Data-Driven Decision Support for Climbing and Passing Lane Improvements Using QGIS-Based Highway Segment Analysis

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Abstract

This study proposes a data-driven decision-support framework for identifying highway segments suitable for climbing and passing lane improvements using QGIS-based spatial analysis. Focusing on Thailand's two-lane highway network, the methodology integrates multiple datasets, including digital elevation models (FABDEM), road geometry, and traffic volumes, with the Highway Capacity Manual (HCM) evaluation criteria. Road segments are standardized and segmented into fixed lengths, then aggregated into 500-meter and 3-kilometer groups for analysis of climbing and passing lanes. Key thresholds include road gradient, percentage of heavy vehicles, and traffic volume filters for candidate segments. The results reveal distinct geographic patterns: passing lane opportunities are concentrated in flatter regions with high traffic flow, while climbing lane needs are predominantly located in mountainous northern corridors. By combining open-source tools and national-scale datasets, the proposed framework enables scalable, objective, and transparent planning of auxiliary lanes, thereby supporting safer and more efficient development of highway infrastructure. The approach is adaptable and cost-effective, with potential for application beyond Thailand.

1. Introduction

Road traffic accidents continue to be a critical public health and economic burden in Thailand. According to the World Health Organization (2023), the country recorded approximately 18,218 traffic-related fatalities in 2021, resulting in a death rate of 25.4 per 100,000 population, one of the highest in Southeast Asia. Many of these fatalities occur on two-lane rural highways, which constitute a large portion of the interprovincial road network and are often characterized by limited safety infrastructure. These roads, especially in remote and mountainous areas, are disproportionately affected by crashes, raising concerns about the adequacy of current road designs and the need for targeted safety interventions.

Among these high-risk settings, two-lane highways in mountainous regions are particularly dangerous due to their geometric limitations and overtaking challenges. When faster vehicles attempt to pass slow-moving trucks, they often must cross into the opposing lane, substantially increasing the risk of head-on collisions (De Jager, 2019). This danger is heightened by sharp curves and limited visibility, which reduce a driver's ability to judge safe passing conditions (Kronprasert et al., 2021; Liu et al., 2024). Additional risks stem from poor road conditions. Faded or missing lane markings and the absence of clear centerlines increase the chance of lane encroachment (Babić et al., 2020). Narrow lanes and a lack of roadside barriers leave little room for error when avoiding oncoming traffic. These design shortcomings, large speed differences between vehicle types, and limited driver decision time make overtaking especially hazardous in these environments (Xiang, 2023). Recent studies by the Department of Highways of Thailand have further highlighted that Thailand's two-lane roadways face persistent congestion and accident issues, especially in areas with challenging terrain (Sapsin et al., 2025).

A practical solution for enhancing safety is the introduction of auxiliary traffic lanes, namely passing and climbing lanes. A passing lane is a short added segment that enables faster-moving vehicles to overtake without entering the opposing lane, alleviating vehicle platooning and reducing driver frustration (Wooldridge et al., 2001). In contrast, a climbing lane is designed for steep inclines and intended to mitigate the impact of large vehicles, such as trucks, that decelerate while ascending. This speed differential increases the risk of collisions, diverting slower cars into a separate lane improves overall traffic flow (Arizona Department of Transportation, 2015).

Several studies assessed the need for passing and climbing lanes. Arpriyanita (2022) designed a climbing lane for Tawangmangu-Plaosan Road, East Java, by manually comparing two candidate segments identified by a preliminary field survey. They collected basic geometric and traffic data, followed by VISSIM-based performance simulation. Their approach provided a detailed analysis of a specific location, but it was limited. There was no systematic way to identify other high-priority segments within the broader road network. The decision process was based on collected data and expert interpretations without integrating larger data records such as digital altitude models and spatial traffic layers. Similarly, Mutabazi (1999) proposed a two-stage framework for selecting passing lane projects in Kansas, combining screening based on project-level and simulations at field observations. However, the final selection of the location is still based on engineering experience. These existing methods are limited by data availability, reliance on manual assessment, and lack of scalability. As a result, a critical research gap remains: the

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absence of a robust, data-driven framework capable of objectively identifying high-priority highway segments for climbing and passing lane improvements across large transportation networks.

