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Zugang und Wirksamkeit im Verkehrssystem

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EDITORIAL

Liebe Leser:innen,

Zugang und Wirksamkeit. Zwei Begriffe geben dieser Ausgabe ihren Titel, und sie gehören enger zusammen, als die getrennte Nennung vermuten lässt. Zugang beschreibt, ob ein Verkehrsangebot für jemanden erreichbar ist. Wirksamkeit beschreibt, ob es für ihn auch funktioniert. Zwischen beidem liegt ein Raum, in dem viele gut geplante Systeme ihre Wirkung verlieren.

Dieser Raum ist selten dort, wo man ihn vermutet. Er liegt nicht in fehlender Infrastruktur, sondern in den letzten Metern davor. Er liegt in der Lücke zwischen Fahrzeugboden und Bahnsteigkante, im Gehsteig, der vor der Haltestelle endet, in der Information, die im entscheidenden Moment nicht verfügbar ist, und in der Buchung, die einmal zu oft nicht trägt. Es sind Defizite, die in keiner Anlagenstatistik auftauchen und die dennoch darüber entscheiden, ob jemand ein Angebot nutzt oder es dauerhaft meidet.

Die Beiträge dieses Hefts nähern sich diesem Raum aus unterschiedlichen Richtungen. Sie fragen, woran sich Erreichbarkeit überhaupt messen lässt und welche Kennzahlen einer ernsthaften Bewertung standhalten. Sie erheben, wo Barrieren im tatsächlichen Reiseverlauf entstehen. Sie zeigen, dass geteilte Angebote im Umland bekannt sein können und trotzdem ungenutzt bleiben. Und sie machen deutlich, dass Zugänglichkeit nicht nur eine Frage der Teilhabe ist, sondern ein volkswirtschaftlicher Faktor, der über Erwerbsbeteiligung und Arbeitskräfteangebot mitentscheidet.

Dass diese Zusammenhänge nicht neu sind, führt der historische Beitrag dieser Ausgabe eindrücklich vor. Friedrich List legte dem französischen König 1837 dar, dass ein Eisenbahnsystem seinen Zweck verfehle, wenn es nur die ertragreichen Strecken bediene. Querfinanzierung, regionale Ausgewogenheit und die Akzeptanz der Bevölkerung waren für ihn keine Nebenbedingungen, sondern die Voraussetzung dafür, dass Investitionen ihre Wirkung entfalten. Knapp zwei Jahrhunderte später diskutieren wir dieselben Zusammenhänge mit besseren Daten, aber nicht mit besseren Antworten.

Bemerkenswert ist dabei, wie eng Zugänglichkeit und Robustheit zusammenhängen. Ein System, das für Menschen mit Behinderungen zuverlässig funktioniert, funktioniert auch für alle anderen besser — für Reisende mit Gepäck, mit Kinderwagen, mit wenig Ortskenntnis oder unter Zeitdruck. Und es hält Störungen besser stand, weil durchgängige Information und verlässliche Wegeketten genau jene Eigenschaften sind, die im Regelbetrieb kaum auffallen und bei Baustellen, Umleitungen oder Ausfällen den Unterschied machen. Barrierefreiheit ist damit kein Zusatz zur Resilienz, sondern einer ihrer Bausteine.

Was sich daraus für die Praxis ergibt, ist unbequem. Investitionsentscheidungen richten sich nach dem, was sich zählen lässt: Kilometer, Fahrzeuge, Ausstattungsmerkmale. Zugang und Wirksamkeit zeigen sich erst im Betrieb und verlangen eine Bewertung, die über die Bilanz des Gebauten hinausgeht. Diese Ausgabe liefert dafür Befunde, Methoden und einige Argumente.

Ich wünsche Ihnen eine anregende Lektüre.



Roman Benedetto

Redaktion



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INVESTING IN RAIL: THE RECOMMENDATIONS OF THE GREAT GERMAN ECONOMIST F. LIST TO THE FRENCH KING LOUIS-PHILIPPE IN 1837 – PROSPECTS FOR FUTURE INVESTMENT IN FRANCE

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Abstract

The discovery in the French Archives Nationales by Prof. Dr. Eugen Wendler in October 1993 of two reports of the famous German economist F. List to the French government in 1837–1840 is of particular interest for transport economists and historians of transportation. In these memoirs, F. List prospects the need for future investment for the development of the French railway network. The analysis of his recommendations confirms that F. List understood the basic knowledge of railway economy: the role of the central state in financing the railway network, differences in acceptability of the population linked with interregional inequalities, cross-subsidy between profitable and unprofitable network parts, and return on investment for the whole national economy. This research confirms the role of F. List as a pioneer of transport economy. In the last part of the paper, we then try to learn from List's recommendations to foster today's French rail policy. The parallel with contemporary issues is stimulating, as technological development is moving so fast and so widely in impact, scale and competencies that we sometimes forget the basics of railway economics. But it should be handled carefully, as the context is largely different.

Keywords: Railway, Finance, France, History of Transportation

In the preamble (p. 5) to workshop 3 of the "Passenger rail infrastructure and services" section of the final report of the Ambition France Transport conference, held before the summer of 2025, it is written that at a time when France's level of investment in transport infrastructure, particularly rail infrastructure, is clearly falling behind that of its comparable European counterparts, the work of the COI (conseil d'orientation des infrastructures, 2022) has highlighted the scale of the investments to be made and the priorities to be set for the rail infrastructure over the next two decades (AFT, 2025).

This sentence is certainly what Louis-Philippe, King of the French, had in mind when he met the great German economist Friedrich List (1789–1846), already a recognized rail expert in Germany, Belgium and the

United States, in Paris on November 21, 1837.

On this occasion, F. List submitted a second report to him, following the more summary one sent from Leipzig in June 1837, with the intention of proposing to the French government the construction of an entire system of railways, and of offering his services to achieve this goal (Memorandum nr. 2). From now on, we refer to M1 for the first report submitted on June 5, 1837, to the French consul in Leipzig, and M2 for the second report submitted on November 16, 1837, in Paris.

These two memoirs were rediscovered at the Archives Nationales in France by Prof. Dr. Eugen Wendler in October 1993 and published in French and German in: *Die Vereinigung des europäischen Kontinents* [The Unification of the European Continent], Verlag Schäffer Poeschel, Stuttgart, 1996.

In 1837, France lagged far behind its English and German partners. The railway revolution in Europe began on September 27, 1825, in England with the opening of the first private railway line, approximately 40 km long, between Stockton and Darlington (as a reminder: 1769: James Watt; 1800: Richard Trevithick and his proposal for a steam locomotive; George Stephenson with his "Locomotion No. 1" in 1825). The first public railway line began operating between Liverpool and Manchester on September 15, 1830, confirming the success of the initial tests (Haase, 2009, p. 210). While the emergence of railways in the British Industrial Revolution can be understood through self-reinforcing mechanisms and private initiatives, their rise in France was very different, with more centralization and state intervention

In 1827, the first railway line in France was built. It connected Saint-Étienne to Andrézieux and spanned 21 km. Its purpose was economic: the line enabled coal to be transported from the mines in Saint-Étienne, an industrial city, to the port of Andrézieux-sur-Loire. And in 1837, on August 24, the Paris–Saint-Germain-en-Laye line was inaugurated. This was the first line in France designed solely for passenger transport and operated with steam locomotives. In 1841, France had just 548 km of track. In 1843, Great Britain had around 3,400 km of track operated by 70 railway companies. And in Germany, some 680 km of track were opened between



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1837 and 1841.

The law of 1842, providing long-term concessions and state support, accelerated the construction of the national network: an original model of public-private partnership was created. The State became the owner of the land chosen for the route and financed the construction of the infrastructure (engineering structures and buildings). It then conceded use of the land to the companies, which built the superstructures (tracks, facilities), invested in rolling stock and enjoyed a monopoly of operation on their lines.

By 1860, 9,400 km were in operation, and by 1875, 19,600 km. From 1875 onwards, the Freycinet plan focused on filling the remaining gaps: by 1885, the 30,000 km mark had been reached.

F. List's intellectual context in the field of railway economics

The F. List model of railway development differs from the model that was implemented in the U.K. at the beginning of the 19th century. That unique development model profoundly transformed the British economy, landscape and society. Unlike the French model, which was highly centralized and state-planned, the English model was based on private initiative and liberal capitalism. Railroads were financed by private companies through the creation of joint-stock companies. Thousands of ordinary investors put their money into them. "Railway Mania," in the mid-1840s, was a full-blown speculative bubble that burst. Everyone wanted to invest in rail, which led to the frenzied construction of thousands of kilometers of tracks, sometimes redundant. State regulation was minimal. The British government did not design the network; its role was limited to approving each project through an Act of Parliament, which was essential to authorize land expropriation. The Gladstone Railway Regulation Act of 1844 required companies to offer at least one train per day at an affordable fare (one penny per mile) so that the working classes could travel. This massive and rapid expansion unified the British market, enabled the low-cost transport of coal, and gave rise to working-class

suburbs and the first mass tourism trips (notably through Thomas Cook).

The rise of the railways in 19th-century Britain had a profound impact on British economic literature of the time. Economists had to develop theories in real time to explain unprecedented upheavals: massive capital investments, natural monopolies, market integration, and financial crises.

Socio-economic analysis of railways then experienced an unprecedented boom that accompanied the development of rail networks in Europe, primarily in the United Kingdom and France. F. List focused his report on state intervention to speed up and finance a national railway network. At the same time, in the UK and France, railway analysis was deeply different. In the UK, Lardner is regarded as the true pioneer of transportation economics with his book *Railway Economy* (1850), the first systematic work on railway management and economics. In it, Lardner analyzes cost structure (distinguishing fixed and variable costs), infrastructure pricing, and the influence of railways on economic centralization. He strongly influenced later economists, notably William Stanley Jevons (1835–1882). John Stuart Mill (1806–1873) was a leading figure in classical liberalism and a firsthand witness to the railroad speculative bubble. In *Principles of Political Economy* (1848), Mill uses railroads to illustrate several fundamental concepts, such as natural monopoly: he observes that competition between road and rail on the same route is absurd and leads to waste, and therefore advocates regulation, or even state intervention. He then examines capital absorption, explaining how massive investments in railways diverted British capital that would otherwise have suffered from a downward trend in profit rates in traditional industries. Later, Alfred Marshall (1842–1924), the British founder of the neoclassical school, would continue this analysis.

In France, the engineering-economic school led under Jules Dupuit (1804–1866). Dupuit laid the long-term foundations of railway economics: railway pricing and economic analysis. His insights directly inspired network



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management practices at SNCF Réseau today: the discovery of marginal utility and “consumer surplus,” the concept of yield management, the status of the railroad as a “natural monopoly” and the imperative for state regulation, and the calculation of the collective optimum (marginal cost pricing).

During the same period, while Dupuit approached the railroad from the technical, mathematical and managerial perspective of an engineer, Frédéric Bastiat (1801–1850) approached it from the perspective of political philosophy and pure liberal economic theory. For Bastiat, the railroad — in its infancy in France in the 1840s — served as a formidable laboratory for observing the benefits of free trade, but also the excesses of protectionism and state clientelism. He criticized the state's approach, as advocated by F. List, of raising taxes to build a railroad line. Unlike List, Bastiat believed that if a railway line is truly useful, the private sector will naturally finance it because it will be profitable; if it requires state subsidies to exist, this is often a sign that it is diverting public resources toward an unviable project at the expense of other, more urgent needs. He also vehemently denounced “crony capitalism.”

In the 19th century, the awarding of railway concessions in France gave rise to intense political maneuvering. Major companies (such as those owned by the Rothschilds) courted the Chamber of Deputies to obtain monopolies, interest guarantees, or subsidies. Bastiat was one of the first to analyze this phenomenon, showing that the railroad, instead of being a tool of freedom, had become an instrument of legal plunder. The major companies used the law to eliminate competition (such as stagecoach or river transport companies) and secure profits guaranteed by the taxpayer.

F. List thus positions himself as a precursor to L. Walras (1857), who also places the State at the center of railroad financing and control: Walras advocates State intervention not only because of the existence of a natural monopoly, but also of a moral monopoly — since railroads participate in the defense of the Nation,

national unity and economic development, the State must directly implement the construction and operation of lines to ensure full control of these beneficial effects for the community (Perennes, 2014). List's recommendations to the French king in 1837 for financing railroads in France

F. List decided to speak directly to the French king, Louis-Philippe, who spoke German and had a particularly advanced European culture. To this end, he had already visited Belgium and was favorably received by the Belgian King, whose wife, Queen Louise, was Louis-Philippe's eldest daughter. E. Wendler even states that the Belgian royal family announced F. List's arrival in France to the Tuileries. On November 21, 1837, List was granted an audience with Louis-Philippe.

From the outset, he placed the debate on political ground: the beneficial effects of railroads are so great that the French people will demand them everywhere, and it is in the interest of the French government not only to satisfy, but to forestall their wishes (M2).

F. List drew on his successful experience with railroads: having built a large railroad in the United States of North America, one of the first executed in that country, he decided in 1836 to travel to France with the intention of proposing to the French government the construction of an entire system of railroads, and to offer his services to achieve this goal (M2). His objective was clear: the creation of paper money for the sole purpose of establishing a complete system of railroads, giving it as a special mortgage to the holders of the paper money (M2, p. 179).

In his first memoir, written on June 5, 1837, and forwarded to the French consul in Leipzig for submission to the French government, F. List clearly announced his objective: in 1830 he considered the accession to the throne of His Majesty the King of the French as a favorable event to realize an idea he had conceived some years earlier — to propose to the French government a whole system of railroads in combination with paper money (M1). During his meetings with the



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high administration, which was to introduce appropriation legislation — in particular with Duke Elie Decazes (1780–1860), a highly influential politician of the July Monarchy — F. List explained how this was done in America and England (M1).

In this first memoir, he indicates that his financing model had been tried out in Germany: he had been happy enough to cause, by his writings, the erection of railroad companies throughout Germany, and even to see some states combine them with the creation of a paper currency; also in the Grand Duchy of Baden, this measure originally proposed by him was approved by the commission appointed by the government to report on the proposal for a railroad from Mannheim to Basel (M1).

Having learned of the launch of major rail projects in France, F. List wanted to show how the admission of paper money in combination with railroads could accelerate the movement. He states that France, with three billion francs in cash, could create paper money up to the value of 1,000 million francs — a third of the amount in cash — with twice the security of paper money in England (M1).

For F. List, railroads offer particular advantages to holders of paper money: they provide security and value which no event can destroy or depreciate. This value is based on a net income subject to neither accidents nor fluctuations. A railroad returning 10% revenue would give at least this much income in all weathers; there is no property whose income, once well established, rests on a surer, more regular and more durable basis. A railroad returning 10 million with more than double security would serve as collateral for the issue of 100 million in paper money. The public, once well informed of this security, would gain such confidence in this paper that no crisis could shake its credit (M1).

F. List clearly indicates that the United States and England had reached such high levels of paper money that it would be inconceivable to increase them. Conversely, in France, it is well known that the French people are strongly repugnant to the creation of paper money dating back to the time of the assignats (M1). He

thus anticipated the response he would receive a few months later from the French government.

In this first memoir, F. List was convinced of the success of his financing method, as railroad construction was “popular.” The whole economy could benefit: the successive issue of a billion banknotes within ten years would give a powerful impulse not only to the railroad system throughout France, but also to national industry, and would at the same time provide great help to tax collection; circulation of this paper would be made all the easier by the fact that banknotes would be received by all public administration coffers (M1).

From the outset, he considers that private companies and large capitalists are not able to support the development of railroads: private companies will only ever deal with roads that promise large revenues, and the great capitalists are only concerned with these enterprises in the hope of raising the price of shares in order to sell them (M2). He therefore concludes that the greater part of the country remains excluded from the benefit of the railroads (M2, p. 177).

He considers private finance too oriented towards short-term gains. He criticizes the great capitalist-entrepreneurs — few in number but of great influence on the stock exchange — who, playing with all the more assurance because they have usually already made gains equal to the value of the shares they hold, can raise or lower the price of shares from day to day according to their interests, to the detriment of those not privy to their secrets: the small capitalists, forced to pay for shares far above their original value. Small shareholders are also victims of agiotage (M2), an old term synonymous with speculation.

F. List therefore ruled out private finance and turned to public funds: the basis of the value of public funds is fixed; everyone knows they yield three or five percent, so in ordinary times the difference in price is very small, and even in the wake of major political events only a few percent (M2). The value of railroad shares, on the other hand, has no fixed basis before the business is up and running, and even then it takes a great deal of experience to know the net income, which is the only basis for their value (M2).



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But here too the values of railroad companies are likely to fluctuate sharply with speculation, as F. List observes already in the railway from Paris to St. Germain and Versailles, as well as in several companies in Germany, and particularly in that of Leipzig, where agiotage has already been the cause of much misfortune (M2). He therefore considers that the current agiotage on railroad company securities could become a plague even dangerous to the repose of the state (M2).

F. List then lists a series of disastrous consequences, numbered exactly in this order (M2):

1. The accumulation of immense fortunes in the hands of a small number of capitalists, to the detriment of the greatest number of useful citizens.
2. The employment of large amounts of capital in the detrimental game of stocks, instead of being destined for the growth of new, useful enterprises.
3. That instead of contributing to the well-being of the mass of the people, and making the transportation of people and goods cheaper, improvements and new inventions would only serve to increase the fortunes of the wealthy.
4. The daily ruin of a number of useful citizens by fluctuations in stock prices — a ruin that will be repeated for an indefinite time.
5. That this bad state of affairs, once established, could not be reformed.
6. That the railroad system, instead of extending over the whole country, would include only the roads most advantageous to contractors, so that the greatest number of inhabitants would not be satisfied.
7. That the mass of the people, instead of being grateful to the government for the beneficence of the new communication, would see in it only a coalition of men of finance and politicians exploiting the new means of transport for their own profit, and would put all the bad consequences on the government.
8. That all these things can only be disadvantageous to the reigning dynasty.

