and has established two advisory committees: the Central Motor Vehicles Rules-Technical Standing Committee (CMVR-TSC) and the Standing Committee on Implementation of Emission Legislation (SCOE).

The CMVR-TSC, chaired by the joint secretary of MoSRT&H, includes representatives from various bodies such as the Ministry of Heavy Industries, Bureau

of Indian Standards (BIS), and automotive industry associations.

Currently, the MV Act of 1988 does not permit fully autonomous systems in vehicles, mandating that a human driver always maintain full control, with testing of such vehicles prohibited. The Motor
Vehicles Act 2022 proposes testing provisions but awaits parliamentary approval [21].

Table 6: Legal Challenges and Opportunities Surrounding AVs

Challenges	Opportunities
Since a major component of AVs is technology and AI, the Information Technology Act 2008 [22] needs to be amended.	Amendment in the IT Act would ensure the safety of the personal details recorded in the AV's system such as live location and theft, destruction and manipulation of such sensitive data would result in punishment.
The Geospatial Information Bill 2016 [23] will also require changes since AVs work on real-time data like weather forecasts and satellite navigation.	Amendments would ensure smooth functioning of AVs which would lead to less traffic congestion, optimum route selection and less emissions.
AVs are just like any other commodities and should come under the Consumer Protection Act 1986 [24]	Framing of guidelines would ensure that consumers are educated about the pros and cons of AVs and would ensure that there are clear liability rules for every possible scenario involving AVs.
The Motor Vehicles Act should include clear guidelines regarding testing, selling and export of AVs	Having a set of clear rules would ensure active and smooth testing of AVs, their commercialization and ultimately speed tracking AVs in India.

D. Comparative Analysis of Regulatory Framework Using Infrastructure Regulatory Systems Model

A. Selection of Parameters for Comparison

The World Bank Handbook model on Infrastructure Regulatory Systems serves as the basis for comparing the regulatory framework of AVs. It focuses on key factors such as the Independence and Accountability of the Regulator, the Relationship between the regulator and policymaker, Autonomy of the Regulator, Formal and informal processes, Transparency of decision-making, Predictability of regulatory decision-making, and Accessibility of regulatory decision-making (Handbook for evaluating infrastructure Regulatory Systems, 2006), [25]. Drawing insights from Brian Levy and Pablo T. Spiller's analysis in "The Institutional Foundations of Regulatory Commitment: A Comparative Analysis of Telecommunications Regulation," which examines institutional characteristics across several countries, the framework for a Regulatory Authority for AVs in India is outlined.

i. The parameters have been classified into three categories-Institutional Regulatory Framework

Number of bodies involved Division of the authority and scope of the regulator Role duplication Role of Ministry and degree of involvement

ii. Office of Consumer Protection

Process of policy and regulation & regulation formation Involvement of Stakeholders Self-Regulation Transparency in the process of policy formation

iii. Autonomy of the Regulator

Financial Autonomy Process of recruitment of top officials Autonomy in recruitment Representation of stakeholders in the Regulators' officials

Note- The capacity building of human resources has been omitted from the analysis tool in the case of AVs as such minute information about these countries is not available.

iv. Criteria for selection of countries

Every year KPMG publishes an AVRI (Autonomous Vehicles Readiness Index) [26][37][43][44][45].

It is a tool to help measure the level of preparedness for AVs across 30 countries and jurisdictions. It is a composite index that combines 28 individual indices into a single score. The top 3 countries in the 2020 edition of this index were selected for comparative analysis.

v. Singapore (2020 score- 25.45)

Singapore has topped the AV Readiness Index, surpassing the Netherlands in both consumer acceptance and policy and legislation. The city-state now tests AVs across all of western Singapore's public roads and plans to deploy AV-enabled buses in three regions in 2022. By 2030, Singapore aims to increase its charging points from 1,600 to 28,000, alongside EV purchase incentives. To offset declining fuel excise duties, a usage tax is gradually being introduced, crucial for enabling widespread AV adoption, especially given their predominantly electric nature.

vi. The Netherlands (2020 score-25.22)

The Netherlands retains top ranking on the infrastructure pillar, leading on EV charging stations per capita and second only to Singapore on road quality. An extensive series of pilots means that 81% of people live near AV testing sites. However, tests on truck platooning in July 2019 found challenges in keeping vehicles always connected. 2019 saw the Netherlands extending its use of smart road furniture, including traffic lights that send their statuses wirelessly to AVs in 60 new areas of the country.

vii. Norway (2020 score-24.25)

Norway extended its use of AVs in 2019, with several bus routes in Oslo now driverless, and the speed limit for driverless vehicles on roads increasing from 16kph to 20kph.