Implementing passing and climbing lanes is typically guided by design standards and operational guidelines established by transportation agencies. These standards help determine when auxiliary lanes are warranted based on factors such as road grade, traffic volume, vehicle composition, and overall operational performance. Notable references include the *Highway Capacity Manual* (National Academies of Sciences, 2022), *AASHTO's Policy on Geometric Design of Highways and Streets* (American Association of State and Transportation, 2018), and various national guidelines used across Europe. These frameworks generally assess conditions such as sustained upgrades, a high percentage of heavy vehicles, or traffic volumes that contribute to limited overtaking opportunities.

In Thailand, the Highway Capacity Manual (HCM) is widely adopted as a standard guideline for evaluating highway operations and planning geometric improvements, including decisions related to passing and climbing lanes. The HCM is a foundational reference that provides quantitative criteria for assessing highway performance and outlines key considerations for identifying suitable segments for such improvements. It also emphasizes that site investigations should inform the planning and implementation phases. Additionally, the HCM is applied in various planning frameworks, including national assessments and pilot implementations of special lanes (Sapsin et al., 2025), which define candidate segments based on Average Annual Daily Traffic, the proportion of heavy vehicles, and road gradient, and the number of recorded accidents.

By combining these factors, the HCM enables transportation planners to prioritize locations where geometric and operational deficiencies justify targeted lane improvements. It highlights the importance of integrating analytical tools, particularly Geographic Information Systems (GIS), to improve the assessment process's accuracy, objectivity, and spatial comprehensiveness.

Geographic Information Systems (GIS) are potent frameworks for capturing, storing, analyzing, and visualizing spatial data. GIS integrates diverse datasets, such as topography, infrastructure, land use, and environmental conditions, to uncover spatial patterns that traditional analysis might miss. Its core strength lies in the ability to overlay diverse datasets within a unified geospatial environment, facilitating complex spatial analysis and improved decision-making. GIS also supports advanced tools such as proximity analysis, elevation modeling, and network analysis, which have proven valuable in fields ranging from urban planning to transportation engineering (Bolstad, 2012; Solutions, 2023).

In the context of highway infrastructure planning, GIS provides a robust decision-support framework for improving two-lane highways. By leveraging spatial datasets such as digital elevation models (DEMs), road alignments, traffic volumes, crash locations, and percentage of heavy vehicles, GIS enables practitioners to identify critical segments where geometric and operational challenges demand intervention. Tools like slope classification, buffer analysis, and visibility mapping help evaluate the suitability of specific sites for passing or climbing lanes. Furthermore, GIS facilitates the visualization of overlapping risk factors and performance indicators, supporting a multi-criteria assessment of potential improvement locations. When integrated with guidelines from the HCM, GIS enhances the objectivity, precision, and transparency of the planning process, leading to more informed and effective highway segment improvements (Zhang et al., 2021).

This study builds on these findings by proposing an analytical framework based on QGIS to facilitate data-driven decision-making for enhancing climbing and passing lanes on two-lane roadways. The goal is to utilize open-source geospatial tools to integrate highway geometry, spatial data, and HCM criteria to select high-priority segments. This research aims to help transportation engineers and planners systematically prioritize improvement locations that maximize safety, efficiency, and cost-effectiveness by creating a scalable and replicable technique.

2. Study Area & Data Collection

This study covers the entire country of Thailand, with a focus on the primary and secondary highway networks overseen by the Department of Highways. These networks serve as critical transportation corridors, connecting urban centers and rural communities across diverse geographic regions. Thailand's topography is notably varied, from central plains and northeastern plateaus to mountainous terrain in the north and coastal lowlands in the south (Tourism Authority of Thailand, 2020). This geographic diversity significantly influences traffic flow and driving conditions, particularly in high-gradient areas where auxiliary infrastructure, such as climbing and passing lanes, can enhance roadway safety and operational efficiency.

To address these challenges, the study evaluates highway segments nationwide to identify those suitable for climbing or passing lane improvements. The analysis incorporates topographic and traffic-related conditions and uses spatial analysis tools within the QGIS platform. Evaluation criteria are adapted from the Highway Capacity Manual (HCM), which provides standardized thresholds for assessing the need for auxiliary lanes. This integrated approach supports a systematic, data-driven identification of high-priority segments where additional lanes could deliver measurable safety and traffic performance improvements.