F. List then proposes four possible solutions (M2):

1. Run the railroads at state expense, as in Belgium.
2. Execute the railroads at departmental expense.
3. Execute the railroads at the expense of the shareholders, under the guarantee of a minimum and the restriction of the dividend to a maximum, reserving for the state a part of the net income exceeding the ordinary interest by 5 percent, and adopting a method of fund subscription that would ensure, for the large number of well-to-do citizens, competition in subscription and the acquisition of shares at the original value.
4. A combination of two or all three of these methods.

F. List then goes into the details of his project. He defines the context essential to the success of this paper-money issue: a country must be well advanced in the political order and in civilization, as well as in industry and commerce, before it can feel the necessity, advantage and possibility of introducing free paper money (M2). It would increase the work, wealth and especially the well-being of the majority of the people, increasing their income, their means of defense and the guarantees of rest.

The issue strengthened the existing regime: Belgium has given proof of this — nothing has contributed so much to strengthening the new Belgian dynasty, and to repressing factions, as the measure to build an entire system of railroads at state expense (M2).

Acceptability is fundamental, and will only be achieved if rail investments cover the entire country: for this measure to be effective, all provinces and major cities must be included, as the net revenue of each individual road, its effectiveness as a promoter of industry, agriculture and trade, increases in proportion to the extent of the system of which it is a part. Most importantly, the political goal can only be achieved when the entire population of the country can share the benefits. Building only a few roads would satisfy the desire of a few million while exciting the envy of all the other French people (M2).



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This last point is very interesting: F. List places the acceptability of his measure and the support of all French people at the heart of his project. In the conclusion of this memoir submitted to Louis-Philippe, he even mentions cross-financing, a very topical element in the financing of rail infrastructure in France today: the net revenue of the major roads would be used to cover the deficits of the less-traveled roads for the benefit of remote areas (M2, p. 182).

While F. List openly criticizes the laissez-faire American banking and federal system, he finds France in a much more favorable situation: here the state can monopolize the right to issue banknotes, and can restrict this issue to a certain sum which can never be exceeded. He proposes a French cash reserve of 3 billion francs and paper money in circulation of 1 billion francs. In the first version of his memoir he mentions an interest rate of 4%, and proposes a gradual introduction into circulation as the work progresses — within the space of six to ten years.

He sees a multiplier effect of this financing: for the construction of these works themselves, the distribution of a billion among the industrial classes, and still more the effects of perfected transport, will require an increase in the means of circulation more than equal to this sum. The creation of paper money could therefore not raise the price of wages and the necessities of life, nor give rise to an outflow of cash from France.

For F. List, the circulation of paper money would be secured for all time by the administration of revenues and by the payments of the state, departments and municipalities; because the holders could be given the railroads as a special mortgage, ensuring their value for all time; and because the French people would be reconciled to this measure by the immense advantages provided by the railways. He places the State at the heart of his analysis: if the State monopolized the issuance of paper money, all private bank issues would be suppressed, and the French nation, enjoying all the benefits of paper money, would be forever protected from its abuses. All the advantages resulting from new

inventions and improved railway construction would be preserved for the public good.

F. List gives two interesting examples. Prussia has in circulation a sum of 100 to 200 million francs in state bills (Tresor-Scheine); this paper is not secured by any special mortgage, holders do not enjoy the guarantee inherent in constitutional government, and there is no guarantee against increase of this sum — not even any exchange funds — yet these papers have not only always maintained their original value but from time to time have even earned an agio of 1/4 percent. The government of the Kingdom of Saxony has also successfully issued several million ecus (M2).

For F. List, the issuance of paper money by the State would ensure the maintenance of public order; order being the principal condition of the value of paper money, all holders of this paper would be interested in its maintenance (M2). He also saw his system as a means of involving the French — particularly the lower classes (M1, p. 185) — in public decision-making and in the development of their nation, by boosting savings: this would be a means of spreading the habit of savings among all classes of people and in the remotest parts of France, even more effective than the savings banks (M2).

Project failures and F. List's lessons for investing in rail transport today

F. List was not rewarded for his scientific and personal commitment to France. His plan to create paper money was a reminder of the assignats debacle, especially for Louis-Philippe and his ministers. With assignats, the French Revolution had created money in huge quantities, then frozen prices (the law of the General Maximum), destabilizing the entire national economy.

In April 1790, assignats were transformed into paper money with a fixed exchange rate against silver, printed in small denominations. The Assembly, faced with this facility, issued new assignats which exceeded the value of the assets on which they were pledged, and



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hyperinflation destabilized the entire Revolution, bringing down Robespierre's regime of terror.

It was the Directoire that put an end to the mechanism by burning the printing plates in Place Vendôme. It is easy to understand the French government's great reluctance to accept F. List's proposal for a paper currency.

If this brief digression on assignats can also serve as a warning today on the question of France's level of debt — which many economists find worrying and even extremely dangerous for the guarantee of sovereignty and the stability of the economy — it is on the railway front that F. List gives us interesting elements to ponder for future investments in France.

1) Firstly, he places the State at the heart of the financing, guarantee and organization of the proposed paper money. He considers it is up to the State to guarantee the functioning of this paper-money market. He strongly rejected the speculative logic that was rapidly developing at the time and could become a plague even dangerous for the repose of the state. His discourse was profoundly social, deeply rooted in a demand for regulation organized by the public authorities. He warns Louis-Philippe of a risk of growing inequality and dissatisfaction that could threaten the reigning dynasty — and we know what social and political crisis led to the fall of the July Monarchy in 1848 and the advent of the Second Republic. F. List thus positions himself as a precursor to L. Walras, who also places the State at the center of railroad financing and control (Perennes, 2014).

2) He insists on the essential acceptability of his financing plan by the French: he sees his system as a means of involving the French in public decisions and in the development of their nation by strengthening savings — a means of extending the habit of savings among all classes of people and in the remotest parts of France, even more effective than the savings banks.

The last two recommendations are frighteningly modern.

3) He even mentions cross-financing, a very topical element of rail infrastructure financing in France today: the net revenue from major roads would be used to cover the deficits of less-frequented roads for the

benefit of remote areas. This is a fundamental element in the operation of rail services today, in a logic of regional planning and equalization. This requirement for cross-subsidies implies a regional or national monopoly, or — and this is the subject of current debate in France — a clarification of regional development missions with the liberalization of rail services.

Today, SNCF is highly critical of freely organized services, where it unprofitably serves many medium-sized towns while new entrants operate on the most profitable lines ("cherry-picking").

4) Finally, he stresses the risks of reinforcing regional inequalities, and de facto dissatisfaction among the regional population, if they are not involved in the development of the rail network: we need to act across the board to involve all territories, because the net income of each individual route increases in proportion to the extent of the system of which it is a part, and the political goal can only be achieved when the entire population can share the benefits. This brings us back to the recurring debate at the COI (conseil d'orientation des infrastructures) on the priorities to be given to the choice of infrastructures, to the selection of LDFT (lignes de desserte fine du territoire, or short railway lines) versus LGVs which often make more discontented people than satisfied mayors: the example of the GPSO LGV is telling — Toulouse waiting impatiently for its LGV while the whole region of Grande Aquitaine and Occitanie, the medium-sized towns in particular, militate more for a network of TERs serving the whole territory.

The current debates on French rail policy can find many potential solutions in the insights of F. List. In June 2026, the issue of regional planning and high-speed rail links — where new entrants seek above all quick profitability (cherry-picking behaviour) and therefore do not extend service to second-tier regional cities — is at the center of the Bussereau Commission's inquiries. This debate had been anticipated by F. List, who advised Louis-Philippe not to overlook rural regions amid the rapid expansion of France's rail network. The issue of cross-subsidies is likewise highly relevant today: the SNCF funds a support fund for SNCF Réseau amounting to €500 million per year, heavily criticized by the SNCF



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because new entrants (Trenitalia, RENFE) on the rail network do not contribute to it. Seeking a solution is on the government's agenda. Yet, by definition, the rail system, due to its deep roots in the territory, requires cross-subsidization, or at least a policy of mobility-focused regional planning towards rural and less dense areas. F. List had recognized this.

Finally, the issue of financing: F. List recommends the use of government borrowing, which safeguards the public interest. France is returning to this same philosophy of acting in the interest of the common good (Yves Crozet, 2023), championed by the state and local authorities, but it lacks the financial means to take on additional debt for rail transport, given the current level of the public deficit relative to GDP (around 5% in 2026, far above the average of our European partners and the 3% threshold). Recently, according to L'Opinion (2026), simulations conducted by the French Ministry of Finance show that, without new cost-cutting measures, the deficit could reach 6.2% of GDP in 2027

Conclusion

The introduction to the Ambition France Transport (AFT) report states that improving the performance of the rail network is also essential from a regional planning point of view, as it is a prerequisite for relieving congestion at rail hubs in major urban centers and developing daily transport (AFT, p. 11). In this quotation one finds the issues and challenges of rail transport today. But the key issues of rail transport remain partially unsolved: when it comes to these essential notions — accessibility to stations and the network for a large number of our fellow citizens, acceptability of the population, financing and cross-subsidization — F. List was right to support the development of rail transport in France and understood the main results of railway economics. There is nothing in the two briefs studied about the intuition of separating public management of the network — he is in fact primarily interested in the development of the rail network — from the rail services running on that network. But then again, this was 1837.

Short biography of F. List (1789–1846)

In his memoir to the King of France in November 1837, F.

List signed his name as Fr. List, Consul of the United States of North America in Leipzig. In the text he also defines himself as “professor of political economy” (M2, p. 179). In 1841 he published his famous work, *Das nationale System der politischen Ökonomie*, in which he defended a very “continental European” vision of public intervention and “educational protectionism.” He put the nation back at the heart of the economic game, as seen in his project to finance France's railroads.

F. List was one of the first liberal Europeans at a time when, in the German states of the first half of the 19th century, promoting economic liberalism and supporting political innovations were synonymous with imprisonment. First elected to the Württemberg Parliament after a campaign in support of the German Customs Union (Petition of Reutlingen, 1821), he was sentenced to ten months of “embastillement” in the fortress of Hohenasperg. He fled to France and settled in Strasbourg, where he quickly learned French. In 1824 he met Victor Cousin and the Marquis de Lafayette. Put under observation by Louis XVIII's police in September 1822, after being considered a “Swabian revolutionary” by Chancellor Metternich, F. List emigrated in 1825 to the United States, where he propagated his railway ideals. Returning to Germany in 1832, he published in 1833 “Über ein sächsisches Eisenbahnsystem als Grundlage eines allgemeinen deutschen Eisenbahnsystems, insbesondere über die Anlegung einer Eisenbahn zwischen Leipzig und Dresden.”

F. List saw in the railroad the end of mankind's ills, in particular wars and famines. Roth (p. 45) notes that many intellectuals developed a cosmopolitan vision of railroad development in Europe.

He took part in the launch of the first long-distance railroad line between Leipzig and Dresden (Guihéry, 2014). At the time, Leipzig was a driving force behind Germany's economic and commercial development (industrialization around weaving, printing, books, fairs, and banking — the Bank of Leipzig was created in 1838) F. List attended the opening of the first section of the line between Leipzig and Althen on April 24, 1837.

Having been sidelined from the project he had initiated, he went into exile in France from October 1837 to May



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1840 with his son Oskar. He wrote articles for A. Thiers's pro-government newspaper *Le Constitutionnel*. In 1840 he was twice nominated for the Prix de l'Académie des Sciences Morales et Politiques. Returning to Germany in 1840, F. List gradually marginalized himself from German and European society, ending his life in November 1846 in Kufstein during a trip to Italy.

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DESIGNING A SYSTEMATIC INDICATOR FRAMEWORK FOR THE 15-MINUTE CITY: BALANCING POLICY RELEVANCE, MODELLABILITY, AND TRANSFERABILITY

VON Y. DENG, D. LAHNSTEINER, B. ZHAO, M. QURASHI, S. CHOWDHURY, E. MAGKOS

1. Introduction

The 15-minute City (15mC) urban planning concept promotes livable, sustainable, and resilient cities where residents can access daily needs—such as work, education, healthcare, and recreation—within a 15-minute walk or bike ride (Moreno et al. 2021). By encouraging local living and multimodal access, it aims to reduce car dependency, support environmental sustainability, and strengthen social cohesion (Allam et al. 2024; Krauze-Maślankowska and Maślankowski 2025; Pozoukidou and Angelidou 2022). Since its introduction by Carlos Moreno in 2016, the concept has been adapted and applied globally in different forms, including x-minute city concepts and complete neighborhoods (C40 Knowledge Hub 2026; Logan et al. 2022). Public transport complements the 15mC perspective by extending accessibility beyond neighborhood boundaries and supporting inclusivity for people who cannot rely solely on active modes.

Recent studies propose multi-dimensional indicator frameworks to assess neighborhood accessibility through proximity, density, diversity, walkability, and spatial equity (Aboulmaga et al. 2025; Caselli 2021; Murgante, Valluzzi, and Annunziata 2024). While most studies identify relevant dimensions of the 15mC, they do not always clarify which indicators can be used for scenario-based evaluation, which indicators require local context specific input data, and which indicators primarily serve as descriptive baseline indicators. This distinction is important for decision-support systems, where indicators need to be not only policy-relevant, but also technically feasible, data-aware and transferable across different urban contexts.

The PERSEUS project (Policy Effect Navigator: A Map-based Tool for Effective and Equitable 15-Minute City Policy Synthesis) addresses this gap by linking conceptual indicator frameworks with analytical modelling and decision support. Within PERSEUS, the Rapidex model (Waller et al. 2021), a rapid origin–destination estimation tool using pervasive traffic data, is used as modelling basis for scenario-responsive indicator calculation. However, not all 15mC indicators can be integrated into such traffic model in the same way. Some indicators can be calculated with generally available open data and/or model outputs, some are computable in principle but require additional local datasets, while others are mainly useful as contextual information for interpreting local planning conditions.

The distinctions of the three types of indicators are provided in Section 3.

2. Objectives

Therefore, the objective of this contribution is to present a simplified classification framework for distinguishing the expected use of 15mC indicators in a decision-support context. The framework groups indicators as model-ready, data-limited, or reference-only according to their modelling suitability, data requirements, and potential integration within a decision support system (DSS). Specifically, the study applies this logic to selected indicators across five thematic areas: Accessibility, Environment, Economy, Equity, and Traffic System. The classification aims to provide a transparent basis for organizing policy-relevant indicators for evidence-based 15mC planning.

3. Methodology

The framework combines conceptual and model-oriented perspectives to identify and structure indicators for sustainable urban mobility and 15mC planning. The process began with a screening of indicators from literature, existing indicator frameworks, previous project work, and planning inputs from six pilot cities across three countries. This ensured that the indicator set reflects both conceptual relevance to the 15mC and practical relevance to local planning contexts.

The collected indicators were then screened according to following criteria: their relevance to 15mC planning, their policy relevance in the pilot-city context, and their expected suitability for scenario-based modelling. In the PERSEUS context, the Rapidex model serves as one reference point for assessing whether selected indicators can be calculated from open data and/or traffic model outputs, or whether additional local datasets are required.

Based on this screening, each indicator was assigned to one of three analytical roles: Model-ready indicators are indicators that can be calculated with available open data and/or computable from the traffic modelling workflow. Data-limited indicators are computable in principle but require additional local datasets whose availability or quality may differ across cities. Reference-only indicators are policy-relevant indicators that are not directly computable within the modelling workflow but support contextual evaluation, benchmarking, or stakeholder discussion.

4. Main Results

The classification framework resulted in a structured indicator set (Table 1) across five thematic categories: Accessibility, Environment, Economy, Equity and Traffic System.



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These categories represent complementary dimensions for cities' transformation toward 15mC, covering multimodal reachability to daily needs and services, environmental impacts of traffic and mobility-related conditions affecting urban livability, economic resources needed for sustainable transport, fairness in accessibility across user groups, and operational performance and safety of the transport system. Beyond the thematic structure, the classification shows that the indicators differ in their expected role within a decision-support context and cross-city transferability (Table 2). Model-ready indicators are directly suited to scenario comparison, data-limited indicators can be used where suitable local datasets are available, and reference-only indicators support interpretation of existing local conditions and planning needs. Accessibility and traffic system indicators such as 15-

minute accessibility, total system travel time and congestion index are directly suited for model-based scenario evaluation, as they are closely linked to spatial accessibility and traffic-flow-related outputs. Environmental indicators (e.g. traffic emissions and traffic noise) can also support scenario evaluation as they are linked to modelled traffic volumes and speeds. By contrast, indicators such as modal split, motorization rate, sociodemographic profile, air quality, and traffic safety remain important for interpreting local conditions, but depend strongly on specific locally maintained datasets, surveys, or monitoring data.

5. Conclusion

This contribution presents a framework for structuring indicators to support 15mC planning, developed within the PERSEUS project.

▼ Table 1. Indicator set by thematic category

Category	Indicators
Accessibility	• 15-minute accessibility • Barrier-free 15-minute accessibility • Infrastructure accessibility score • Accessibility to public transport and shared mobility services • Public transport service quality class
Environment	Environmental impact and exposure: • Traffic emissions • Traffic noise • Heat stress index • Air quality Mobility-related spatial conditions: • Quality for walking • Quality for biking • Street greening index • Share of cycling network, shared streets and pedestrian zones • Number of parking spaces in public space
Economy	• Traffic energy and fuel consumption • Infrastructure costs for active mobility • Infrastructure costs for public transport
Equity	• Equity in 15-minute accessibility by mode • Equity in infrastructure accessibility score • Socio-demographic profile
Traffic System	• Total system travel time • Congestion index • Modal split • Motorization rate • Traffic safety



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▼ Table 2. Indicator classification and expected DSS role, transferability and examples.

