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Research article

Better road construction to empower human-powered vehicles

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Abstract: The daily commute to work and other purposes is becoming difficult and costly in metro cities in developing and developed countries. Sustainable and environmentally friendly vehicles, such as smart or electric vehicles, are gaining increased interest. However, the power source to run electric vehicles is still a big concern. Human-powered vehicles (HPVs) help people travel short distances. Though HPVs are environmentally friendly, they are not always time-efficient and feasible for all road conditions. A better method for road infrastructure construction, where gravity could help HPVs run smoothly and faster, might be an effective way to empower sustainable daily commutes in metro cities, as it would save fuel and reduce environmental pollution. This paper highlights the necessity of specialized road construction for HPVs for daily commuting. The study results show how smooth road construction and gravity could help provide a better experience for daily HPV commuters. This study's findings can help urban planners and policymakers develop sustainable, energy-efficient road networks that improve commuter safety and encourage human-powered transport.

Keywords: Human Powered Vehicle (HPVs); sustainable transportation; energy efficient; energy-efficient commuting

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1. Introduction

The growing concerns of urban congestion, environmental pollution, and declining physical activity have intensified global interest in HPVs such as bicycles, tricycles, and velomobiles as sustainable, cost-effective, and health-promoting alternatives for daily commuting. HPVs encourage active lifestyles, reduce greenhouse gas emissions, and minimize fuel dependency. Cities like Paris (France) and Montreal (Canada) have successfully implemented daily HPV commuting initiatives, motivating several U.S. cities, including Washington, D.C., New York City, Chicago, and Minneapolis, to adopt similar programs [1]. However, widespread adoption requires behavioral encouragement and well-designed, HPV-friendly road infrastructure that supports safety, comfort, and energy efficiency.

Despite the growing popularity of cycling and other human-powered modes, vulnerable road users, particularly pedestrians and bicyclists, remain at a significantly higher risk of injury or fatality in mixed traffic environments. Prior studies emphasize these risks. Macioszek et al. [2] identified critical factors increasing the probability of pedestrian deaths in collisions with motor vehicles. At the same time, Macioszek and Grana [3] analyzed bicyclist–vehicle crashes and found that road geometry, driver behavior, and visibility conditions significantly influence the severity of cyclist injuries. These findings underscore the urgent need for dedicated HPV-specific infrastructure that reduces conflict points and enhances commuter safety.

In parallel, the expansion of active transport is increasingly recognized as a key component of sustainable urban development. Macioszek and Ciesla [4] highlighted in their environmental analysis of sustainable bike-sharing systems that promoting human-powered mobility contributes to urban sustainability and supports public health and energy efficiency. With growing environmental awareness and the global push for low-carbon transport, the number of HPV commuters is projected to rise steadily. This trend calls for infrastructure to ensure smooth, comfortable, and safe daily commuting experiences.

HPV road design must therefore balance engineering precision with human comfort. Commuters typically seek routes that minimize effort, time, and physical strain. Streets with varying gradients and surface qualities directly affect ride smoothness, energy expenditure, and overall travel time. Although many cities have introduced bike lanes, these facilities often fail to accommodate the diverse designs of modern HPVs. Specialized HPV routes, incorporating consistent gradients, optimized curvature, and high-quality materials, are needed to promote wider adoption and long-term sustainability.

From a mechanical perspective, HPV performance is influenced by several physical factors: Aerodynamic drag, rolling resistance, rider weight, and surface gradient [5]. These parameters determine how efficiently energy is converted into motion, directly linking roadway design to human exertion and travel comfort. Yet, few studies have examined these mechanical dynamics with civil-engineering considerations, leaving a significant research gap at the intersection of transportation physics and sustainable infrastructure design.

Although the fundamental relationships between surface smoothness, rolling resistance, and gradient are well established in transportation engineering and cycling mechanics, these principles are rarely translated into practical, route-scale guidance for everyday HPV commuting. Existing studies often address these factors in isolation, either through abstract mechanical modeling or qualitative infrastructure assessment without demonstrating how they jointly influence real-world route performance. As a result, planners and engineers lack clear, physically grounded illustrations of how modest roadway design choices can affect HPV efficiency at the neighborhood scale.