A majority of passenger vehicles bought in Norway in 2019 were battery or plug-in hybrids, as a result of high taxes on internal combustion vehicles and fuels and subsidies for EVs. The country is testing AVs in extreme weather, with pilots of driverless trucks, cars and buses on the snow-bound Svalbard islands in the Arctic Circle.

Table 7: Analysis of AV Regulatory Framework

Act of Establishment	Autonomous Vehicles Rules, (2017) [27]	The 'Experimenteerwet Zelfrijdende Auto' (The Experimental Law) 2019 [28]	Norway's Act Relating to Testing of Self-Driving Vehicles, 2017 [29] [36]
Number of bodies involved	Land Transport Authority of Singapore (LTA)	RDW (Dutch Vehicle Authority), DAVI (Dutch Automated Vehicle Initiative, EU (European Union), the police, Dutch Institute for Road Safety Research (SWOV)	Norwegian Public Roads Administration
Division of the authority and scope of the regulator	Testing and licensing of AVs in the country, ensuring proper maintenance of existing AVs, defining liability insurance guidelines, ensuring installation of data collection from data recorder and keeping records regarding AV testing and licensing [30].	Admission of AVs for testing and commercialization, traffic safety during demonstrations, licensing AV after successful testing [31].	Testing, licensing and certification of AVs, ensuring safe and smooth testing. (Norwegian government planning to promote autonomous vehicle) [32].
Role Duplication	No, the sole regulator	No, the sole regulator	No, the sole regulator
Role of the Ministry and degree of involvement	The LTA reports to the Ministry of Transport (Self Driving Vehicles, 2016)	The RDW reports to the Ministry of Infrastructure and Water Management [33].	The Public Roads Administration reports to the Ministry of Transport
Office of Ombudsman/Consumer Protection	-	-	-
Process of policy and regulation formation	All policies regarding AV are made through the standard Public Policy Making Process in Singapore in lieu of the LTA and Ministry of Transport.	The Dutch parliament along with the ruling government forms law in lieu of the RDW.	-
Financial autonomy	LTA is a statutory body and all funds are regulated by the Ministry of Transport	RDW is a non-departmental public body (NDPB) and is funded by fees	-
Leadership & Tenure of Chairperson and the Regulator	**Chairperson**-Mr Na Lang is the Chairperson of LTA (September 2020-present) [34]. The Ministry of Transport is the official regulator of LTA	Chairperson-Mr Ab Van Ravestein (September 2014-present) The Ministry of Infrastructure and Water Management is the official regulator of RDW	-
Profile of past and current Chairperson	Present Chairman- Ng Lang has been appointed Chief Executive and Board Member of LTA, Singapore's Land Transport Authority since September 2020. He concurrently holds the appointment of Chairman, MSI Global Pvt Ltd and Director, SG HSR Pvt Ltd. Lang also serves on the boards of Singapore-Suzhou Township Development Pvt Ltd, China-Singapore Suzhou Industrial Park Development Group Co. Ltd. and Mandai Park Holdings Pvt Ltd. He is a member of the Singapore Management University Real Estate Program Advisory Board. Prior to joining LTA, Lang was the Chief Executive Officer of JTC from September 2017 to August 2020, CEO of the Urban Redevelopment Board from 2010 to 2017, and CEO of the National Parks Board from 2006 to 2010. Mr Ng has also served in various capacities in the Singapore public service, including the Singapore Foreign Service and the public healthcare sector. In 2018, he was awarded the Public Administration Medal (Gold) in recognition of his contribution to the Public Service. **Former Chairman**- Mr Alan Chan Heng Loon is the former Chairperson of LTA Singapore. He had a 4-year term from April 2016 to September 2020. He is also the CEO of Singapore Press Holdings.	**Present Chairman**- Mr Ab Van Ravestein has been appointed as the Managing Director of RDW, Netherlands's Vehicle Regulation Authority since September 2014. Prior to this he was the Director-General of the Netherlands Enterprise Agency and has also held sensitive positions like Director General Executive Sales and MD NL Agency. He is a visionary and is primarily focused on developing technologies like Digital Service Provision, AVs, ICT vehicles and MaaS in the near future. **Former Chairman**- Mr J Hakkenberg was the former MD at RDW Netherlands. He had a term of 4 years from March 2010- September 2014 [36-42].	-

V. DISCUSSIONS OF THE FINDINGS

A specific framework of rules and regulations has been established as an 'act' in three countries to ensure clarity in all processes related to autonomous vehicles (AVs). The responsible authorities act based on recommendations from relevant bodies such as the EU, police departments, and Ministries responsible for Road Transport, ensuring comprehensive coverage of all aspects. There is a strong focus on rapid yet robust testing and certification of AVs, alongside managing secondary issues like insurance liability and data collection.