Classification	DSS Role	Transferability	Example Indicators
Model-ready	Used as scenario-sensitive indicators for scenario comparison and model-based evaluation	Comparable where open data and model outputs are consistent	15-minute accessibility; total system travel time; congestion index; traffic emissions; traffic noise
Data-limited	Used where local datasets are available	Dependent on local data availability and quality	Barrier-free 15-minute accessibility; accessibility to public transport and shared mobility services
Reference-only	Used for context and interpretation	Useful for comparison where definitions are harmonized; not directly model-based	Modal split; motorization rate; socio-demographic profile; air quality; traffic safety

By combining spatial, economic, equity and traffic system perspectives, it links the proximity-based urban living concept with the practical requirements of modelling and decision support. The distinction between model-ready, data-limited, and reference-only indicators clarifies that policy-relevant indicators differ in their suitability for scenario evaluation, data requirements, and transferability across urban contexts. Challenges remain regarding data availability, data quality, and the integration of locally specific indicators into transferable modelling workflows. At the same time, the framework supports more transparent and evidence-based decision-making, especially where open data and modelling outputs can be used consistently across cities. Future work will test and refine model-ready indicators using pilot-city data and traffic modelling outputs, discuss the results with pilot-city stakeholders, and incorporate their feedback. The refined indicator set will then be integrated into the PERSEUS decision support system.

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GETEILTE MOBILITÄT IM SUBURBANEN RAUM – NUTZUNG, HÜRDEN UND QUALITÄTSHEBEL AM BEISPIEL PERCHTOLDSDORF

VON B. SEYWERTH, M. WEBER

Kurzfassung

Geteilte Mobilitätsangebote gelten als wichtiger Baustein einer nachhaltigen Mobilitätswende. Während sie in urbanen Räumen zunehmend etabliert sind, bleibt ihre Alltagstauglichkeit im suburbanen Kontext häufig begrenzt. Gerade Gemeinden im Stadtumland sind durch hohe Pkw-Verfügbarkeit, disperse Wegebeziehungen, Pendelverflechtungen und differenzierte Mobilitätsbedürfnisse geprägt. Die zentrale Herausforderung besteht daher weniger darin, einzelne Angebote bereitzustellen, sondern diese so in den lokalen Mobilitätsalltag einzubetten, dass sie als verlässliche, leicht zugängliche und situationsadäquate Alternative wahrgenommen werden.^[1]

Der Beitrag untersucht am Beispiel der Marktgemeinde Perchtoldsdorf, wie ausgewählte bestehende und ehemalige Angebote geteilter Mobilität – P'Taxi, Nextbike, Postbus Shuttle sowie ein früheres Carsharing-Angebot – von Einwohner:innen wahrgenommen, genutzt und hinsichtlich ausgewählter Qualitätsdimensionen bewertet werden. Methodisch basiert die Untersuchung auf einem Mixed-Methods-Design. Im Zeitraum von 24. September bis 30. November 2025 wurde ein standardisierter Onlinefragebogen mit geschlossenen Bewertungsfragen und offenen Freitextfeldern eingesetzt. Insgesamt gingen 51 vollständig ausgefüllte Fragebögen in die Auswertung ein. Die quantitativen Daten wurden deskriptiv ausgewertet, die offenen Antworten mittels qualitativer Inhaltsanalyse strukturiert.^[2]

Die Ergebnisse zeigen ein wiederkehrendes Muster: Die untersuchten Angebote sind in der lokalen Bevölkerung grundsätzlich präsent, ihre tatsächliche Nutzung bleibt jedoch deutlich hinter der Bekanntheit zurück. Als zentrale Nutzungsgründe werden Flexibilität, Komfort, Zeitersparnis, die Vermeidung von Parkplatzsuche sowie die Funktion als Ersatzlösung bei fehlender Pkw-Verfügbarkeit genannt. Demgegenüber wirken Kosten, eingeschränkte Betriebszeiten, räumlich ungünstige Erreichbarkeit, Wartezeiten, Zuverlässigkeitsprobleme und komplexe bzw. störungsanfällige Buchungsprozesse als zentrale Nutzungshürden.^[3] Besonders relevant ist dabei die Kumulation einzelner Barrieren: Bereits kleinere Defizite in Verfügbarkeit, Information oder Prozessqualität können das Vertrauen in ein Angebot erheblich reduzieren.

Der Beitrag leitet daraus Qualitätshebel für Gemeinden und Betreiber ab. Prioritär erscheinen eine höhere betriebliche Verlässlichkeit,

transparente Informations- und Buchungsketten, bedarfsgerechte Betriebszeiten, eine stärkere tarifliche und kommunikative Integration in den öffentlichen Verkehr sowie eine standortbezogene Angebotsplanung. Für den suburbanen Raum zeigt sich damit: Nicht das grundsätzliche Interesse an geteilten Mobilitätsangeboten ist der Engpass, sondern deren Service- und Prozessqualität sowie ihre systemische Einbettung in bestehende Alltagsmobilität.

1. Einleitung

Die Transformation des Verkehrssystems zählt zu den zentralen Aufgaben kommunaler und regionaler Mobilitätspolitik. Während in dicht bebauten urbanen Räumen kurze Wege, hohe ÖV-Dichten und multimodale Angebotsstrukturen vergleichsweise günstige Voraussetzungen für eine Reduktion des motorisierten Individualverkehrs schaffen, stellt sich die Ausgangslage in suburbanen Räumen deutlich komplexer dar. Dort treffen hohe Pkw-Verfügbarkeit, disperse Siedlungsstrukturen, unterschiedliche Zielgruppenbedürfnisse und starke Pendelverflechtungen aufeinander. Nachhaltige Mobilitätsangebote müssen daher nicht nur ökologisch wünschenswert, sondern im Alltag zuverlässig, verständlich, leistbar und zeitlich konkurrenzfähig sein.^[4]

Die Marktgemeinde Perchtoldsdorf steht exemplarisch für diese Herausforderung. Die Gemeinde liegt im südlichen Wiener Umland und ist funktional eng mit Wien, insbesondere mit dem Verkehrsknoten Wien Liesing, verflochten. Eine lokale Mobilitätsaufnahme weist darauf hin, dass in Perchtoldsdorf an einem Werktag 57 % der Wege mit dem motorisierten Individualverkehr und 17 % der Wege mit dem öffentlichen Verkehr zurückgelegt werden.^[5] Ergänzende Mobilitätsangebote wie kommunale Taxiangebote, Bike-Sharing, On-Demand-Shuttles oder Carsharing können hier potenziell eine Brückenfunktion übernehmen. Sie können Wege zum öffentlichen Verkehr erleichtern, Lücken im Linienverkehr schließen, Mobilität ohne eigenes Fahrzeug ermöglichen und damit die Abhängigkeit vom privaten Pkw reduzieren.

Gleichzeitig zeigt die Praxis, dass die bloße Verfügbarkeit solcher Angebote nicht automatisch zu einer regelmäßigen Nutzung führt. Viele Angebote werden wahrgenommen, aber nur selektiv oder gar nicht in Routinen integriert. Für Gemeinden und Betreiber:innen stellt sich daher die Frage, welche Qualitätsmerkmale über Akzeptanz und Nutzung entscheiden. Im Fokus stehen dabei nicht nur klassische Angebotsparameter wie Preis, Betriebszeit oder räumliche Abdeckung, sondern ebenso Prozessmerkmale: Wie einfach ist die Buchung? Wie nachvollziehbar sind Haltepunkte oder Stationen? Wie zuverlässig ist die tatsächliche Leistungserbringung?



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Wie transparent wird über Wartezeiten, Verfügbarkeit oder Störungen informiert?

Der vorliegende Beitrag greift diese Fragen anhand einer empirischen Untersuchung in Perchtoldsdorf auf. Analysiert werden vier Mobilitätsangebote mit unterschiedlichen Betriebslogiken: das kommunale P'Taxi, das stationsbasierte Fahrradverleihsystem Nextbike, das On-Demand-Angebot Postbus Shuttle sowie ein früheres stationsbasiertes Carsharing-Angebot.^[6] Ziel ist es, Nutzungsmuster, Wahrnehmungen und Qualitätsurteile vergleichend zu untersuchen und daraus übertragbare Hinweise für die Weiterentwicklung geteilter Mobilität im suburbanen Raum abzuleiten.

Die leitende Fragestellung lautet: Welche Nutzungshürden und Qualitätshebel lassen sich aus der Wahrnehmung und Bewertung geteilter Mobilitätsangebote im suburbanen Raum ableiten?

2. Geteilte Mobilität im suburbanen Raum als Umsetzungsproblem

Geteilte Mobilität wird häufig als Bestandteil einer multimodalen und ressourcenschonenden Verkehrsentwicklung verstanden.

Sie umfasst Angebotsformen, bei denen Fahrzeuge oder Fahrdienste nicht individuell besessen, sondern gemeinschaftlich oder bedarfsbezogen genutzt werden.

Dazu zählen Bike-Sharing, Carsharing, On-Demand-Shuttles, Rufbus- und Taximodelle sowie lokale Mischformen kommunaler Mobilitätsdienste.^[7] Ihr Beitrag zur Verkehrswende hängt jedoch wesentlich davon ab, ob sie private Pkw-Wege ersetzen, öffentliche Verkehrssysteme ergänzen oder neue Mobilität zusätzlich erzeugen. Im suburbanen Raum ist diese Wirkung besonders voraussetzungsreich. Zum einen bestehen dort häufig längere Wege, topografische Unterschiede und geringere Angebotsdichten des öffentlichen Verkehrs. Zum anderen ist der private Pkw vielfach verfügbar und aus Nutzer:innensicht mit hoher Flexibilität verbunden. Geteilte Mobilitätsangebote treten somit nicht nur in Konkurrenz zu anderen öffentlichen Angeboten, sondern vor allem zum Komfort- und Sicherheitsversprechen des eigenen Fahrzeugs.

Die Nutzung geteilter Mobilität setzt daher ein Mindestmaß an Verlässlichkeit voraus: Das Angebot muss im entscheidenden Moment verfügbar, verständlich zugänglich und als risikoarm wahrgenommen werden.



▲ Abbildung 1: Untersuchungslogik des Beitrags – von Angebotspräsenz über Nutzungserfahrung zu Qualitätshebeln



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Für die Bewertung solcher Angebote reicht eine rein infrastrukturelle Betrachtung nicht aus. Relevant sind sowohl funktionale Eigenschaften – etwa Betriebszeiten, Stationendichte, Preisstruktur oder Buchungsmöglichkeiten – als auch nicht-funktionale Qualitätsmerkmale wie Zuverlässigkeit, Transparenz, subjektive Sicherheit, Bedienbarkeit und Vertrauen. Gerade im Alltag können nicht-funktionale Merkmale entscheidend sein. Ein Angebot, das grundsätzlich vorhanden ist, aber mehrfach nicht erscheint, dessen App unzuverlässig funktioniert oder dessen Stationen unklar auffindbar sind, verliert rasch seine praktische Relevanz. Umgekehrt kann ein Angebot mit begrenztem Umfang dann akzeptiert werden, wenn seine Nutzung einfach, planbar und verlässlich ist.

Die untersuchten Angebote in Perchtoldsdorf repräsentieren unterschiedliche Varianten dieser Logik. Das P'Taxi ist ein kommunal gestütztes Ortstaxi, das auf Türnähe und flexible Einzelwege ausgerichtet ist.^[8] Nextbike steht für ein stationsbasiertes Bike-Sharing-Angebot, das insbesondere kurze Wege, Anschlussmobilität und spontane Nutzung adressiert.^[9] Das Postbus Shuttle war als On-Demand-Angebot konzipiert und sollte flexibel zwischen definierten Haltepunkten verkehren.^[10]

Das frühere Carsharing-Angebot wiederum zielte auf die gemeinsame Nutzung eines Fahrzeugs und damit auf eine Alternative zum privaten Pkw-Besitz ab.^[11] Die Vergleichbarkeit dieser Angebote liegt nicht in ihrer Betriebsform, sondern in der Frage, ob sie aus Nutzer:innenperspektive alltagstaugliche Ergänzungen zum bestehenden Verkehrssystem darstellen.

3. Untersuchungsdesign

Die Untersuchung folgt einem Mixed-Methods-Ansatz mit Triangulationsdesign.^[12] Quantitative und qualitative Daten wurden parallel erhoben und in der Auswertung aufeinander bezogen. Der standardisierte Onlinefragebogen enthielt geschlossene Fragen zu Bekanntheit, Nutzung, Bewertung und möglichen Verbesserungen sowie offene Freitextfelder zur Erfassung individueller Erfahrungen und Kritikpunkte. Die geschlossenen Fragen ermöglichten eine deskriptive Auswertung von Häufigkeiten und Bewertungsmustern. Die offenen Antworten dienten dazu, die dahinterliegenden Begründungen, Nutzungserfahrungen und wahrgenommenen Problemlagen sichtbar zu machen.

Die Erhebung fand zwischen 24. September und 30. November 2025 statt. Der Fragebogen wurde über digitale Kanäle und lokale Aushänge verbreitet.

	 P'Taxi	 Nextbike	 Postbus Shuttle	 Carsharing
 Betriebslogik	kommunales Ortstaxi	stationsbasiertes Bikesharing	On-Demand-Shuttle	stationsbasiertes Fahrzeugsharing
 Räumliche Logik	gemeindeweit / haustürnah	Stationsnetz	Bediengebiet mit Haltepunkten	einzelne Standorte
 Zugang / Buchung	Telefon / Reservierung	App / Kundenkonto	App / Vorausbuchung	digitale Buchung
 Zielnutzen	flexible Alltagswege	kurze Wege & Anschlussmobilität	Ergänzung zum öffentlichen Verkehr	Alternative zum privaten Pkw
 Typische Nutzungshürden	Kosten, Wartezeit	Stationsdichte	App & Zuverlässigkeit	geringe Bekanntheit

▲ Abbildung 2: Angebotslandschaft geteilter Mobilität in Perchtoldsdorf

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▲ Abbildung 3: Methodisches Vorgehen und Auswertungslogik

Insgesamt wurden 77 Fragebogeneinträge begonnen; 51 vollständig ausgefüllte Fragebögen wurden in die Auswertung einbezogen.^[13] Die Stichprobe erlaubt damit keine repräsentative Abbildung der Gesamtbevölkerung Perchtoldsdorfs. Sie bietet jedoch eine explorative Grundlage, um erste Muster, wiederkehrende Nutzungshürden und prioritäre Qualitätsdimensionen zu identifizieren.

Die untersuchten Bewertungsdimensionen orientierten sich an vier Hauptkategorien: Verfügbarkeit, Kosten, Zugänglichkeit und Zufriedenheit. Ergänzend wurden Zuverlässigkeit, Flexibilität, Komfort, Informationsqualität und Umweltwahrnehmung berücksichtigt.^[14]

Diese Dimensionen bilden eine Schnittstelle zwischen klassischer Angebotsbewertung und serviceorientierter Qualitätsanalyse. Die Auswertung der offenen Antworten erfolgte thematisch nach dem Grundprinzip der qualitativen Inhaltsanalyse.^[15] Wiederkehrende Aussagen wurden gebündelt und Kategorien zugeordnet, etwa Zuverlässigkeit und Pünktlichkeit, Betriebszeiten, Buchungsprozess, Preisgestaltung, Stationsdichte,

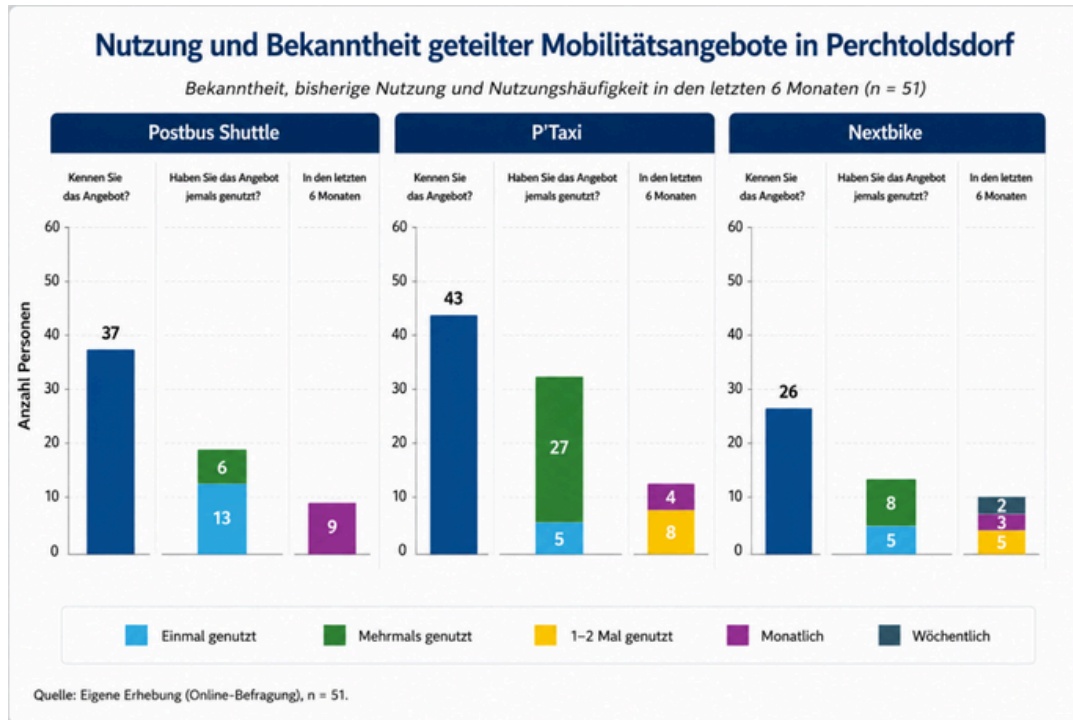
Informationsqualität oder Verhalten des Fahrpersonals. Methodisch ist die Untersuchung explorativ angelegt. Ihr Anspruch liegt nicht in einer repräsentativen Wirkungsanalyse, sondern in der systematischen Verdichtung von Nutzer:innenwahrnehmungen zu kommunal relevanten Qualitätshebeln. Gerade für Gemeinden kann ein solcher Zugang wertvoll sein, weil Nutzungsentscheidungen häufig nicht allein aus objektiven Angebotsdaten erklärt werden können. Wahrnehmung, Vertrauen und Alltagserfahrung beeinflussen, ob ein Mobilitätsangebot als reale Option in Betracht gezogen wird.