The scientific contribution of this work lies in analytically examining and illustrating the relationship between gradient, rolling resistance, and HPV acceleration using physics-based modeling and route-level comparison, an aspect rarely addressed in previous transportation studies. The social contribution involves promoting energy-efficient, low-emission commuting through the design of HPV-friendly roads, thereby supporting public health, reducing urban congestion, and advancing global sustainability goals. Rather than introducing new physical laws, this work provides a proof-of-concept framework that translates accepted engineering principles into actionable insights for HPV-oriented road design.

The rest of the paper will be organized as follows: Following this introduction, Section 2 will present a brief literature review, Section 3 will describe the research methodology of the work, Section 4 will present results and related discussion, and finally, conclusions will be presented.

2. Literature review

Research on HPVs, cycling infrastructure, and sustainable commuting has grown significantly in recent years, reflecting the global movement toward greener mobility systems. Several studies (e.g., Buehler et al. [6]; Mendiate et al. [7]) highlight the role of urban design, infrastructure quality, and cyclist safety as critical determinants of active transport adoption. These works consistently demonstrate that continuous, smooth, and well-maintained bicycle routes encourage daily commuting by HPVs. However, limited research links these infrastructure elements with the physical mechanics of HPV motion, such as rolling resistance and gravitational effects along varied gradients.

Sears et al. [8] investigated the effect of weather on bicycle commuting across northern U.S. communities and found that temperature, wind, and snow depth strongly influence commuting frequency. The study [8] indicates that environmental factors beyond personal motivation affect the viability of HPVs as daily commuting options. Similarly, Hull and O'Holleran [9] emphasized that cities must provide coherent, safe, and comfortable bicycle networks to sustain long-term cycling behavior. Their case studies in six European cities concluded that road surface smoothness, continuity, and visibility are vital in promoting cycling participation.

Further extending the safety perspective, Meuleners et al. [10] examined road design features contributing to bicycle crashes in Perth, Australia. Their findings revealed that roundabouts, steep gradients, and complex intersections elevate accident risk, underscoring the need for specialized HPV infrastructure that reduces conflict points and abrupt elevation changes. Fenre and Klein-Paste [11] provided experimental evidence that surface conditions directly affect rolling resistance and comfort, showing that snow, slush, and wet conditions drastically increase effort requirements. Their study demonstrated how road surface texture and maintenance influence riders' physical energy expenditure.

Recent studies have also emphasized ride quality and material design. Ahmed et al. [12] analyzed 13 cycling paths in Belgium and found that asphalt surfaces provided superior ride comfort compared to concrete or cobblestone. Similarly, Trembecka et al. [13] used the DEMATEL method to identify infrastructure factors that most influence cycling growth, concluding that investment in smooth pavement and signage yields the highest returns in safety and usability. Biassoni et al. [14] investigated psychological aspects of infrastructure perception, revealing that perceived smoothness and directness of routes improve both satisfaction and environmental attitudes among cyclists.

Weikl and Mayer [16] applied data-driven quality assessments to cycling networks, linking digital mobility data with infrastructure ratings. Their work introduces a new direction toward smart infrastructure management, integrating engineering design with digital monitoring. In parallel, Macioszek and Ciesla [4] proposed sustainability frameworks for bike-sharing systems that account for environmental and social factors, reinforcing the relevance of infrastructure in achieving energy-efficient urban mobility.

The reviewed literature demonstrates strong convergence regarding the importance of high-quality and continuous cycling infrastructure for promoting HPV use. Across diverse urban and climatic contexts, studies consistently report that smooth pavement surfaces, route continuity, and safe infrastructure design improve rider comfort, perceived safety, and commuting frequency [6,9,12].