Policy formation follows established procedures to expedite the development of AV-related regulations.

The Ministry responsible for Road Transport serves as the regulatory body, ensuring fairness and alignment with public interests. The appointed Chairpersons of these authorities bring extensive experience in automobiles and policymaking, having held critical strategic roles in the past.

A. Recommendations and Best Practices to be Adopted

Table 8. Recommendations and Best Practices for AV Regulation

Recommendations and Best practices for AV regulation
Establishment of an Authority 
Promotion of AV technology 
Testing, licensing and certification 
Liability guidelines in case of a traffic violation or accident 
Insurance guidelines 
Data Protection and Regulation 

After studying the scope of AVs, their evolution, the present scenario in India and the regulatory framework of the leading countries in the AV industry, we have come down to the following recommendations for policymakers-

- **Establishment of an Authority** to overlook the whole process of AV adoption in India, a separate autonomous authority regulated by the Ministry of Road Transport and Highways and this body will be responsible for everything related to AVs including conducting tests, awarding certification and data collection. The existing RTO organization won't be suitable to discharge the tasks mentioned above as they are not trained to address issues related to Artificial intelligence, driverless technology etc. and overburdening them with such a responsibility could lead to ineffectiveness and inefficiency of the organization.
- **Promotion of AV Technology** to encourage more tech-centric companies, start-ups and the budding youth of this country, the government should start a campaign for awareness of Automation technology. From social media advertising to the grassroots level to separate courses in Engineering courses, all this would help ignite interest in Indians which could lead to some groundbreaking innovations.
- **Testing, Licensing and Certification**- Testing autonomous cars necessitates adhering to specific guidelines to ensure safety and efficiency. The government should locate separate routes and designated time slots for testing by both individuals and companies. Regulatory authorities, inspired by The Netherlands AV framework, will conduct rigorous inspections to verify the vehicles' safety and functionality. Upon passing inspection, the cars will be licensed for sale and importation to the public. Owners must undergo mandatory training provided either by manufacturers or the government before being authorized to operate these vehicles. To facilitate a smooth transition, special zones exclusively for autonomous vehicles will be established in cities for a period of five years. Once both drivers and vehicles gain familiarity with Indian traffic patterns and regulations, they will gradually integrate into public road systems.
- **Liability Guidelines in Case of a Traffic Violation or Accident**-In the case of a traffic violation or accident, clear and crisp guidelines shall be made for liability as the current Motor Vehicles Act is only equipped to handle liability issues related to the consumer and the manufacturer, but when autonomous vehicles are introduced, a third set of liability issues pertaining to the vehicle itself would also need to be addressed.
- **Insurance Guidelines**- The existing car insurance won't be feasible for AVs as presently it only addresses the insurance liability of either the consumer, the manufacturer or the third person. But when AVs are introduced, a fourth set of insurance guidelines pertaining to the vehicles itself would be required and consequently, it will modify the existing insurance guidelines as well. Therefore the government shall instruct the IRDAI (Insurance Regulatory and Development Authority of India) to make fresh and separate insurance guidelines that would govern self-driven cars in India.
- **Data Protection and Regulation**-Autonomous cars drive with the assistance of real-time information like weather forecasts, route analysis etc. To ensure that no tampering is done to this viable information; the government to make laws that dictate how all this information shall be granted and regulated. These cars also contain personal information like driver license details, bank account details, blood group etc. To ensure that no tampering, theft, duplication or destruction happens to this data, the government should add a clause to the Data Protection Act 2022 [35], which would give guidelines to address such information leaks to ensure the protection of such sensitive information.

VI. CONCLUSION

After analysing the current scenario of AVs, their benefits and growing market trends we conclude that they are the next step in the evolution of sustainable, efficient, safe and environment-friendly Transportation.

We also studied and analysed the leading countries in AV innovation and concluded that their rapid AV testing, government support and clear and efficient regulatory framework to govern AV are helping them move forward towards this next step of automobile evolution. By following the same direction with modifications according to the country's political, economic, social, environmental and legal aspects, they too can make the process easier, more efficient and faster. In the end, we would like to conclude that the introduction of AVs would fast-track India's progress towards becoming a developed nation.

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