4. Ergebnisse

4.1 Bekanntheit und Nutzung: Sichtbarkeit ist nicht gleich Alltagsintegration

Über alle betrachteten Angebote hinweg zeigt sich ein konsistentes Muster: Die Angebote sind grundsätzlich bekannt, ihre tatsächliche Nutzung bleibt jedoch deutlich dahinter zurück.^[16] Besonders beim P-Taxi und beim Postbus Shuttle ist die Sichtbarkeit vergleichsweise hoch. Viele Befragte kennen die Angebote, nutzen sie aber selten oder gar nicht. Auch Nextbike weist eine gewisse Bekanntheit auf, erreicht jedoch nur eine begrenzte Nutzung. Das frühere Carsharing-Angebot ist demgegenüber nur einem kleineren Teil der Befragten

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▲ Abbildung 4: Bekanntheit und tatsächliche Nutzung der untersuchten Angebote ((N=51; Anzahl gültiger Antworten variiert je Frage bzw. Filterführung.)

bekannt und wurde kaum genutzt.

Dieses Ergebnis verweist auf eine zentrale Differenz zwischen Angebotspräsenz und Angebotsintegration. Ein Mobilitätsangebot kann lokal sichtbar sein, ohne im Alltag als verlässliche Option etabliert zu sein. Für die kommunale Angebotsentwicklung ist diese Unterscheidung wesentlich. Bekanntheit stellt lediglich eine Vorbedingung dar. Alltagsintegration entsteht erst, wenn ein Angebot in wiederkehrenden Situationen tatsächlich als geeignet, verlässlich und leicht zugänglich erlebt wird.

Die untersuchten Angebote erfüllen aus Sicht der Befragten durchaus spezifische Funktionen. P'Taxi wird insbesondere mit Haustürnähe, Komfort und Flexibilität verbunden. Nextbike wird als umweltfreundliche, spontane und bewegungsorientierte Option wahrgenommen, insbesondere für kurze Wege oder als Ersatz bei Ausfällen im öffentlichen Verkehr. Das Postbus Shuttle wird in der Idee als ergänzendes Angebot anerkannt, insbesondere für Zeiten oder Relationen mit eingeschränktem Linienverkehr. Carsharing wird eher als potenzielle Option verstanden, sofern Standort, Verfügbarkeit und Buchungslogik stimmen. In allen Fällen entscheidet jedoch die konkrete Umsetzung darüber, ob aus grundsätzlicher Zustimmung tatsächliche Nutzung wird.

4.2 Nutzungsgründe: Flexibilität, Komfort und Ersatzfunktionen

Als wichtigste Nutzungsgründe treten Flexibilität und Komfort hervor. Diese Motive beziehen sich einerseits auf die räumliche Nähe bzw. Haustürnähe einzelner Angebote, andererseits auf die Möglichkeit, unabhängig von Fahrplänen oder starren Linienwegen mobil zu sein. Insbesondere das P'Taxi wird in diesem Zusammenhang als komfortorientierte Ergänzung wahrgenommen. Auch das Postbus Shuttle und Nextbike werden dort positiv bewertet, wo sie spontane Mobilität ermöglichen oder Lücken im bestehenden Angebot schließen.^[17]

Ein zweites Motiv ist Zeitersparnis. Angebote geteilter Mobilität werden dann als attraktiv wahrgenommen, wenn sie Wartezeiten reduzieren, Umwege vermeiden oder den Zugang zu zentralen Verkehrsknoten erleichtern. Für Perchtoldsdorf ist hierbei insbesondere die Verbindung zum Bahnhof Wien Liesing relevant. Die Vermeidung von Parkplatzsuche stellt ein weiteres wiederkehrendes Motiv dar. Geteilte Mobilität wird in solchen Fällen nicht primär als ideologische Alternative zum Auto verstanden, sondern als pragmatische Lösung für konkrete Situationen.

Ein drittes Motiv betrifft Ersatzfunktionen. Befragte nennen die Nutzung bei fehlendem eigenem Fahrzeug, bei zeitweise nicht verfügbarer Pkw-Nutzung oder bei Lücken im öffentlichen Verkehr. Damit übernehmen die Angebote eine



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Sicherungsfunktion im Mobilitätssystem. Sie werden nicht zwingend täglich genutzt, können aber in bestimmten Situationen entscheidend sein. Für Gemeinden ist dies relevant, weil der Nutzen solcher Angebote nicht allein über hohe tägliche Nutzungsfrequenzen bewertet werden sollte. Auch eine robuste Verfügbarkeit in Randzeiten, bei Störungen oder für spezifische Zielgruppen kann einen hohen kommunalen Mehrwert erzeugen.

Bei Nextbike treten zusätzlich Umweltfreundlichkeit sowie Bewegung und Gesundheit als Motive auf. Diese Motive sind jedoch nicht ausreichend, wenn räumliche oder praktische Hürden bestehen. Umweltargumente können eine Nutzung unterstützen, ersetzen aber nicht die Anforderungen an Erreichbarkeit, Verfügbarkeit und einfache Handhabung.

4.3 Nutzungshürden: Kosten, Betriebszeiten, Erreichbarkeit und Prozessqualität

Die Gründe gegen eine Nutzung sind differenzierter und zeigen, dass mehrere Barrieren gleichzeitig wirken können. Beim P'Taxi werden insbesondere Kosten, eingeschränkte Betriebszeiten, Wartezeiten und Zuverlässigkeitsprobleme genannt.^[18] Der Wunsch nach längeren Abend- und Nachtbetriebszeiten ist deutlich ausgeprägt. Dies verweist auf eine typische Funktion solcher Angebote: Sie werden nicht nur für planbare Tageswege, sondern gerade auch für Situationen mit

eingeschränkter ÖV-Verfügbarkeit oder erhöhtem Komfortbedürfnis nachgefragt.

Beim Postbus Shuttle treten vor allem Wartezeiten, komplizierte Buchung, App-Probleme und betriebliche Unzuverlässigkeit hervor.^[19] In den offenen Antworten verdichten sich diese Erfahrungen zu grundlegenden Vertrauensproblemen. Wenn ein On-Demand-Angebot nicht zuverlässig erscheint, Buchungen nicht nachvollziehbar funktionieren oder Hilfestellungen als unzureichend erlebt werden, wird die Nutzungsschwelle deutlich erhöht. Gerade On-Demand-Systeme leben jedoch vom Versprechen spontaner, flexibler und digital unterstützter Mobilität. Treten hier Brüche auf, wird das zentrale Leistungsversprechen des Systems infrage gestellt.

Bei Nextbike ist die räumliche Erreichbarkeit der Stationen die zentrale Hürde.^[20] Für viele Befragte liegt die nächstgelegene Station zu weit entfernt. Hinzu kommen begrenzte Transportmöglichkeiten, fehlende E-Bikes oder Lastenräder sowie die eingeschränkte Eignung für ältere oder mobilitätseingeschränkte Personen. Damit wird deutlich, dass Bike-Sharing im suburbanen Raum stark von Stationsdichte, topografischer Eignung und Fahrradtyp abhängt. Ein klassisches Fahrradangebot kann kurze Wege erleichtern, deckt aber nicht automatisch heterogene Alltagsbedürfnisse ab.

Beim früheren Carsharing zeigen sich geringe Bekannt-

Nutzungshürden nach Angebotsform				
Nutzungshürden	P'Taxi	Nextbike	Postbus Shuttle	Carsharing (ehemalig)
Kosten	hoch (n = 16)	gering (n = 2)	mittel (n = 5)	mittel (n = 3)
Betriebszeiten (Verfügbarkeit)	hoch (n = 12)	mittel (n = 6)	hoch (n = 10)	
Räumliche Erreichbarkeit / Stationen		hoch (n = 15)	mittel (n = 6)	mittel (n = 5)
Wartezeit	mittel (n = 7)		hoch (n = 13)	
Zuverlässigkeit	hoch (n = 10)	gering (n = 2)	hoch (n = 12)	mittel (n = 3)
Buchung / App (Handhabung)	mittel (n = 6)	mittel (n = 5)	hoch (n = 12)	mittel (n = 5)
Informationsqualität (Transparenz)	hoch (n = 11)	mittel (n = 3)	hoch (n = 15)	
Zielgruppeneignung (Barrierefreiheit)	mittel (n = 7)	hoch (n = 20)	gering (n = 2)	

geringe Relevanz (wenige Nennungen)
mittlere Relevanz (mittlere Anzahl an Nennungen)
hohe Relevanz (viele Nennungen)
keine eindeutige Datenbasis

▲ Abbildung 5: Nutzungshürden nach Angebotsform (Mehrfachnennungen möglich)



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heit, geringe Nutzung und zurückhaltendes Interesse.^[21] Als Hürden werden unter anderem komplizierte Buchung, entfernte Stationen, fehlender Bedarf, Kosten und Verfügbarkeit genannt. Für eine mögliche Neuauflage wäre daher nicht allein ein Fahrzeug entscheidend, sondern die Einbindung in ein lokales Mobilitätssystem: gute Standorte, einfache digitale Zugänge, transparente Preise und Kooperationen mit ÖV- oder Gemeindestrukturen.

4.4 Servicequalität als Schlüsselfaktor

Ein zentrales Ergebnis ist die Bedeutung der Service- und Prozessqualität. Die untersuchten Angebote werden nicht ausschließlich anhand ihrer Existenz oder ihres grundsätzlichen Nutzens bewertet, sondern stark anhand konkreter Nutzungserfahrungen. Dabei sind Zuverlässigkeit, Pünktlichkeit, einfache Buchung, transparente Information und nachvollziehbare Abläufe besonders relevant.

Beim P'Taxi bewegen sich die Bewertungen überwiegend im mittleren Bereich, weisen jedoch eine deutliche Spannweite auf. Dies deutet darauf hin, dass individuelle Erfahrungen stark variieren. Positive Wahrnehmungen entstehen dort, wo das Angebot zuverlässig, komfortabel und unkompliziert funktioniert. Negative Wahrnehmungen entstehen dort, wo Fahrzeuge zu spät kommen, nicht erscheinen oder das Serviceverhalten als unzureichend wahrgenommen wird. Beim Postbus Shuttle fällt die Bewertung stärker durchmischt aus. Die offenen Antworten legen nahe, dass technische und

organisatorische Probleme besonders stark auf die Gesamtbewertung wirken. Eine fehleranfällige App, unklare Vorausbuchungen oder mangelnde Hilfestellung über die Hotline sind nicht bloß technische Randprobleme, sondern berühren die Kernfunktion des Angebots. Gerade bei digitalen Mobilitätsdiensten ist die Buchungskette Teil der Servicequalität.

Bei Nextbike wird die grundsätzliche Nutzbarkeit positiver bewertet, die Eignung für ältere oder mobilitätseingeschränkte Personen jedoch deutlich kritischer gesehen. Dies zeigt, dass Servicequalität zielgruppenspezifisch bewertet werden muss. Ein Angebot kann für eine mobile, digital affine und fahrraderfahrene Nutzer:innengruppe gut funktionieren, gleichzeitig aber für andere Gruppen faktisch nicht zugänglich sein.

5. Diskussion: Vom Angebotsdenken zur Qualitätslogik

Die Ergebnisse legen nahe, geteilte Mobilität im suburbanen Raum weniger als isolierte Angebotskategorie und stärker als Qualitäts- und Integrationsaufgabe zu verstehen. Die zentrale Frage lautet nicht nur, ob ein Angebot vorhanden ist, sondern ob es in den relevanten Alltagssituationen verlässlich funktioniert. Daraus ergeben sich vier übergreifende Diskussionslinien.

Erstens ist Bekanntheit notwendig, aber nicht hinreichend. Die untersuchten Angebote zeigen, dass lokale Sichtbarkeit nicht automatisch zu Nutzung führt. Informationskampagnen allein werden daher nur



▲ Abbildung 6: Von Einzelhürden zu kritischen Nutzungsbarrieren - Verdichtung der Freitextantworten (Mehrfachnennungen möglich)



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begrenzt wirken, wenn zentrale Nutzungshürden bestehen bleiben. Kommunikation muss mit einer tatsächlichen Verbesserung der Leistungserbringung verbunden sein.

Zweitens entscheidet Verlässlichkeit über Vertrauen. Wiederholte negative Erfahrungen – etwa verspätete Fahrzeuge, nicht nachvollziehbare Buchungen oder unklare Stationen – können ein Angebot dauerhaft diskreditieren. Besonders problematisch ist dies bei Angeboten, die als Ersatz für den privaten Pkw oder als Ergänzung zum öffentlichen Verkehr dienen sollen. Wer ein Angebot für Anschlusswege, Randzeiten oder wichtige Termine nutzen möchte, toleriert nur begrenzte Unsicherheit.

Drittens muss Zugänglichkeit breiter verstanden werden. Zugänglichkeit umfasst nicht nur räumliche Nähe, sondern auch digitale Bedienbarkeit, Verständlichkeit, Barrierearmut, Preistransparenz und soziale Servicequalität. Gerade ältere Personen, Menschen mit Mobilitätseinschränkungen oder digital weniger affine Gruppen können durch komplexe Buchungsprozesse, unklare Informationen oder fehlende Hilfestellung ausgeschlossen werden.

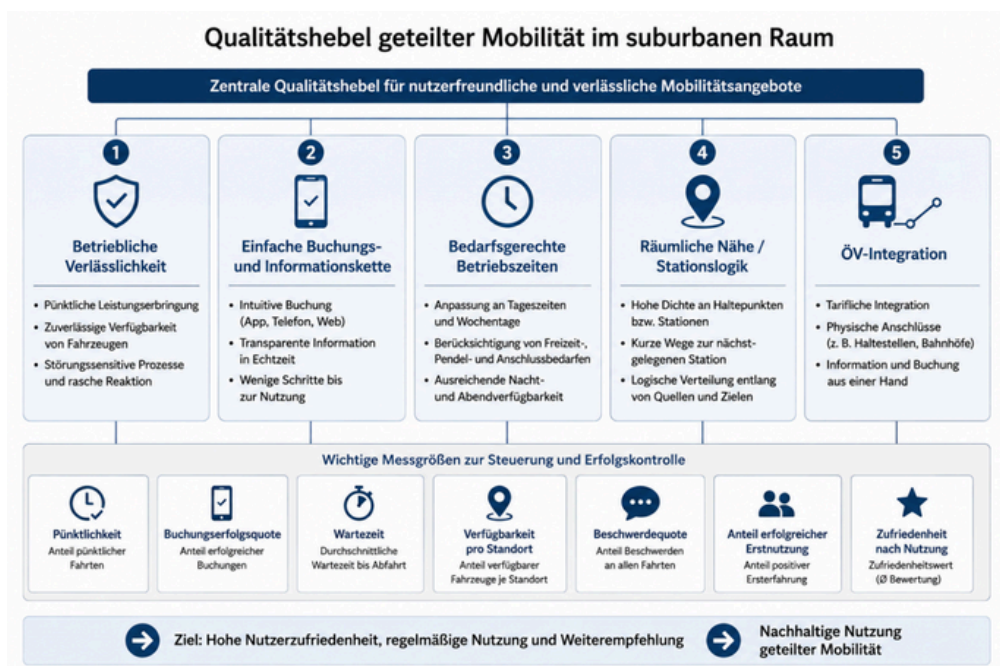
Viertens braucht geteilte Mobilität eine stärkere Integration in den öffentlichen Verkehr. Mehrere Befragte wünschen eine Kombination mit ÖV-Tickets oder eine bessere Anbindung an Knotenpunkte.^[22]

Dies verweist auf ein systemisches Problem: Solange Angebote als separate Einzeldienste erscheinen, bleiben sie Zusatzoptionen. Erst durch tarifliche, informationelle und räumliche Verknüpfung können sie als Bestandteil einer integrierten Mobilitätskette wirken. Für kommunale Mobilitätspolitik ergibt sich daraus ein Perspektivenwechsel. Nicht jedes Angebot muss maximal ausgebaut werden. Entscheidend ist, jene Qualitätshebel zu identifizieren, die den größten Einfluss auf Nutzung und Vertrauen haben. Im vorliegenden Fall sind dies insbesondere Verlässlichkeit, einfache Buchung, klare Information, bedarfsgerechte Betriebszeiten und räumliche Nähe. Diese Merkmale lassen sich als nicht-funktionale Anforderungen an kommunale Mobilitätsangebote verstehen: Sie beschreiben nicht nur, was ein Angebot leisten soll, sondern wie gut, wie zuverlässig und unter welchen Nutzungsbedingungen es funktionieren muss.

6. Handlungsempfehlungen

Aus den Ergebnissen lassen sich angebotsbezogene und übergreifende Handlungsempfehlungen ableiten.