Experimental evidence further shows that increased surface roughness and adverse conditions significantly elevate rolling resistance and physical effort, thereby reducing cycling efficiency [11]. At the same time, safety-focused research highlights that roadway geometry, including gradients and intersection design, plays a critical role in cyclist risk exposure [10]. Despite these shared conclusions, the literature exhibits divergence in methodological approaches: Some studies rely on controlled experimental measurements of resistance [11], others employ user-perception and ride-quality assessments [12], and others adopt qualitative infrastructure scoring or policy-based analyses [4,9]. These differences limit direct comparability and often fragment the understanding of how infrastructure characteristics influence HPV performance.

Importantly, most prior studies treat road surface quality and gradient as contextual or qualitative variables rather than as explicit engineering parameters linked to mechanical performance. While environmental and behavioral research emphasizes weather conditions, policy frameworks, and user perceptions as determinants of HPV adoption [4,8], few studies analytically relate roadway geometry and surface properties to the physical dynamics governing HPV motion. This reveals a clear methodological gap at the intersection of transportation planning and engineering analysis. The novelty of the present study lies in addressing this gap by integrating fundamental principles of mechanics with real-world route comparisons to analytically examine how roadway gradient and rolling resistance jointly influence HPV acceleration, speed, and commuting efficiency. By linking infrastructure design parameters to measurable performance outcomes, this work extends the state of the art beyond descriptive and perception-based assessments and contributes an engineering-informed framework to support energy-efficient, HPV-friendly road design aligned with sustainable and smart-mobility objectives.

Therefore, this paper extends the literature by integrating spatiophysical modeling into infrastructure planning, demonstrating how specialized HPV route construction, guided by mechanical efficiency and sustainability principles, can enhance daily commuting experiences and contribute to smart, energy-efficient cities.

3. Methodology

3.1. HPV mechanical concepts

The system of an HPV (bike, trick, etc.) and rider riding along a straight line is affected by several forces. The forces acting on the HPVs and the rider could be expressed as follows:

$$Ftotal = Fgravity + Frolling + Fdrag. \tag{1}$$

Equation 1 represents the total resistance acting on a moving HPV. It combines the effects of gravity due to road slope, rolling resistance from tire-road interaction, and aerodynamic drag from air, which together determine the pedaling force needed to maintain motion. These force relationships demonstrate how the design and gradient of roads directly influence HPV efficiency. Smoother surfaces reduce rolling resistance, while gentle gradients (0.5%–1%) assist in gravity-aided motion, reducing human energy output and enhancing travel comfort.

On a relatively flat and smooth road with zero gradients, the significant forces are air resistance (Fdrag) and rolling resistance (Frolling). The present experiment did not consider air resistance; however, it could be reduced following a technique called drafting by building a special envelope around the bike, in which the rider always sits in a recumbent position [15]. The mechanical model adopted in this study is intentionally simplified to emphasize the influence of roadway gradient and rolling resistance on HPV motion.

Rolling resistance depends on the road surface, tire pressure, diameter, and tread. This study focused on road surfaces. Newly built or well-maintained asphalt road surfaces ensure the most riding comfort and comparatively better riding speed than rough road surfaces. Therefore, rolling resistance would be less on smooth road surfaces. The term *smooth asphalt surface* refers to roadway conditions typically associated with an International Roughness Index (IRI) below ~2.0 m/km, a value considered comfortable and energy-efficient for bike riding.

The experiment was conducted in a suburban city in Kansas, USA. This city's roads are mostly flat, making it a good choice for HPVs or bike commuting. Though the city is mostly flat, a few locations were found with a 1%–3% gradient, both incline and decline, during the experiment. A 1% gradient means there might be a 1-foot incline or decline in a 100-foot distance. This moderate percentage of gradients makes those streets more HPV-friendly. HPVs could self-roll while riding moderate down slopes (0.5%–1%), increasing riding comfort. In Eq 2, the acceleration of a bike self-rolling down a 1% slope is

$$a = g \times (0.01 - \mu), \tag{2}$$

where a is the acceleration, g is the acceleration due to gravity, and μ is the coefficient of rolling resistance.