Für das P'Taxi sollte die betriebliche Verlässlichkeit priorisiert werden. Dazu zählen klare Qualitätsstandards für Pünktlichkeit, nachvollziehbare Bestell- und Rückmeldeprozesse sowie eine transparente Kommunikation bei Verzögerungen. Der starke Wunsch nach längeren Abend- und Nachtbetriebszeiten spricht dafür, das Angebot gezielt für Randzeiten zu prüfen. Eine



▲ Abbildung 7: Qualitätshebel geteilter Mobilität im suburbanen Raum



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Angebot	Zentrales Problem (laut Befragung)	Prioritäre Maßnahme	Mögliche Kennzahl	Kommunaler Steuerungsansatz
 P'Taxi	• Zu teuer • Ungünstige Betriebszeiten • Zu lange Wartezeiten • Unzuverlässigkeit	 Betriebszeiten ausweiten (Abend/Nacht) und Zuverlässigkeit erhöhen; Preismodell überprüfen bzw. anpassen.	 • Ø Wartezeit • Pünktlichkeit • Preisakzeptanz • Beschwerdequote	 • Leistungsvereinbarungen mit Mindeststandards • Zuschuss-/Anreizsysteme für Abendbetrieb • Monitoring & Qualitätsreports
 Nextbike	• Stationen zu weit entfernt • Kein E-Bike / zu anstrengend • Lastentransport schwierig	 Stationsnetz verdichten, E-Bikes und Lastenräder ausbauen.	 • Verfügbarkeit pro Standort • Auslastung • Anteil Fahrten (> 2 km) • Nutzerzufriedenheit	 • Standortplanung & Flächenbereitstellung • Förderungen für E-Lastenräder • Datenbasierte Standortsteuerung
 Postbus Shuttle / On-Demand	• Buchung kompliziert • Zu lange Wartezeiten • Ungünstige Betriebszeiten • Zuverlässigkeit / App-Probleme	 Buchung und Information vereinfachen (App/Online), Wartezeiten senken und Betriebszeiten an Bedarf anpassen.	 • Buchungserfolgsquote • Ø Wartezeit • Pünktlichkeit • Nutzungsfrequenz	 • Digitale Plattform integrieren • Dynamische Einsatzsteuerung • Kommunikation & Transparenz verbessern
 Carsharing	• Stationen zu weit entfernt • Fahrzeug oft nicht verfügbar • Buchung kompliziert • Geringe Bekanntheit	 Standorte ausweiten, Fahrzeugverfügbarkeit sichern und Buchung vereinfachen.	 • Verfügbarkeit pro Standort • Auslastung • Anteil aktiver Nutzer • Erstnutzungsquote	 • Flächen & Parkplätze bereitstellen • Partnerschaften mit Anbietern • Kommunikationskampagnen & Zielgruppenansprache

▲ Abbildung 8: Angebotsbezogene Handlungsempfehlungen und kommunale Steuerungslogik

App-gestützte oder zumindest digital unterstützte Buchungsoption könnte die Zugänglichkeit erhöhen, sollte aber eine telefonische Alternative nicht ersetzen. Für ältere Personen und mobilitätseingeschränkte Nutzer:innen ist zudem das Serviceverhalten – etwa Hilfestellung beim Ein- und Aussteigen – als Qualitätsmerkmal zu definieren.^[23]

Für Nextbike stehen Stationsdichte, Verfügbarkeit und Fahrradtypen im Vordergrund. Eine Erweiterung des Stationsnetzes sollte nicht nur zentrale Orte, sondern auch Wohnlagen und relevante Wegeketten berücksichtigen. E-Bikes oder Lastenräder könnten die Nutzbarkeit im suburbanen Raum erhöhen, insbesondere bei längeren Wegen, Steigungen oder Transportbedarfen. Gleichzeitig braucht es klare Informationen zur Verfügbarkeit und zum Rückgabeprozess, um spontane Nutzung zu erleichtern.^[24]

Für On-Demand-Angebote wie das Postbus Shuttle sind stabile Buchungs- und Dispatchingprozesse zentral. Eine App ist nur dann ein Qualitätsgewinn, wenn sie verlässlich funktioniert, Echtzeitinformationen bereitstellt und bei Problemen verständliche Alternativen anbietet. Haltepunkte müssen eindeutig kommuniziert und vor Ort nachvollziehbar sein. Vorausbuchungen, Wartezeitinformationen und Störungsmeldungen sollten so gestaltet werden, dass

Nutzer:innen Planungssicherheit erhalten. Darüber hinaus ist die Rolle des Fahrpersonals als Teil der Servicequalität zu berücksichtigen.^[25]

Für ein mögliches zukünftiges Carsharing-Angebot wäre eine isolierte Fahrzeugbereitstellung nicht ausreichend. Entscheidend wären gut erreichbare Standorte, eine einfache Buchung, transparente Kosten, ausreichende Verfügbarkeit und eine Kooperation mit Gemeinde, ÖV-Angeboten oder lokalen Institutionen. Carsharing sollte als Baustein eines integrierten Mobilitätsangebots verstanden werden, nicht als alleinstehende Einzelmaßnahme.^[26]

Übergreifend empfiehlt sich für Gemeinden eine Qualitätslogik mit messbaren Mindestanforderungen. Dazu könnten Kennzahlen wie durchschnittliche Wartezeit, Buchungserfolgsquote, Pünktlichkeit, Verfügbarkeit pro Standort, Beschwerdequote, Anteil erfolgreicher Erstnutzung oder Zufriedenheit nach Nutzung zählen. Ergänzend sollten qualitative Rückmeldungen systematisch erfasst werden, da sie Hinweise auf konkrete Prozessbrüche liefern. Ein regelmäßiges Monitoring kann helfen, Angebote nicht nur einzuführen, sondern iterativ weiterzuentwickeln.

7. Fazit

Die Ergebnisse lassen innerhalb der untersuchten Stichprobe eine grundsätzliche Offenheit gegenüber geteilten Mobilitätsangeboten erkennen. Ihre Nutzung wird jedoch



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wesentlich von der konkreten Service- und Prozessqualität beeinflusst. Am Beispiel Perchtoldsdorf wird sichtbar, dass Bekanntheit und grundsätzliche Zustimmung nicht ausreichen, um Mobilitätsangebote in Alltagsroutinen zu überführen. Entscheidend ist, ob Angebote in relevanten Nutzungssituationen verfügbar, zuverlässig, verständlich, leistbar und einfach zugänglich sind.

Die Erkenntnisse aus den Erhebungen deuten darauf hin, dass Nutzungshürden weniger aus einem grundsätzlichen Desinteresse der Befragten als aus der praktischen Umsetzung der Angebote resultieren. Demgegenüber stehen klare Qualitätshebel: verlässliche Leistungserbringung, transparente Informationsketten, einfache Buchung, bedarfsgerechte Betriebszeiten, bessere Stations- und Haltepunktlogik sowie stärkere Integration in den öffentlichen Verkehr.

Für vergleichbare Gemeinden im suburbanen Raum bedeutet dies: Geteilte Mobilität sollte nicht primär als Sammlung einzelner Angebote geplant werden, sondern als integriertes Dienstleistungssystem mit klaren Qualitätsanforderungen. Gerade dort, wo der private Pkw weiterhin eine starke Stellung hat, müssen alternative Angebote nicht nur vorhanden, sondern im Alltag vertrauenswürdig sein. Die Verkehrswende im suburbanen Raum entscheidet sich damit wesentlich an der Qualität der Umsetzung.

ANMERKUNGEN UND QUELLEN

[1] vgl. VCÖ, „Nachhaltige Mobilität für regionale Zentren“, 5. Dezember 2025; Swarco, „Mobilität der Zukunft“, 12. Dezember 2025.

[2] vgl. Benedikt Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, Bachelorarbeit, Technische Universität Wien, 2026, 2, 13–14.

[3] vgl. Seywerth, Nachhaltige Mobilitätsoptionen, 15–25; Benedikt Seywerth und Marcel Weber, „Geteilte Mobilität im suburbanen Raum: Nutzungshürden und Qualitätshebel“, Kurzdarstellung, 2026.

[4] vgl. VCÖ, „Nachhaltige Mobilität für regionale Zentren“; AustriaTech, „Sharing im Mobilitätsbereich“, 25. Februar 2026.

[5] vgl. Marktgemeinde Perchtoldsdorf, Mobilitätskonzept Mobil2030, Gemeinderatsbeschluss vom 1. Dezember 2020, zit. nach Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel

Perchtoldsdorf, TU Wien, 08.02.2026, Seite 5.

[6] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 5, –11.

[7] vgl. AustriaTech, „Sharing im Mobilitätsbereich“; Bundesministerium für Innovation, Mobilität und Infrastruktur, „Sharing Strategie“, 25. Januar 2026.

[8] vgl. Marktgemeinde Perchtoldsdorf, „P'Taxi“, 24. Juli 2025; Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 10.

[9] vgl. Nextbike, „Nextbike Niederösterreich“, 24. Juli 2025; Marktgemeinde Perchtoldsdorf, „Öffentliches Fahrradverleihsystem NEXTBIKE in Perchtoldsdorf“, 24. Juli 2025; Nextbike, „Standorte“, 25. Januar 2026.

[10] vgl. Postbus, „Mobilregion Mödling“, 27. Juli 2025; MGP Postbus Shuttle, „Was kommt nach dem Postbus Shuttle?“, 4. September 2024.

[11] vgl. regio-aktuell, „Perchtoldsdorf fährt elektrisch“, 7. April 2016; VCÖ, „Carsharing erhöht Effizienz und ersetzt viele Privat-Pkw“, 2024.

[12] vgl. Nicola Döring, Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften, 6. Aufl. (Berlin/Heidelberg: Springer, 2023).

[13] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 13–14.

[14] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 11–12.

[15] vgl. Philipp Mayring, Qualitative Inhaltsanalyse: Grundlagen und Techniken (Weinheim/Basel: Beltz, 2015).

[16] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 15–22.



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[17] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 16– 22.

[18] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 16–17.

[19] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 20–21.

[20] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 18–19.

[21] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 21–22.

[22] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 16–21.

[23] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 26.

[24] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 26.

[25] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 27.

[26] vgl. Seywerth, Nachhaltige Mobilitätsoptionen im suburbanen Raum am Beispiel Perchtoldsdorf, TU Wien, 08.02.2026, Seite 27; VCÖ, „Carsharing erhöht Effizienz und ersetzt viele Privat-Pkw“, 2024.



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EXPLORING BARRIERS TO PUBLIC TRANSPORT ACCESSIBILITY FOR PEOPLE WITH DISABILITIES

VON F. SALMAN, L. JÓNA

1. Introduction

Assessing accessibility is an important part of planning transport systems that meet the needs of different groups of society. Despite efforts to improve equal access, many people with disabilities still experience a gap between available transport services and their real mobility requirements. These limitations often lead to difficulties in reaching important places and affect their life (Wahyuni et al. 2016). Recent research indicates that accessibility challenges are not only physical, but also relate to information and user support, which emphasizes the urgent need for appropriate solutions (Padhil et al. 2024).

Several studies have highlighted the importance of understanding accessibility from the perspective of people with disabilities themselves. User experience can provide valuable insights into difficulties that may not be identified through infrastructure assessments alone. Incorporating users' perspectives into accessibility evaluation can therefore support a more comprehensive understanding of existing transport challenges (Orczyk and Młodystach 2022).

This study aims to explore the main challenges faced by people with disabilities in accessing public Transport and provide practical solutions to improve transport services and make them more inclusive for everyone.

2. Literature Review

Research on public transport accessibility has shown that people with disabilities encounter a variety of barriers when using transport services. Structural barriers, including high platforms, the absence of ramps, inadequate vehicle design, and limited assistance from transport staff, can reduce the usability of public transport and restrict independent mobility (Hossen Sajib 2022; Gorzelanczyk et al. 2022). In addition to physical obstacles, accessibility may also be affected by the availability and accessibility of travel information, particularly for passengers with sensory impairments (Crudden et al. 2015). Furthermore, studies have suggested that compliance with accessibility standards does not always guarantee a satisfactory travel experience, as operational conditions and service delivery can influence how accessibility measures function in practice (Aarhaug and Elvebakk 2015). To better understand these challenges, several studies have emphasized the importance of incorporating the perspectives of people with disabilities into accessibility evaluation.

User experiences can reveal practical difficulties encountered during everyday travel that may not be fully reflected in technical standards or infrastructure assessments (Alldredge 2019; Pigeon et al. 2026). This perspective provides a more comprehensive understanding of accessibility challenges and supports the development of transport services that better address users' needs.

3. Methodology

The study adopted a mixed-methods approach combining field study, a questionnaire survey, and semi-structured interviews. Field studies were conducted at selected public transport locations in Győr to obtain an initial understanding of accessibility conditions and to support the development of the survey and interview questions. The field study focused on aspects related to pedestrian access, stop infrastructure, information provision, and boarding conditions.

Based on the field study, a questionnaire survey was developed to collect users' perspectives on accessibility within the public transport system. The survey consisted of four main sections covering respondents' personal characteristics, travel behaviour and public transport usage, accessibility challenges, and perceptions of safety and comfort while using public transport services. The questionnaire was distributed online between July 8 and October 26, 2025, and received 158 valid responses, primarily from residents of Győr. The responses provided valuable insights into recurring accessibility challenges experienced by public transport users.

To gain a deeper understanding of the issues identified through the survey, semi-structured interviews were conducted with people with disabilities. The interviews explored participants' travel experiences, the difficulties encountered during daily journeys, and their suggestions for improving accessibility. This qualitative component provided additional context and supported a more detailed interpretation of the survey results.

4. Results

The survey sample included a diverse group of public transport users. Females represented 51% of respondents, males accounted for 37%, while 12% preferred not to specify their gender. The largest age group was 41–50 years (29%), followed by respondents aged 18–30 years (21%).

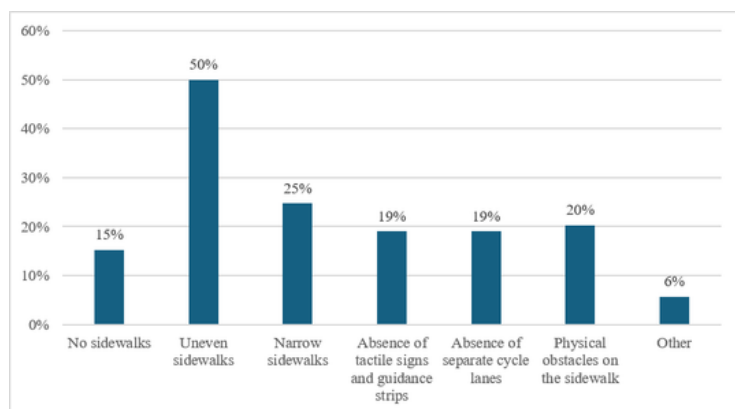
Nearly (48%) of the respondents reported having a disability or a close family member with a disability. Among the reported disability categories, mobility impairments were the most common (35%), followed by autism spectrum disorders (4%) and visual impairments (3%). This distribution is particularly relevant to the study, as mobility-related limitations are among the most significant factors affecting accessibility to public



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transport services. Most respondents reported travelling daily (76%), with shopping and commuting to work representing the most common trip purposes. Walking was the most frequently used mode of transport within the city (59%), followed by private cars (57%) and buses (53%). In addition, approximately 20% of respondents reported not owning a personal vehicle. These findings highlight the importance of maintaining accessible public transport services, particularly for users who rely on them for daily activities.

Most respondents reported relatively short walking distances to the nearest public transport stop. A total of 43% indicated that they could reach the nearest stop in less than five minutes, while 34% reported a walking time of between five and ten minutes. Furthermore, 80% of participants stated that they usually access public transport stops on foot. These findings highlight the importance of pedestrian infrastructure as an essential component of an accessible public transport system, particularly for users with limited mobility.

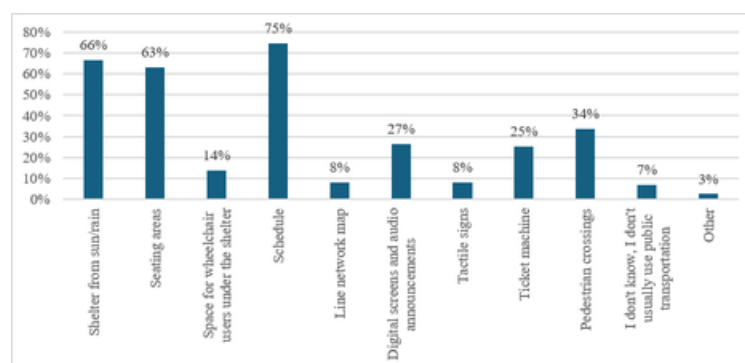


▲ Figure 1. Challenges of walking to the public transport stop

Figure 1 illustrates the main challenges reported by respondents when walking to the nearest public transport stop. Uneven sidewalks were identified as the most common difficulty, affecting 50% of participants. Narrow sidewalks were reported by 25% of respondents, while 20% indicated that physical obstacles such as parked vehicles, waste bins, and advertising boards created difficulties along pedestrian routes.

Other accessibility-related concerns were also reported. The absence of dedicated cycling lanes was identified by 19% of respondents, and a further 19% highlighted difficulties associated with the lack of tactile paving and guidance features. These findings suggest that many users encounter accessibility barriers before reaching public transport stops, potentially affecting the overall travel experience.

Figure 2 presents the accessibility-related features available at the public transport stops most frequently used by respondents. Timetables were the most commonly reported feature (75%), followed by covered shelters (66%) and seating areas (63%). A nearby pedestrian crossing was reported by 34% of respondents, while digital information displays and audio announcements were available at 27% of stops. Ticket machines were identified at 25% of the surveyed locations. Lower levels of availability were reported for features that support the needs of passengers with disabilities. Only 14% of respondents indicated the presence of designated wheelchair space within covered stop areas, while tactile paving and guidance features were reported in just 8% of cases. The results reveal considerable variation in the availability of accessibility features across public transport stops.

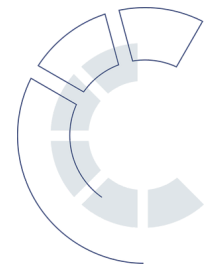


▲ Figure 2. Features at public transport stops

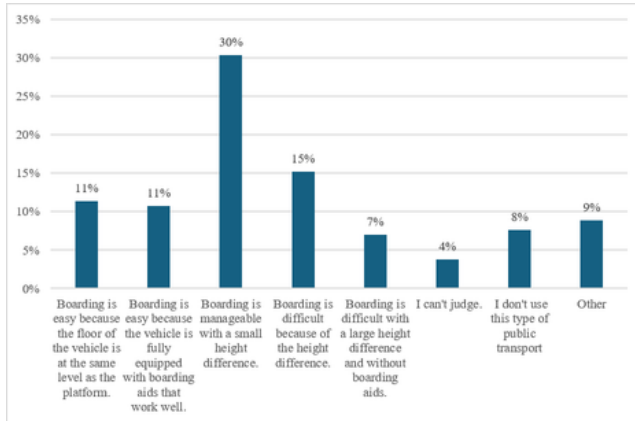
Figure 3 presents respondents' perceptions of the ease of boarding public transport vehicles. The largest group of participants (30%) reported that they were able to board vehicles despite a small height difference between the vehicle and the platform. However, 15% indicated that boarding remained difficult because of this height difference.

Positive experiences were reported less frequently. A total of 11% of respondents stated that boarding was easy because vehicles were equipped with appropriate boarding aids, while another 11% reported that boarding was facilitated by level access between the vehicle floor and the platform. In contrast, 7% of participants experienced difficulties due to a large height difference combined with the absence of boarding aids.

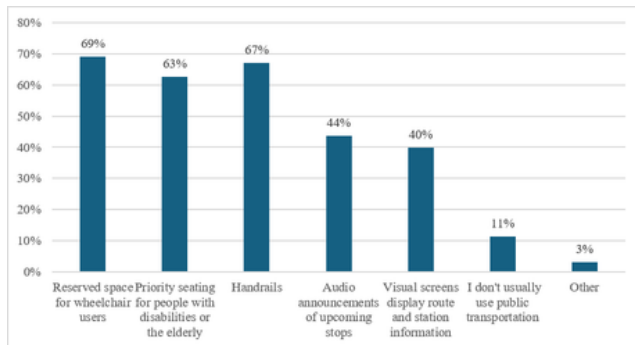
A small proportion of respondents (4%) were unable to evaluate the boarding process, while 9% selected the "other" category. Comments provided by these respondents highlighted issues such as vehicles stopping at a distance from the platform and uncertainty regarding the availability of low-floor vehicles. Overall, the findings demonstrate that users



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▲ Figure 3. Boarding public transport vehicles



▲ Figure 4. Public Transport Vehicle Features

experience different levels of accessibility when boarding public transport vehicles.

Figure 4 presents the accessibility features most frequently reported on public transport vehicles. Reserved spaces for wheelchair users were identified by 69% of respondents, making them the most reported accessibility feature. Handrails were reported by 67% of participants, while 63% indicated the presence of priority seating for people with disabilities and older passengers.

Features supporting access to travel information were reported less frequently. Audio announcements were available on 44% of vehicles, while digital information screens were identified by 40% of respondents. In addition, a small number of participants (3%) mentioned fold-out ramps as an accessibility feature available on some buses. These findings indicate differences in the availability of accessibility features across public transport vehicles, particularly between physical accessibility measures and information-related features. To better understand accessibility from the users' perspective, semi-structured interviews were conducted with people with disabilities.

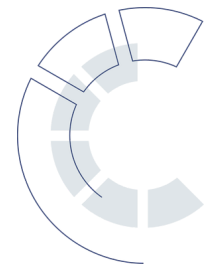
The interviews provided detailed accounts of everyday travel experiences and revealed how accessibility challenges can differ according to individual needs and types of disability.

Interview participants reported a range of accessibility challenges affecting different stages of their journeys. Although some barriers were common across participants, the nature of the difficulties often depended on the type of disability. The findings were therefore grouped into three categories: wheelchair users, people with visual impairments, and people with hearing impairments.

Interview participants who used wheelchairs described several challenges that limited their independent use of public transport. A lack of reliable information regarding the availability of low-floor buses reduced their ability to plan journeys effectively. Moreover, even when low-floor vehicles were available, participants reported that residual gaps and height differences between the vehicle floor and the curb could make boarding difficult and potentially unsafe (Figure 5). Participants also highlighted insufficient assistance from drivers and station staff, particularly when support was required during boarding or alighting. In addition, the absence of elevators at some stations restricted access to platforms and reduced mobility within transport facilities (Figure 6). Overall, the findings indicate that wheelchair users encounter a combination of informational, operational, and infrastructural barriers that negatively affect the accessibility and usability of public transport services.



▲ Figure 5. Gap between the curb and the bus

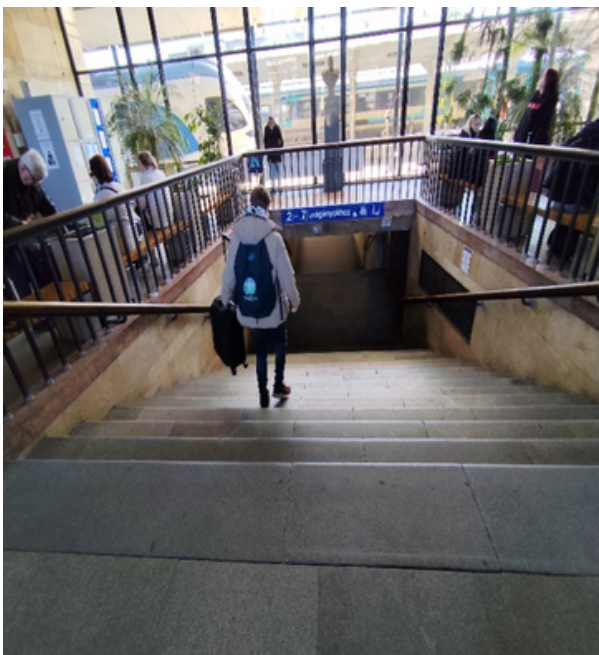


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Participants with visual impairments described difficulties throughout different stages of their journeys. Obstacles along pedestrian routes (Figure 7) and the lack of tactile guidance features (Figure 8) complicated navigation and the identification of platforms and boarding areas. Participants also reported difficulties at pedestrian crossings, where similar audible signals from different directions created confusion. In addition, unreliable information displays and announcements on board vehicles and at stops and stations limited access to travel information. The arrival of multiple vehicles at the same time further complicated the identification of the correct bus or train.

These findings suggest that people with visual impairments face a combination of physical and informational barriers that limit independent mobility and reduce the usability of public transport services.

▼ Figure 6. Absence of elevator at railway station



Participants with hearing impairments reported that access to travel information represented one of the main challenges during their journeys. The lack of accessible and clearly visible information regarding delays, platform changes, and other operational updates limited their access to important travel information. Participants also experienced difficulties communicating with drivers and station staff when assistance or additional information was required. Taken together, these findings highlight that people with hearing

impairments face primarily communication and information-related barriers that affect the accessibility and usability of public transport services.

Overall, the interview findings revealed that accessibility barriers differ according to the type of disability and encompass physical, informational, and operational aspects of the travel experience.

▼ Figure 7. Obstacles on sidewalk



5. Discussion

The findings indicate that accessibility challenges extend beyond physical infrastructure and affect multiple stages of the travel experience. Although barriers varied according to the type of disability, three broad categories emerged: physical, informational, and operational barriers. Physical barriers, including boarding gaps, the absence of elevators, and inadequate tactile guidance, limited independent mobility for users with mobility and visual impairments. These findings are consistent with previous studies that identified infrastructure deficiencies as a major factor restricting access to public transport (Hossen Sajib 2022; Gorzelanczyk et al. 2022)

The interviews also revealed the importance of operational factors, particularly the role of drivers and station staff in providing assistance. These findings suggest that compliance with technical accessibility standards alone may not guarantee an accessible travel experience, as service quality and operational practices strongly influence users' ability to travel independently. Similar observations have been reported by Aarhaug and Elvebakk (2015), who found that operational conditions affect how accessibility measures function in practice.



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Overall, the results emphasize the need for a user-centered approach to accessibility planning. Improving public transport accessibility requires not only infrastructure upgrades but also reliable information systems and appropriate staff support to address the diverse needs of people with disabilities.



▲ Figure 8. Limited Tactile signs

6. Conclusion

This study showed that people with disabilities encounter a range of accessibility challenges in public transport, including inadequate infrastructure, vehicle design limitations, insufficient information provision, and limited operational support. The findings also demonstrated that the nature of these barriers varies according to the type of disability and affects different stages of the journey. Improving accessibility therefore requires integrated measures, including the provision of safer and more accessible pedestrian infrastructure, the wider availability of low-floor vehicles, enhanced tactile, visual, and audio information systems, and improved training for drivers and transport staff. Such measures can contribute to the development of a more inclusive public transport system that better meets the diverse needs of people with disabilities.

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Declaration

The authors declare that they have no conflict of interest. Generative AI tools were employed for language refinement. The authors retain full

responsibility for the accuracy and integrity of the content

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EXPLORING BARRIERS TO PUBLIC TRANSPORT ACCESSIBILITY FOR PEOPLE WITH DISABILITIES

Wahyuni, Endang Sri, Bhisma Murti, and Hermanu Joebagio. 2016. 'Public Transport Accessibility for People With Disabilities'. Journal of Health Policy and Management 1 (1): 1–7.



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Abstract

The availability of transport accessible infrastructure and services are indispensable elements of inclusive mobility systems. They enhance social participation, independence and strengthen diversity in society and the labour market. This paper examines the importance of accessibility in public transport, and selected examples from research and practice that prove how accessibility leads to a more inclusive and resilient transport system through a self-determined mobility for all.

1. Introduction

Accessibility is no longer a marginal topic in transport policy; it is a core quality requirement for modern mobility systems. The World Health Organization estimates that around 15% of the global population lives with a form of disability, which means that accessibility concerns a substantial share of society (World Health Organization 2010). At the same time, many people experience temporary or situational limitations due to injury, age, heavy luggage, stroller use, or unfamiliarity with a place or language. In this sense, accessibility is relevant across the entire life course and for a wide range of travel situations. Despite the fact that in an aging population everyone is likely to be affected by some kind of disability or either physical limitation, it is thus reasonable to speak about people with reduced mobility (PRM).

Access to transport determines whether people can participate equally in education, employment, health care, and social life. When public transport systems, stations, ticketing platforms, or information services are not usable without obstacles, people are excluded from opportunities that others may take for granted. The UN Convention on the Rights of Persons with Disabilities therefore frames accessibility as a human rights issue and as a prerequisite for independent living and full participation in society (OHCHR 2006).

Barriers in public transport are created not only by missing ramps or elevators, but also by unclear information, lack of consistent travel chains, complex replacement services, and insufficient assistance. Disruptions such as construction works or service changes are especially problematic because they reduce predictability and increase the need for support. For people with disabilities, these situations often create disproportionate

burdens, since reliable information and accessible routing are essential for autonomous travel.

From this perspective, accessibility is not merely a social add-on, but a design principle for efficient, inclusive, and hence functional transport systems. Accessibility is not a niche programme for 15% of the population affected by a disability nor for PRM, but all passengers by making the entire network easier to use. Accessibility therefore has a dual effect: it improves individual participation and strengthens the quality of the system as a whole.

2. Accessibility: The key to inclusive mobility

2.1 Foundation of inclusive mobility

The availability of accessible and barrier-free transport infrastructure forms the foundation in promoting social inclusion for person with disabilities and for those experiencing temporary mobility restrictions. Considering the current shortage of skilled labour, the participation of person with disabilities in the workforce represents a significant potential that can be strengthened through improved accessibility and inclusive mobility systems.

Approaches to improve accessibility can be divided into two complementary dimensions. The first focuses on awareness-raising, which induces voluntary action and motivates companies and institutions to provide accessible infrastructure, vehicles, and services. The second dimension concerns the legal and regulatory framework, which is essential as awareness alone has proven insufficient to achieve inclusion. Both approaches create the conditions for inclusive mobility and there is usually also a certain trade-off between awareness rising and legal enforcement.

When environments and services are easier for person with disabilities to use, they also become more convenient for everyone else. As a result, no individual is disadvantaged and at the same time usability as well as the efficiency of mobility systems are raised.

Enhancing accessibility fosters greater diversity and inclusion. On the one hand, this dual effect improves transport services, and on the other hand, it makes independence and social participation possible. Consequently, accessibility contributes not only to social justice but also to economic resilience and sustainable development.

2.2 Legal framework

At the European level, accessibility is firmly anchored in legislation and policy. A central instrument is the European Accessibility Act (EAA – Directive (EU) 2019/882), an legislative framework that has been in force since June 28,



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2025, harmonizing accessibility requirements for products and services across all Member States (European Commission 2026). It represents a milestone in European inclusion policy by establishing a set of accessibility standards for key sectors such as digital services, transport and the public sector (European Commission AccessibleEU 2025).

In addition, several harmonised standards are being developed or revised to support the implementation of the EAA, respectively. They cover areas such as the accessibility of non-digital product information and customer support services like helpdesks and technical services. These new standards will form the practical basis for applying the EAA across the EU.

In practice, this means accessibility must be integrated early into planning and procurement processes. Retrofitting is often more expensive and less effective than inclusive design from the outset. Effective accessibility therefore depends on legal rules, technical standards, user involvement, and institutional responsibility working together.

3. Initiatives and practical applications

Efforts to improve accessibility are being pursued through a variety of initiatives that combine scientific research, practical implementation and stakeholder engagement. In the following sections some outstanding examples are presented.

3.1 DANOVA NEXT

Financed by the European Fund for Regional development (ERDF), DANOVA NEXT project expands on the earlier DANOVA initiative and focuses on all disabilities. The aim is to improve the accessibility of transport hubs by upgrading physical design and information systems. This project shows how accessible communication and clear wayfinding allow individuals to travel independently (Interreg Danube Region 2025; Wirtschaftsuniversität Wien 2024).

The project does not focus on one transport mode only; instead, it addresses air transport, water transport, and urban transport, which makes it particularly relevant for intermodal mobility systems.

The project introduces three main innovation areas: 1) improving physical accessibility at transport facilities through innovative services, 2) providing data on

network accessibility through fully accessible DTIS, and 3) creating a Smart Network that shares data, practices, and services across the Danube region. These are important changes because they shift accessibility from a local, site-specific issue to a regional, digitally coordinated system. In other words, the project changes not only infrastructure, but also the way accessibility information is produced and shared.

A further practical change is the development of a regional digital platform, the DANOVA NEXT Application, which provides fully accessible travel information services. The app offers accessibility information for buses, trams, metro systems, and other public transport modes, and it also integrates port-related accessibility data. This means that passengers no longer need to rely on scattered or incomplete information; instead, they can access centralized and more transparent mobility data.

The consortium is also unusually broad. It includes 16 partners and two associated partners, among them five airports, two seaports, and three urban public transport providers. This matters because the project does not treat accessibility as a single-agency task. Instead, it changes cooperation structures by linking airports, ports, transport providers, and disability organizations in 1 shared network.

Overall, DANOVA NEXT changes accessibility practice in three ways: it upgrades the physical travel environment, it digitalizes accessibility information, and it institutionalizes cross-sector cooperation. These changes make the project scientifically important because they show how accessibility can be improved at system level rather than only through individual site adaptations.

3.2 AirWorld - Door2Door

AirWorld Door2Door, supported by the Austrian Research Promotion Agency (FFG), targets accessibility across the whole travel chain with a specific focus on air travel. The project examines how each travel stage, starting from booking to boarding, can be made inclusive. It proves that cooperation between airports and transport providers improves service quality and inclusion (FFG 2024).

One major change introduced by the project is the move from isolated aviation accessibility to a full intermodal perspective. The project explicitly targets system barriers outside traditional aviation, especially in baggage transport, information, booking, and accessibility-related processes. That means the project does not only ask whether airport is accessible, but whether the



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whole chain can function smoothly across several service providers.

The expected results are also concrete. The project aims to produce 1) a comprehensive analysis of barriers in intermodal travel chains, 2) AI-supported end-to-end door-to-door

The expected results are also concrete. The project aims to produce 1) a comprehensive analysis of barriers in intermodal travel chains, 2) AI-supported end-to-end door-to-door services, 3) measures to improve baggage handling, information, booking, and deviation management, 4) greater acceptance of sustainable arrival and departure options, and 5) a basis for further technological and organizational development. These changes are important because they translate accessibility from a principle into operational improvements.

The project also introduces several specific innovations. According to the project description, these include concepts for same-day baggage delivery, virtual concierge services for navigation and booking, and end-to-end escort services for persons with reduced mobility and unaccompanied minors. These are not minor adjustments; they change how passengers move through the travel chain and how support is organized. In practical terms, they reduce uncertainty, increase independence, and make travel more predictable.

AirWorld Door2Door also changes the cooperation model in aviation. The project brings together netwiss OG, Austrian Airlines, Vienna Airport, ÖBB PV AG, TU Vienna, FH JOANNEUM Graz, N+P Experience Design, and the Austrian Association for the Blind and Visually Impaired. This broad consortium matters because accessibility in aviation depends on multiple actors acting together, not on a single company working in isolation. The project therefore changes both service design and institutional coordination.

3.3 VR4Mobility

VR4Mobility is a highly innovative project that uses Virtual Reality to support orientation and mobility training for visually impaired people. According to the project description, its main aim is to provide basic mobility training through VR technology (Access Austria 2024; ENVITER 2024). The project is organized around 4 planned steps: training specialized teachers and mobility

trainers in the use of VR, training them in creating 360° videos, training them in creating virtual 3D environments as digital twins, and implementing VR technology in partner organizations. The most important change here is the shift from conventional mobility instruction to a digitally enhanced learning environment. Instead of relying only on real-world training situations, the project creates 360° videos and 3D digital twins that can be used in VR headsets. This allows learners to rehearse routes and orientation tasks in a safe, repeatable, and controlled environment before encountering real-world complexity.

The project also changes the role of trainers. It does not simply provide a tool for end users; it builds competence among teachers and mobility instructors so that VR can become part of professional practice. This is important because accessibility innovations often fail when staff are not trained to apply them. VR4Mobility therefore changes not only the learning environment, but also the skill profile of the professionals involved.

Another notable aspect is the European network structure. VR4Mobility is an ENVITER project and involves eight project partners from several European countries. This means the project does not develop isolated solution, but a transferable model for accessible mobility training. The international structure increases the likelihood that methods, curricula, and tools can be adapted across different contexts.

In scientific terms, the project changes accessibility training in three ways: it introduces immersive simulation, it strengthens professional training, and it supports cross-border knowledge exchange. These changes are especially relevant for people with visual impairments because they combine safety, autonomy, and skill development in a single approach.

3.4 Inclusive working group of the Austrian Disability Council

The Inclusive Working Group of the Austrian Disability Council, supported by the Austrian Federal Social Ministry, connects national disability organizations to advise public transport operators such as Wiener Linien, Wiener Lokalbahnen and ÖBB. It ensures that accessibility is considered from the earliest stages of planning.

3.5. Accessibility Committee, Vienna International Airport

In response to criticism after the opening of Terminal 3 in 2012, Vienna International Airport set up an Accessibility Committee in cooperation with national disability organisations. Since then, the committee has become a role model of inclusive planning.