Without friction ($\mu = 0$) as shown in Eq 3, the acceleration would be purely due to the slope's gradient:

$$a = g \times 0.01. \tag{3}$$

The bike would accelerate due to gravity alone on a 1% gradient.

The rolling resistance reduces the acceleration shown in Eq 4:

$$a = g \times (0.01 - \mu). \tag{4}$$

For example, with a typical rolling resistance coefficient (μ) of 0.005, the acceleration would be

$$a = 9.81 \times (0.01 - 0.005). \tag{5}$$

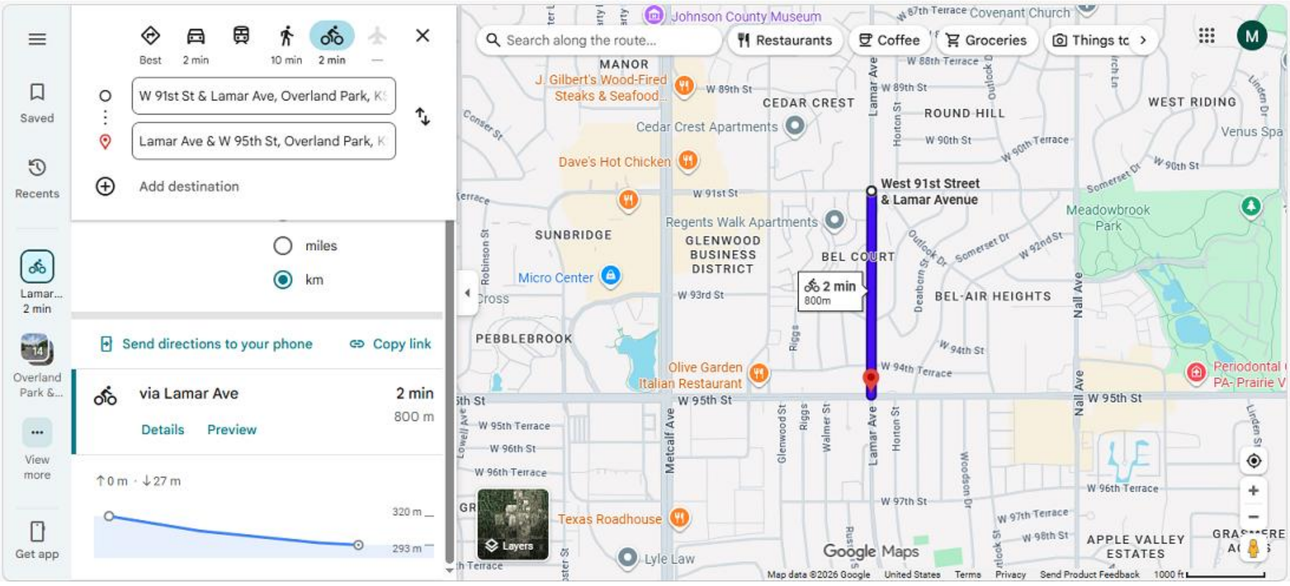
Equation 5 highlights the slope's gradient and the rolling resistance factor in the overall acceleration of a bike rolling down the slope.

3.2. Data collection

This study adopts an empirical, segment-based field methodology to examine how longitudinal roadway gradient and pavement smoothness influence the efficiency and comfort of HPV commuting. Data was collected on four streets—Metcalf Avenue, Antioch Road, Lamar Avenue, and Nall Avenue—located in Overland Park, Kansas. All data were collected during off-peak, low-traffic conditions to minimize traffic interference and eliminate stop-related delays. The same rider and bicycle were used across all routes to control rider-specific variability.

Each street was divided into four contiguous spatial segments aligned with cross streets (87–91, 91–95, 95–99, and 99–103). Segment-level analysis was employed to increase the number of empirical observations while preserving real-world riding conditions. This approach yielded 32 segment observations across the four streets. Segmenting the routes enables statistical evaluation of how localized changes in gradian and pavement condition relate to measured HPV performance.