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All new airport projects are reviewed early in planning to ensure accessibility.

There are many more initiatives dedicated to promoting accessibility in mobility systems. Among them are Accessible Barrier-Free Public Transport (BFPT) Summer School, OnTours, UnLock4All, AM4Kids, Digi4All and POPTIS.

4. Conclusion

Accessibility is not a secondary feature of public transport; it is the condition that makes inclusive mobility possible in the first place. A transport system may be technically advanced, fast, or digitally sophisticated, but if it cannot be used independently by persons with disabilities, older adults, or people with temporary impairments, it remains incomplete from a social and democratic perspective. The core argument of this paper is therefore that accessibility must be understood as a structural principle rather than an optional add-on. It affects not only a specific user group, but the quality, reliability, and fairness of the entire mobility system.

The legal framework leaves little room for ambiguity. Article 9 of the UN Convention on the Rights of Persons with Disabilities places accessibility at the center of equal participation and requires States Parties to identify and remove barriers in transport, information, communication, and the built environment (OHCHR 2006; UN 2014). At the European level, Directive (EU) 2019/882, the European Accessibility Act, strengthens this obligation by harmonizing accessibility rules for products and services that are especially relevant for everyday participation, including transport-related services and digital interfaces (European Commission 2026). Together, these frameworks show that accessibility is not merely a matter of good practice; it is a legal and ethical responsibility.

The examples discussed in this paper demonstrate that accessibility becomes most effective when it is approached as a system-wide task. DANOVA NEXT shows how accessibility can be expanded across three transport modes — air, water, and urban transport — while also linking physical improvements with accessible digital travel information. AirWorld Door2Door demonstrates that the actual journey begins long before boarding and ends long after arrival, which means that the first and last mile, baggage handling, booking, and disruption management are all part of accessibility in

practice. VR4Mobility, in turn, illustrates how 360° videos, virtual 3D environments, and VR-based training can improve orientation and mobility instruction for visually impaired people while also strengthening the competence of trainers across a European network.

These examples make clear that innovation matters most when it changes the full travel experience rather than 1 isolated step.

What emerges from the combination of law, research, and practice is a broader understanding of mobility resilience. A resilient transport system is not only one that can cope with technical disruptions or passenger volumes, but also one that remains usable under diverse human conditions. Accessibility contributes to this resilience by making journeys more predictable, information more understandable, and services more adaptable. In situations such as construction works, detours, or service interruptions, accessible design reduces dependence on individual assistance and helps passengers maintain autonomy. This is particularly important because disruptions in public transport are never distributed equally: they tend to affect people with disabilities more strongly, and they can quickly turn a manageable inconvenience into a complete travel barrier.

Accessibility also has clear economic and social implications. Accessible transport supports access to jobs, education, health services, and markets, while also broadening labour supply and improving social inclusion. In a context where many societies face labour shortages and demographic change, excluding persons with disabilities from transport systems means excluding potential workers, consumers, students, and citizens. In this sense, accessibility is not only a question of equity but also of social and economic efficiency. Investments in accessibility can therefore be understood as investments in participation, productivity, and long-term system performance.

Another important conclusion is that accessibility must be planned early. Retrofitting can solve some problems, but it is often more expensive, more fragmented, and less effective than inclusive planning from the beginning. This applies to station design, vehicle procurement, digital service development, and emergency or replacement transport arrangements. The projects analyzed in this paper reinforce that point: DANOVA NEXT



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links accessibility with digital infrastructure from the start; AirWorld Door2Door treats accessibility as a door-to-door issue rather than a single airport feature; and VR4Mobility embeds accessibility into training and professional learning rather than treating it as a late-stage correction. In all 3 cases, accessibility succeeds because it is embedded in the design logic, not appended afterward.

In all 3 cases, accessibility succeeds because it is embedded in the design logic, not appended afterward.

At the same time, the paper shows that technical solutions alone are insufficient. Accessibility is most sustainable when it is supported by institutional cooperation and by the participation of affected users. Disability organizations, transport operators, public authorities, researchers, and service providers all play a role in defining what accessible mobility means in practice. This is why advisory structures, committees, and transnational partnerships matter: they turn accessibility into an ongoing governance task instead of a one-time compliance exercise. The projects discussed here are therefore not only examples of innovation, but also examples of how participation can improve planning quality.

In conclusion, accessibility should be understood as a universal improvement strategy for mobility systems. It increases independence for individuals, expands participation in education and employment, strengthens the reliability of services, and improves the resilience of the transport network as a whole. The strongest lesson from the legal framework and the project examples is that accessibility works best when it is treated as a core design principle from the outset, supported by regulation, research, and user participation. A transport system that is truly accessible is not just more inclusive; it is also more efficient, more adaptable, and more future-proof.

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Declaration

The authors declare that they have no conflict of

interest. Generative AI tools were employed solely for language refinement. The authors retain full responsibility for the accuracy and integrity of the content.

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BUILDING RESILIENT AUTOMATED MOBILITY SYSTEMS: SPATIO-TEMPORAL CRASH PATTERNS AND OPERATIONAL RISKS IN CALIFORNIA

VON H. AL-MAHAMEED, A. AL-LAMI, Á. TÖRÖK

1. Introduction

The growing deployment of autonomous vehicles (AVs) on public road networks introduces new challenges and opportunities for building resilient and reliable mobility systems (Abdel-Aty and Ding 2024). As AVs increasingly operate alongside human-driven vehicles, understanding where and when crashes occur is essential for evaluating operational robustness, environmental vulnerability, and infrastructure readiness (California Department of Motor Vehicles 2025). California hosts the world's most mature AV testing ecosystem and requires manufacturers to report all AV-involved crashes through DMV Form OL-316. These reports provide highly detailed, real-world incident data and offer a unique opportunity to examine AV system behavior under varying spatial and temporal conditions.

This study analyzes 127 AV crashes reported between September 2024 and September 2025, focusing on two core testing hubs: the San Francisco Bay Area and the Los Angeles Basin. By examining seasonal variations, day-night exposure, and geographic clustering, the study evaluates the stability of AV operational performance and its interactions with the surrounding transport environment. The insights contribute directly to the ETC 2026 theme on resilient and reliable mobility systems, demonstrating how AV deployments respond to environmental dynamics and identifying locations where operational risks may be more concentrated.

2. Data and Methods

2.1. Data Source

All crash records were obtained from DMV OL-316 collision reports submitted by licensed AV developers (California Department of Motor Vehicles 2025). Each report includes the incident date, time, location, operational mode, weather, lighting, and narrative description. Only complete and verifiable cases ($n = 127$) were included in the analysis.

2.2. Geocoding and Spatial Processing

Crash locations were manually interpreted from the narrative descriptions provided in the dataset and subsequently geocoded using Python combined with the Google Maps API (Patel et al. 2024). All geocoded coordinates were validated in Google Earth Pro to ensure positional accuracy. Geographic processing was then conducted in QGIS to produce point-level crash maps, regional clustering layers, and kernel density surfaces for each autonomous-vehicle testing region,

enabling a consistent spatial representation of crash distributions across the study area.

2.3. Temporal Classification

Temporal exposure in the dataset was classified according to two dimensions. The first distinguishes between daytime and nighttime conditions, while the second reflects the four meteorological seasons: winter, spring, summer, and autumn. This categorization makes it possible to examine whether variations in environmental context and time-related factors have a measurable effect on the spatial or behavioral patterns associated with autonomous-vehicle crashes.

2.4. Statistical Analysis

Chi-square tests of independence were applied to assess the relationship between crash frequency and temporal exposure across the study regions. The analysis focused on two comparisons: the distribution of crashes across day and night, and the distribution across the four seasons. These tests were intended to determine whether autonomous-vehicle crash patterns vary meaningfully among the major testing hubs, which would suggest underlying geographical or infrastructure-related differences in system resilience.

3. Results

3.1. Spatial Distribution

Crash events were predominantly concentrated within well-established autonomous-vehicle operational corridors. In the San Francisco Bay Area, incidents were clustered around San Jose, Mountain View, Palo Alto, and the central districts of San Francisco. A similar pattern appeared in the Los Angeles Basin, with notable concentrations in Santa Monica, Culver City, and downtown Los Angeles. These spatial clusters correspond closely with areas characterized by complex road networks, high operational density, and continuous AV fleet deployment. The observed patterns underscore the extent to which AV testing activities depend on dense, multimodal urban environments that provide both infrastructural capacity and diverse traffic conditions.

3.2. Temporal Patterns

An examination of the 127 recorded incidents shows that most crashes occurred during daylight hours, accounting for just over half of all events, while the remaining incidents took place at night. Seasonal variation in crash frequency was modest, with winter, spring, summer, and autumn each representing roughly comparable portions of the total. This relatively even temporal distribution indicates that autonomous-vehicle operations remain active throughout the year and are not



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markedly affected by seasonal or environmental conditions.

An analysis of recorded incidents shows that 58.3% of crashes occurred during the day, while the remaining 41.7% occurred at night. Seasonal variation was relatively limited, with crashes distributed across winter (26.0%), spring (20.5%), summer (29.1%), and autumn (24.4%). These proportions indicate that autonomous-vehicle activity remains consistent throughout the year, with no substantial seasonal disruptions influencing crash occurrence.

3.3. Regional Comparison

The analysis of temporal patterns showed a broadly similar distribution of autonomous vehicle (AV) testing activity across both regions. Day–night variation in crash occurrence was nearly identical: 57.1 percent of incidents in the Bay Area and 58.6 percent in the Los Angeles Basin occurred during the daytime, while nighttime incidents accounted for 42.9 percent and 41.4 percent, respectively. The chi-square test ($\chi^2 = 0.000$, $p = 1.000$) confirms that there is no statistically significant difference between the two regions.

Seasonal patterns also demonstrated comparable trends. Los Angeles exhibited slightly higher activity during the summer months, whereas the Bay Area showed a more balanced distribution across seasons. However, the chi-square test ($\chi^2 = 1.62$, $p = 0.655$) indicates that these variations are not statistically significant.

Overall, the lack of significant temporal differences suggests that AV exposure remains operationally stable across regions. The consistency of performance across seasons and lighting conditions indicates that the underlying AV systems function reliably under varying environmental contexts. Moreover, the infrastructure in both regions appears supportive of predictable AV operations, implying that environmental fluctuations do not substantially

4. Discussion

Environmental Robustness

The minimal variation across seasons and diurnal periods suggests that current AV testing practices—and possibly AV system performance—are resilient to environmental shifts. This is a critical feature for large-scale deployment in the face of real-world climate variability.

Infrastructure Dependence

Spatial clustering in dense urban corridors highlights the dependence of AV operations on technologically advanced, high-capacity roadway environments. These areas likely facilitate improved mapping accuracy, sensor performance, and operational reliability.

Operational Resilience

Consistent temporal patterns across regions demonstrate that AV systems maintain stable behavior despite differences in climate, traffic dynamics, and exposure conditions between Northern and Southern California.

Risk Identification

Hotspot corridors indicate locations where infrastructure adaptations—such as enhanced road markings, V2X connectivity, or digital-twin integration—could strengthen resilience and reduce operational risk.

5. Conclusions

This study demonstrates that autonomous vehicle (AV) crash occurrences in California exhibit pronounced spatial clustering but limited temporal variability. The San Francisco Bay Area and the Los Angeles Basin account for the majority of AV crashes; however, both crash timing and seasonal exposure remain statistically indistinguishable across these regions. The absence of significant regional or temporal variation ($p = 1.000$) indicates a high degree of spatio-temporal uniformity in AV operations, suggesting that testing exposure is distributed consistently across major hubs. This uniformity further implies that AV systems are currently governed by standardized operational protocols that are largely insulated from the behavioral fluctuations typical of human-driven traffic.

These patterns suggest that current AV systems—and the infrastructure supporting them—operate in stable, resilient conditions. The findings provide several key insights for the design and deployment of resilient automated mobility systems. First, AV operations appear robust across environmental and temporal variations. Second, infrastructure in major testing hubs supports consistent system performance. Third, identifying spatial hotspots highlights the potential for targeted interventions to further enhance system reliability and safety outcomes.

Overall, the proposed spatio-temporal framework offers a valuable basis for resilience-oriented planning, infrastructure adaptation, and policy development as autonomous mobility transitions toward broader real-world deployment.



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Keywords: Autonomous vehicles; AV safety; Spatio-temporal analysis; Mobility resilience; GIS; California DMV OL-316; Infrastructure reliability; Seasonal exposure; Automated mobility systems; Urban transport resilience.

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Declaration

While preparing this work, the authors used ChatGPT-OpenAI 4.0 solely for grammatical checks and restructuring only. The analysis and results presented in the paper are entirely our own. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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TOWARDS THERMALLY COUPLED HYDROGEN ECOSYSTEMS: INTEGRATING FUEL-CELL VEHICLE WASTE HEAT INTO GREEN HYDROGEN PRODUCTION AT REFUELING STATIONS

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Abstract

Hydrogen Fuel-Cell Vehicles (FCVs) are expected to play an important role in the decarbonization of long-distance and heavy-duty transport [1]. While significant progress has been made in fuel-cell and hydrogen production technologies, a substantial share of the hydrogen energy supplied to the FCV is still rejected as waste heat through the vehicle cooling system [2], [3]. This thermal energy is typically dissipated to the environment despite being available at temperatures suitable for industrial heat recovery applications.

This study investigates a thermally integrated hydrogen ecosystem in which waste heat generated by FCVs is recovered, stored, translated, and reused within hydrogen refueling infrastructure. The proposed concept combines an onboard phase change material (PCM) thermal storage system with a thermal exchange interface at a hydrogen refueling station. During vehicle operation, heat from the fuel-cell cooling circuit is stored in the PCM module. Upon arrival at the refueling station, the stored thermal energy is transferred through a heat exchanger to preheat electrolyzer feed water, thereby reducing the station's auxiliary heating demand. A simulation-oriented analytical framework was developed to evaluate hydrogen demand, waste-heat recovery potential, PCM storage requirements, thermal losses, heat-transfer performance, and station operational flexibility. A representative dual-pressure hydrogen refueling station serving passenger vehicles at 700 bar and heavy-duty trucks at 350 bar was considered. The investigated mixed-fleet scenario resulted in a hydrogen demand of 550 kg/day, corresponding to an electrolyzer electricity demand of 27.5 MWh/day.

The results indicate that approximately 510 kWh/day of thermal energy can be recovered from the vehicle fleet. After accounting for storage and transport losses, approximately 433.5 kWh/day remains available for station-side utilization. The recovered heat increases electrolyzer feed-water temperature from ambient conditions to approximately 67 °C, which lies within the preferred operating range for PEM electrolysis systems. In the baseline case, approximately 433.5 kWh/day of recovered waste heat is delivered to the refueling station after thermal losses. Compared with the assumed electrolyzer feed-water preheating demand of 440 kWh/day, this recovered heat can theoretically cover about 98.5% of the preheating requirement.

As a result, only around 1.5% of the feed-water preheating demand would still need to be supplied by auxiliary electrical heating. The main electrical energy required for water electrolysis remains unchanged.

The findings demonstrate that FCVs can serve not only as hydrogen consumers but also as mobile thermal energy carriers. By establishing a direct thermal connection between hydrogen utilization and hydrogen production, the proposed approach improves energy utilization within hydrogen infrastructure and provides a practical pathway for integrating waste-heat recovery into future hydrogen mobility systems.

1. Introduction

The accelerated transition toward climate-neutral transportation requires alternative energy carriers capable of supporting long-range operation, short refueling times, and high energy density. Hydrogen has emerged as one of the most promising solutions for decarbonizing sectors [4] where battery-electric systems face limitations, particularly heavy-duty freight transport, buses, rail applications, and long-distance mobility [5].

Green hydrogen, produced through water electrolysis using renewable electricity, enables nearly carbon-free operation across the entire energy chain. However, the efficiency of hydrogen production remains strongly dependent on both electrical and thermal operating conditions [6]. Modern electrolyzers require substantial electrical energy input and often rely on auxiliary heating systems to maintain feed-water temperatures within their optimal operating range [7], [8].

At the same time, hydrogen FCVs continuously reject thermal energy during operation. Proton Exchange Membrane Fuel Cells (PEMFCs) typically operate at temperatures between 60 and 80 °C and convert only a portion of the chemical energy of hydrogen into electrical power. Depending on operating conditions, approximately 40–55% of the hydrogen energy may be released as thermal energy through the cooling system [9], [10].

Although a small portion of this heat is occasionally utilized for cabin conditioning, most of the available thermal energy is ultimately rejected to the environment [10], [11]. Consequently, an opportunity exists to recover and reuse this energy stream within the broader hydrogen infrastructure.

The present work investigates a novel concept in which FCVs serve not only as consumers of hydrogen but also as temporary thermal energy storage units. Waste heat generated during vehicle operation is captured and stored using latent thermal energy storage based on phase-change materials.



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The stored heat is subsequently transported to a hydrogen refueling station where it is discharged through a heat exchanger and integrated into the electrolyzer feed-water circuit.

This approach introduces a direct thermal interaction between hydrogen consumption and hydrogen production, creating a thermally coupled hydrogen ecosystem. Such integration has the potential to reduce auxiliary electrical demand, improve station efficiency, and enhance overall energy utilization across the hydrogen value chain [12].

2. State of the Art, Research Question & Technology Gap

2.1 FCV Waste Heat Recovery

PEM fuel-cell systems are characterized by relatively low operating temperatures compared with combustion engines. Nevertheless, significant thermal energy is generated as a by-product of electrochemical conversion processes [10], [13].

Commercial FCVs such as the Toyota Mirai, Hyundai Nexo, and BMW iX5 Hydrogen operate with coolant temperatures between 70 and 85 °C [14], [15]. The thermal energy is primarily removed through dedicated cooling circuits designed to maintain stack temperature stability and prevent performance degradation [16].

Previous investigations have focused primarily on vehicle thermal management, cabin heating, and stack cooling optimization [3], [11]. Relatively little attention has been given to recovering this thermal energy for external applications beyond the vehicle boundary.

2.2 Phase Change Material Thermal Storage

Latent thermal energy storage using phase-change materials has become increasingly attractive due to its ability to store large amounts of thermal energy within compact volumes.

Paraffin-based phase change materials with melting temperatures between 70 and 80 °C are well suited for this application due to their high latent heat storage capacity, chemical stability, non-corrosive properties, and long service life [17]. Their operating temperature range closely matches that of PEM fuel-cell cooling systems, allowing efficient capture, storage, and subsequent release of waste heat generated during vehicle operation [18].

2.3 Thermal Requirements of Electrolysis Systems

Electrolyzers require feed-water conditioning to achieve efficient operation. Feed-water temperatures between 60 and 70 °C improve reaction kinetics, reduce voltage losses, and contribute to higher hydrogen production efficiency [12], [19]

Current hydrogen refueling stations generally satisfy these thermal requirements using electrical heating systems. While technically straightforward, this approach increases electricity consumption and reduces the overall efficiency of green hydrogen production.

2.4 Technology Gap

Current research on hydrogen mobility mainly focuses on individual components such as fuel-cell thermal management, waste-heat recovery, thermal energy storage, electrolyzer operation, or hydrogen refueling infrastructure [2], [3], [5], [8], [11]. Although these technologies have been extensively investigated, they are generally considered separate systems. As a result, the potential of FCVs to provide recoverable thermal energy for hydrogen production has received little attention.

A system-level concept that combines vehicle-side waste-heat recovery, onboard thermal storage, thermal energy transport, station-side heat exchange, and electrolyzer feed-water preheating has not yet been established. Consequently, waste heat generated during vehicle operation is largely dissipated in the environment instead of being integrated into the hydrogen production process.

This study addresses this gap by introducing a vehicle-to-station thermal energy transfer concept that links hydrogen utilization with hydrogen production. By recovering and reusing waste heat for electrolyzer feed-water preheating, the proposed approach contributes to improved energy efficiency, enhanced integration of hydrogen infrastructure, and more effective utilization of available energy resources.

3. Methodology

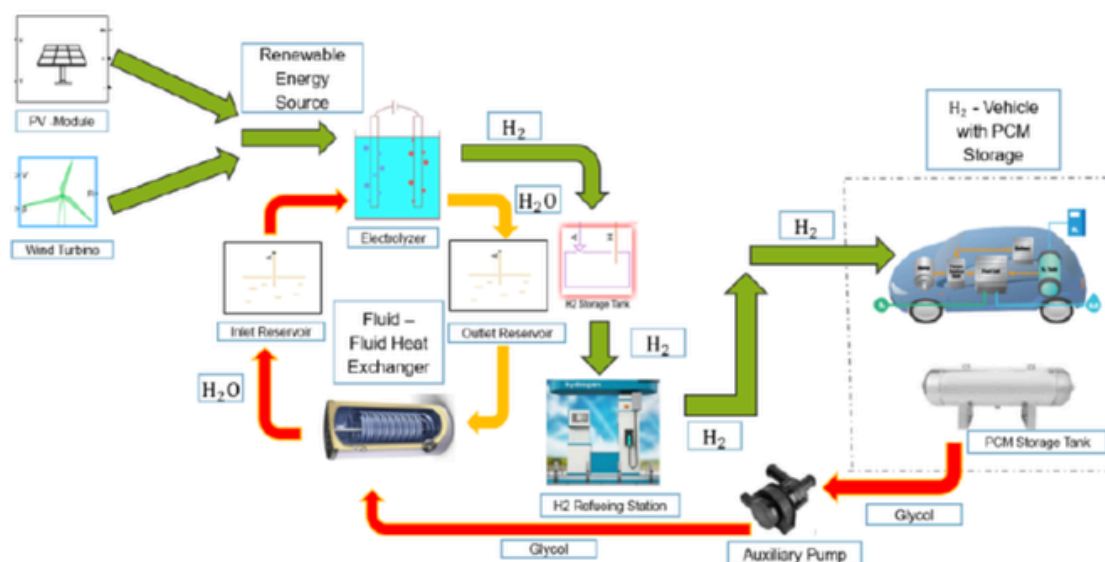
The methodology is structured as a two-domain thermal integration between vehicle and station: an onboard subsystem captures fuel-cell waste heat in a PCM module [20], [21] during driving and transports it to the refueling site, while a station-side subsystem accepts this heat to preheat electrolyzer feed water within its preferred temperature range. The vehicle domain comprises hydrogen storage, PEM fuel cell, cooling loop, PCM storage with insulation, and a thermal discharge interface that couples to a station heat exchanger upon arrival. The station domain includes renewable-powered electrolysis,

hydrogen compression and storage with dual-pressure dispensing (700 bar for passenger vehicles and 350 bar for heavy-duty vehicles), and a thermal exchange interface that transfers heat from the vehicle PCM loop into the electrolyzer feed-water circuit. The operating flow proceeds from hydrogen use and waste-heat generation, to latent storage and transport, to thermal docking at the dispenser where heat is exchanged to elevate feed-water temperature and reduce auxiliary electrical heating. An analytical, simulation-oriented architecture underpins this flow, partitioned into modular blocks for source heat estimation, PCM storage [21], transport-loss representation, station heat exchange, and feed-water heating, sized and evaluated against a representative mixed-fleet station scenario to quantify delivered heat and the offset of electrical preheating demand. The result is a clear vehicle-to-station thermal pathway that leverages natural temperature compatibility to minimize added hardware complexity while providing a scalable basis for detailed dynamic implementation.

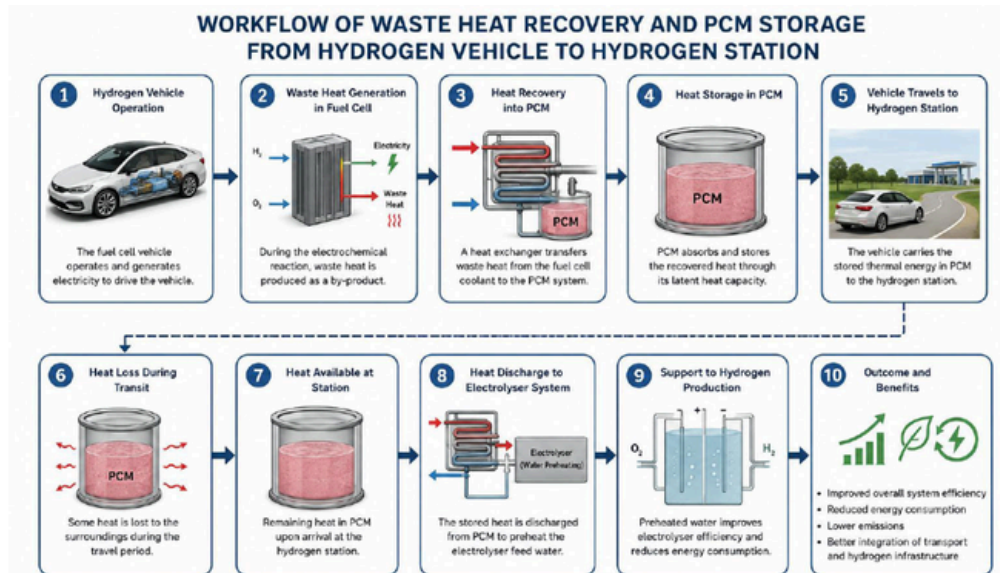
Vehicle Subsystem

Refueling Station Subsystem

▼ Figure 1: Schematic block diagram illustrating the proposed system architecture and the complete thermal cycle



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▲ Figure 2: Schematic block diagram illustrating the proposed system architecture and the complete thermal cycle (Image: AI generated, edited by authors)

workflow. Renewable electricity drives the electrolyzer, which produces hydrogen for compression, storage, and dual pressure dispensing to passenger vehicles at 700 bar and heavy duty trucks at 350 bar, while a dedicated thermal exchange interface links vehicle supplied heat to the station's feed water circuit. Upon vehicle arrival, the thermal docking/connector engages a station side heat exchanger that transfers stored heat from the vehicle PCM to the electrolyzer feed water [22], replacing a portion of the station's auxiliary electrical heating and creating a direct thermal interaction between hydrogen consumption and hydrogen production. Feed water preheating to the preferred 60–70 °C range supports improved electrolysis kinetics and lower voltage losses, and the natural temperature compatibility between PEM fuel cell coolant and electrolyzer feed water enables this coupling without heat pumps or high temperature upgrading systems, simplifying integration. Station operations therefore proceed as follows: hydrogen dispensing at the required pressure tier; simultaneous or sequenced thermal discharge through the heat exchanger to elevate feed water temperature; and reduced auxiliary heater duty due to vehicle supplied heat, forming a thermally coupled hydrogen ecosystem that improves overall station energy utilization. A practical consideration is the mismatch between short hydrogen refueling times and longer thermal discharge durations; stations may require high capacity thermal docking or buffer arrangements to ensure effective heat transfer within operational constraints.

Operational Sequence

The cycle begins on the road as the FCV consumes hydrogen and rejects heat through its cooling loop. Instead of dissipating this heat, the vehicle transfers it into an onboard paraffin-based PCM module operating around 70–80 °C, where it is stored as latent heat compatible with PEM stack temperatures. The stored heat is then carried to the station; insulation preserves the PCM state of charge during transport, limiting losses so usable thermal energy remains available at arrival. At the refueling station, vehicles are served by dual-pressure dispensing 700 bar for passenger cars and 350 bar for heavy-duty trucks while a thermal docking interface connects the vehicle to a station-side heat exchanger. During or immediately after dispensing, the exchanger transfers the vehicle's stored heat to the electrolyzer feed-water circuit, lifting feed-water into the preferred 60–70 °C range and reducing the station's auxiliary electrical heating demand. This is enabled by the natural temperature compatibility between PEM fuel-cell coolant and electrolyzer feed-water, avoiding heat pumps or temperature upgrading and simplifying integration. Heavy-duty vehicles, with higher stack cooling loads, contribute disproportionately to the station's thermal supply, further strengthening the impact of the thermal coupling in mixed fleets. A practical constraint is the mismatch between short hydrogen refueling events and the longer durations often required for full thermal discharge, which may necessitate high-capacity thermal docking or buffer arrangements to ensure effective heat transfer within operational windows.

4. Analytical Modeling & Calculations

The analytical model architecture was structured around



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several interacting modules.

4.1 Vehicle Thermal Source Model

This model quantifies the recoverable waste heat from the PEM fuel-cell cooling loop over a driving interval using,

$$E_{th} = P_{th} * t_d \quad (1)$$

where P_{th} is the thermal reject power and t_d is the operating duration. Representative sizing values are 25 kW for 0.5 h for a passenger FCV and 120 kW for 1 h for a heavy-duty FCV, providing the baseline thermal energy available before transport and discharge losses.

4.2 PCM Storage Model

Onboard latent storage is sized to capture the target heat using,

$$m_{pcm} = \frac{Q_{target}}{L} \quad (2)$$

where Q_{target} is the desired stored energy and L is the PCM latent heat capacity [21]. A paraffin PCM operating between 70 and 80 °C with $L \approx 200$ kJ/kg is selected to align with PEM stack temperatures and enable compact latent storage of the captured waste heat during driving.

4.3 Heat Loss Model

Thermal retention during transport is evaluated with a lumped thermal resistance approach:

$$Q_{loss} = U_A * \Delta T * t \quad (3)$$

where U_A is the overall thermal conductance of the storage and insulation, ΔT is the temperature difference between the PCM module and ambient, and t is the transport time. Minimizing Q_{loss} through effective insulation preserves PCM state of charge and maximizes delivered energy upon station arrival

4.4 Heat Exchanger Model

At the station, stored heat is transferred from the vehicle PCM loop to the electrolyzer feed-water circuit according to

$$Q = U_A * \Delta T_l m \quad (4)$$

where U_A is the exchanger conductance–area product and ΔT_l is the logarithmic mean temperature difference between hot and cold streams. This relation governs the

discharge rate and total heat delivered within the available docking window

4.5 Electrolyzer Feed-Water Model

The temperature rise of the feed water is determined by

$$\Delta T = \frac{Q}{(mcp)} \quad (5)$$

where Q is the heat transferred, m is the mass flow rate, and cp is the specific heat capacity of water. The model links delivered thermal power to the achieved temperature lift, targeting feed-water in the preferred 60–70 °C range for efficient PEM electrolysis operation. [23]

5. Results

5.1 Hydrogen Demand

Hydrogen demand at the representative dual-pressure station (serving 40 passenger vehicles and 10 heavy-duty trucks per day) is 550 kg/day, corresponding to an electrolyzer electricity requirement of 27.5 MWh/day. This establishes the station's energy scale and the potential impact of integrating vehicle-supplied heat into the thermal balance.

5.2 Thermal Recovery Potential

Thermal recovery evaluations indicate that approximately 510 kWh/day of waste heat can be captured onboard across the mixed fleet, with 433.5 kWh/day delivered to the station after accounting for 76.5 kWh/day of transport and storage losses. Sensitivity results highlight that heavy-duty operation yields the highest recovery due to larger stack cooling loads, while inadequate insulation significantly degrades delivered energy, underscoring insulation quality as a critical design parameter

5.3 PCM Performance

PCM performance remains robust under baseline assumptions: the paraffin-based storage arrives at the station at roughly 85% state of charge, and its operating temperature window stays compatible with electrolyzer feed-water heating requirements throughout discharge. This alignment supports effective transfer of recovered heat to the station without temperature upgrading and maintains preheating performance within the preferred range

5.4 Feed-Water Preheating

Recovered vehicle heat lifts electrolyzer feed-water from about 15 °C to approximately 67 °C, placing it squarely within the preferred operating band for PEM electrolysis and directly reducing the need for auxiliary electrical heating at the station.



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Under the evaluated mixed-fleet scenario, the delivered thermal energy can supply up to 98.5% of the preheating requirement, cutting auxiliary electrical heating by roughly 433.5 kWh/day and lowering total electrolyzer-related electricity consumption.

5.5 Sensitivity Analysis

Sensitivity results show the strongest thermal recovery under heavy-duty operation due to larger stack cooling loads, while inadequate insulation substantially erodes delivered energy. Consequently, insulation quality emerges as a critical design parameter to preserve PCM state of charge and maximize station-side heat delivery.

6. Discussion

The analysis confirms that FCVs can perform a secondary role as mobile thermal energy storage systems.

The proposed concept creates a novel interaction between hydrogen production and hydrogen consumption infrastructure. Instead of discarding waste heat generated during vehicle operation, the thermal energy is reintegrated into the hydrogen production cycle.

One of the most significant findings is the natural temperature compatibility between PEM fuel-cell cooling systems and electrolyzer feed-water requirements. This compatibility eliminates the need for heat pumps or high-temperature upgrading systems, thereby simplifying implementation.

A second important finding concerns the role of heavy-duty vehicles. Due to their larger fuel-cell systems and higher thermal rejection rates, trucks provide substantially greater thermal recovery potential than passenger vehicles.

The main engineering challenge identified is the mismatch between thermal discharge duration and vehicle refueling time. Full thermal discharge may require longer connection times than typical hydrogen refueling events. Future infrastructure may therefore require dedicated thermal buffer tanks or high-capacity thermal docking interfaces.

Despite these challenges, the results demonstrate that thermally integrated hydrogen infrastructure can improve station efficiency while making productive use of energy that would otherwise be lost to the environment.

7. Conclusion

This work presented a thermally integrated hydrogen ecosystem in which FCV waste heat is recovered, stored, transported, and reused to support hydrogen production at refueling stations.

The proposed framework combines onboard PCM thermal storage with station-side heat exchange and electrolyzer feed-water preheating. Simulation results indicate that approximately 510 kWh/day of thermal energy can be recovered from a representative mixed vehicle fleet, with 433.5 kWh/day remaining available after transport losses.

The recovered thermal energy was shown to increase feed-water temperatures to the desired electrolyzer operating range and substantially reduce auxiliary heating demand. The study demonstrates that FCVs can contribute to hydrogen infrastructure not only through hydrogen consumption but also through thermal energy recovery.

Future work will focus on dynamic MATLAB/Simscape implementation, transient PCM behavior, detailed station operational modeling, thermal docking system development, and techno-economic assessment of large-scale deployment.

Abbreviations

The following abbreviations are used in this manuscript:

FCV	Fuel Cell Vehicle
AI	Artificial Intelligence
PCM	Phase Change Material
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cells

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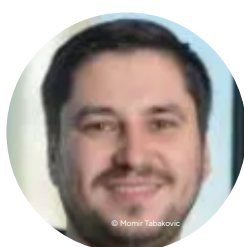
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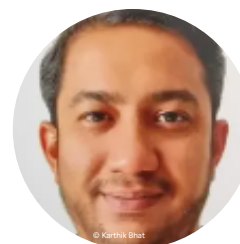
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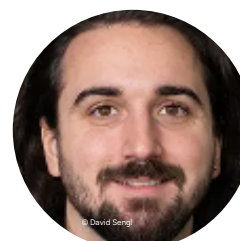
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Veranstaltungskalender

Wann	Was	Wo
8. Oktober	ÖVG Workshop Mobility Forum Salzburg	Salzburg
8. & 9. Oktober	DACH Tagung	München
14. Oktober	6. Busforum	Wien
20. Oktober	RAILCONNECT: Innovation & Einstieg	Graz
22. Oktober	Exkursion Innsbrucker Verkehrsbetriebe	Innsbruck
3. & 4. November	Weichentagung	St. Pölten
5. November	Exkursion Gerlitzten Kanzelbahn	Annenheim
10. November	Karrieretag der Jungen ÖVG	Wien
12. November	Souveräne Infrastruktur?!	Wien
3. & 4. Dezember	8. Kongress Fahrstromanlagen	Wien
7. Jänner 2026	Praxisnah! Die ÖVG Campus Sessions: Gleisbettgeflüster	Graz
18. Jänner 2026	Exkursion zur ASFiNAG	Wien
9. - 12. März 2026	25. Wiener Eisenbahnkolloquium + SRE	Wien
27. - 29. April 2026	Fahrwegtagung	Salzburg





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