For each segment, distance (km) and travel time (s) were recorded using GPS, and the computed speed (distance × 3600/travel_time) was recorded. Elevation changes were collected from Google Maps, as shown in Figure 1, and segment-level longitudinal grade (%) was computed using net elevation change. Positive elevation change indicates uphill segments, while negative values indicate downhill segments. Pavement smoothness was quantified using the IRI (m/km) obtained from a smartphone-enabled roughness measurement application. Lower IRI values represent smoother pavement and improved riding conditions. Rider comfort was assessed using a 0–10 subjective comfort scale, where higher values indicate greater comfort during the segment.



W 91st St & Lamar Ave, Overland Park, K

Lamar Ave & W 95th St, Overland Park, K

Add destination

○ miles

● km

via Lamar Ave 2 min 800 m

↑0 m · ↓27 m

Figure 1. Elevation changes to a road segment.

3.3. Statistical analysis

Descriptive statistics are reported to show route summary (empirical segment averages) for all segments. Regression analysis is used to quantify the independent effects of longitudinal grade and pavement smoothness on HPV commuting performance while accounting for their simultaneous variation and the clustered nature of segment-level field data.

4. Results and discussion

The route comparisons presented in this study are based on HPV riding conducted along four suburban streets in Kansas. Segment-level gradients varied from moderate downhill to moderate uphill conditions, while pavement smoothness, quantified using the IRI, exhibited noticeable variation across routes and segments. Corresponding differences were observed in measured riding speed and reported comfort, indicating sensitivity of HPV performance to both longitudinal gradient and surface condition. Descriptive statistics for all segments are summarized in Table 1.

Table 1. Route summary (empirical segment averages).

Route	Direction	Total distance (km)	Net elevation change (m)	Mean grade (%)	Mean IRI (m/km)	Mean speed (km/h)	Mean comfort (0–10)
Antioch Rd	North	3.35	−40	−1.24	2.00	12.19	7
Antioch Rd	South	3.35	42	1.24	2.00	10.30	6
Lamar Ave	North	3.25	−56	−1.74	1.70	13.60	7
Lamar Ave	South	3.25	56	1.74	1.70	10.60	6
Metcalf Ave	North	3.35	−36	−1.11	1.78	14.57	7
Metcalf Ave	South	3.35	36	1.00	1.73	11.38	6
Nall Ave	North	3.25	−58	−1.81	1.75	12.91	7
Nall Ave	South	3.25	58	1.81	1.75	10.63	6

Regression analysis demonstrates that longitudinal gradients are a significant predictor of riding speed. After controlling pavement smoothness, an increase in segment grade is associated with a measurable decrease in average riding speed. As shown in Table 2, a one-percentage-point increase in grade corresponds to an approximate 0.8 km/h reduction in segment speed, highlighting that even modest slopes can influence commuting efficiency. This effect was consistent across all streets, reinforcing the role of grade as a fundamental determinant of HPV performance.

Pavement smoothness also exhibits a strong and statistically significant association with riding speed. Higher IRI values, indicating rougher pavement, are linked to lower segment speeds. Specifically, the results in Table 2 show that a one-unit increase in IRI (m/km) is associated with an approximately 3.1 km/h decrease in riding speed, independent of gradient effects. This finding provides quantitative empirical support for the commonly cited but often unmeasured claim that smoother pavement improves HPV travel efficiency.

Table 2. Segment speed ~ grade + IRI (cluster-robust SE by route).

Predictor	Beta	Standard error	p_value
Grade_%	−0.80	0.11	1.1062565645168096e-13
IRI	−3.07	1.5	0.04

Analysis of rider comfort further emphasizes the importance of pavement conditions. As shown in Table 3, comfort ratings decline significantly as IRI increases, with rougher segments producing noticeably lower comfort scores. A one-unit increase in IRI corresponds to an average 1.3-point reduction in comfort rating, indicating that surface roughness directly affects rider experience. In contrast, once pavement smoothness is accounted for, longitudinal gradient does not exhibit a statistically significant association with comfort, suggesting that under moderate slope conditions typical of suburban corridors, perceived comfort is driven primarily by pavement quality rather than slope alone.

Table 3. Segment comfort ~ grade + IRI (cluster-robust SE by route).

Predictor	Beta	Standard error	p_value
Grade_%	−0.07	0.10	0.41
IRI	−1.32	0.51	0.01

Overall, the results demonstrate that moderate longitudinal gradients and smooth pavement surfaces jointly contribute to improved HPV commuting efficiency, while pavement smoothness plays a dominant role in rider comfort. These empirical findings are consistent across multiple corridors and segments and provide measured, field-based evidence linking roadway design characteristics to HPV performance under real-world commuting conditions.

From the experiment findings and literature reviews, a few crucial points are recommended for better road construction to encourage daily HPV commuting, as summarized in Table 4.

Table 4. Recommendations for better HPV road construction.

Recommendation	Benefits
Connected and direct HPV routes	Safe, time-efficient, and enjoyable daily commuting
Bidirectional HPV lanes, maintaining 0.5%–1% moderate down slope for HPV lanes on each side of the roadway	A steady speed with less pedaling effort allows commuters to travel faster and more effortlessly
High-quality road construction materials for a smoother road surface	Less rolling resistance and increased riding comfort
Safety road sign for commuters	Enhances riders' safety

An important consideration in roadway design is the inherent bidirectionality of commuting routes, where downhill travel in one direction corresponds to uphill travel in the opposite direction. The present analysis does not advocate a globally tilted roadway favoring a single direction of travel. Instead, the proposed design concept assumes direction-specific HPV lanes, where each lane is engineered with a gentle longitudinal gradient (approximately 0.5%–1.0%) aligned with its respective direction of travel. For example, the northbound HPV lane would feature a slight northward descent, while the southbound HPV lane would incorporate a corresponding southward descent, as shown in Figure 2. This approach enables gravity-assisted motion for HPV commuters in both directions while maintaining overall roadway balance and avoiding uphill penalties associated with traditional bidirectional slopes.

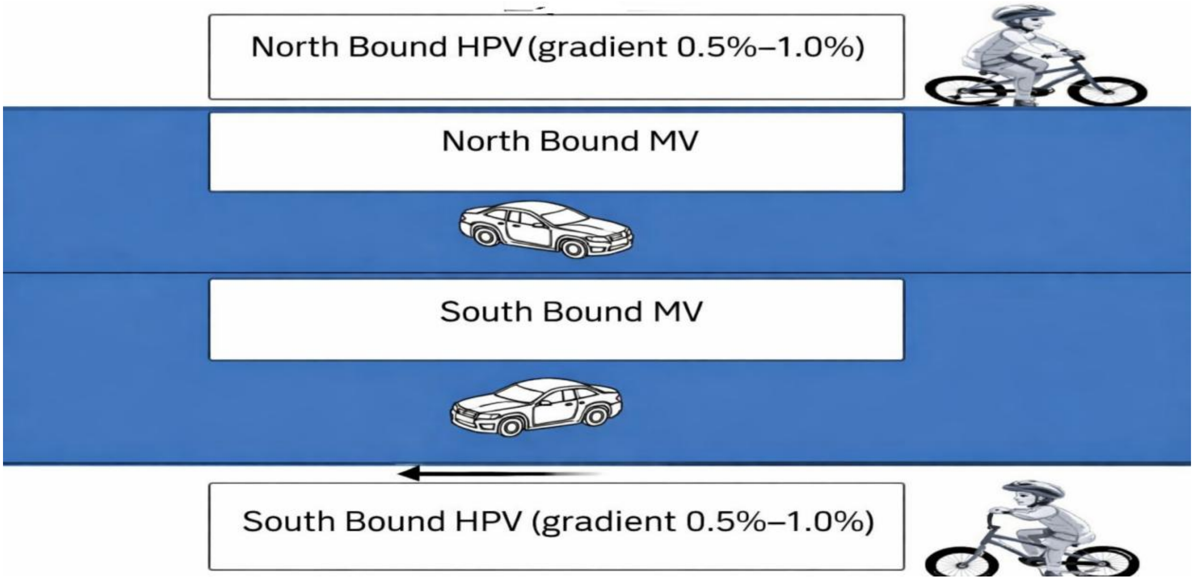


Figure 2. Proposed bidirectional HVP lanes on a roadway.

This study is intended as an exploratory, proof-of-concept analysis demonstrating how established mechanical principles can be translated into route-level infrastructure considerations. The localized suburban case study serves to illustrate feasibility under simplified conditions rather than to provide universally applicable design prescriptions. From a policy perspective, the proposed framework may support preliminary evaluation of HPV-friendly design concepts in suburban or low-gradient urban contexts. Its primary value lies in informing pilot studies and feasibility assessments rather than serving as a comprehensive policy guideline. The applicability of the proposed design concepts is most relevant to suburban or gently graded urban corridors with sufficient right-of-way to accommodate direction-specific HPV lanes. Dense urban cores, highly variable topography, and complex intersections require additional analysis beyond the scope of the present study. It is important to clarify that the proposed HPV corridor concept does not imply artificially creating opposing slopes or mechanically altering roadway elevations. Rather, the analysis is grounded in existing bidirectional topography, where a natural downhill gradient in one direction inherently corresponds to an uphill gradient in the reverse direction, consistent with basic physical laws of energy conservation. The study therefore emphasizes strategic corridor selection and surface optimization within realistic terrain constraints, rather than geometric reconstruction of established roadways.

5. Conclusions

This study demonstrates the novel integration of physical dynamics into HPV infrastructure design, bridging the gap between engineering, transportation sustainability, and human energy efficiency. By quantitatively analyzing the effects of road gradient, rolling resistance, and surface quality on HPV performance, this research introduces a new analytical framework for designing roads that optimize rider comfort and energy use. The empirical comparison of four suburban routes in Kansas indicates that moderate gradients between 0.5% and 1%, combined with well-maintained asphalt surfaces (IRI values below ~2.0 m/km), substantially enhance HPV speed and reduce pedaling effort by minimizing rolling resistance and vibration-induced energy losses. These findings provide engineering evidence that even minor design adjustments can significantly improve daily commuting efficiency for HPV users.

Beyond the technical results, the study contributes to the ongoing discourse on sustainable urban mobility and energy transition. As cities shift toward low-emission and human-centered transport systems, specialized HPV infrastructure can be key in achieving carbon-neutral and health-promoting transportation goals. The proposed design recommendations, such as connected HPV routes, smooth gradients, and durable surface materials, serve as actionable guidelines for planners, engineers, and policymakers to foster active transportation systems that align with digital and smart-city initiatives.

While smoother surfaces and gentler gradients are widely recognized as beneficial for cycling, the novelty of this study lies in its explicit integration of these factors within a unified, route-level engineering perspective. Unlike previous qualitative assessments of cycling comfort, this study quantifies the influence of gravitational forces and surface friction on HPV mobility, providing a scientific foundation for future computational modeling and simulation of HPV dynamics.

The findings of this study provide a transparent framework for understanding the relative influence of gradient and surface quality on commuting efficiency. While the current research focuses on a suburban U.S. context, its methodological framework can be extended to other geographical regions and types of HPVs. Future studies may integrate sensor-based data collection, GIS mapping, and machine learning to simulate large-scale HPV route networks under varying climatic and urban conditions. Through such advancements, the engineering of HPV-friendly roads can evolve into a critical component of smart, sustainable, and inclusive transportation ecosystems worldwide.

Use of AI tools declaration

The author declares he has not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The author declares there is no conflict of interest.

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