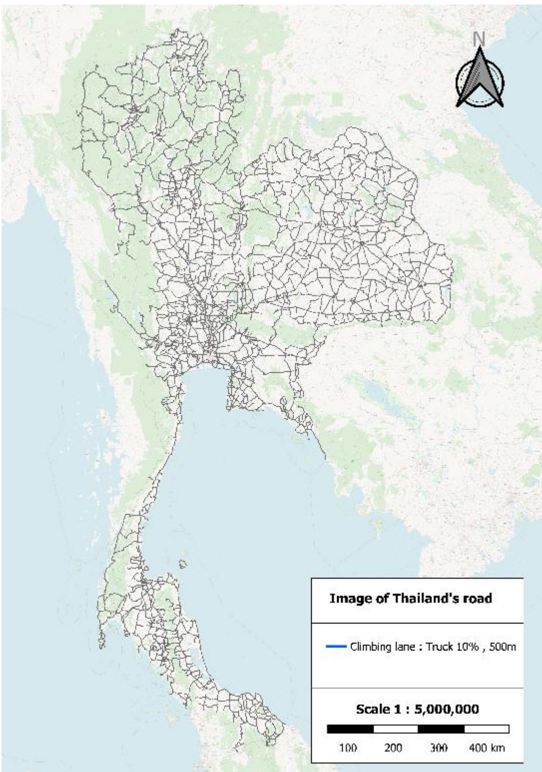

Figure 1. QGIS Visualization of Thailand's Highway Network Shapefile

Most of the spatial and traffic-related datasets used in this study were obtained from the Department of Highways (DOH), Thailand. Figure 1 shows Thailand's national highway network visualized from a geospatial dataset as a polyline shapefile. This dataset represents the alignment of major roads across the country in vector format, serving as the spatial foundation for analysis in QGIS, such as road segmentation, terrain overlay, and the integration of various attribute data. According to the dataset, Thailand's two-lane highway network spans approximately 52,969 kilometers, underscoring the need for scalable and systematic analysis techniques to evaluate infrastructure improvement priorities across diverse geographic contexts.

Additional datasets are integrated during analysis to support data-driven decision-making for highway segment improvements. One key dataset is the road attribute table, which contains essential information such as segment identifiers (e.g., road names and highway numbers), the number of traffic lanes, and Annual Average Daily Traffic (AADT). AADT represents the average number of vehicles passing a road segment per day over the course of a year. It is included in the evaluation criteria based on HCM guidelines, as it reflects traffic demand and operational strain on two-lane highways. Segments with high AADT are more susceptible to congestion, vehicle queuing, and unsafe overtaking behavior, conditions that climbing or passing lanes are specifically intended to address (National Academies of Sciences, 2022). The proportion of heavy vehicles, or the percentage of heavy vehicles in the traffic stream, reflects the presence of slower-moving vehicles, such as trucks and buses, which can significantly reduce travel speeds on upgrades and create overtaking pressure on level terrain. Road gradient, typically expressed as a percentage, measures the steepness of a segment's longitudinal slope and is especially relevant for climbing lane decisions. Steeper gradients can cause heavy vehicles to slow down markedly, disrupting traffic flow and increasing the likelihood of unsafe overtaking attempts.

In addition, elevation data from the Forest and Buildings removed Copernicus Digital Elevation Model (FABDEM), developed by the University of Bristol, is integrated to support terrain analysis. FABDEM provides elevation data at a 30-meter spatial resolution, with surface obstructions such as forests and buildings removed from the original Copernicus DEM, offering a more accurate representation of the bare-earth terrain (Hawker, 2022). Figure 2 presents a QGIS-based elevation map of Thailand using the FABDEM dataset, with green indicating low-lying terrain and red indicating higher elevations. The visualization highlights the flat topography of the central and southern regions, while the northern and western areas, especially along the Myanmar border, exhibit steep, mountainous terrain. These patterns provide essential input for gradient analysis, which supports the identification of road segments potentially suitable for climbing or passing lane improvements. This criterion aligns with the Highway Capacity Manual (HCM), which recommends implementing climbing lanes on sustained upgrades where steep gradients significantly reduce the speeds of heavy vehicles and impair overall traffic flow.

All datasets underwent initial quality control procedures before analysis, including validation and reprojection into a standard coordinate reference system using QGIS. This preprocessing step ensured the spatial data was consistent and aligned, enabling accurate overlay and gradient analysis in later stages. The cleaned and standardized datasets form the basis for the segmentation and integration processes described in the methodology section.

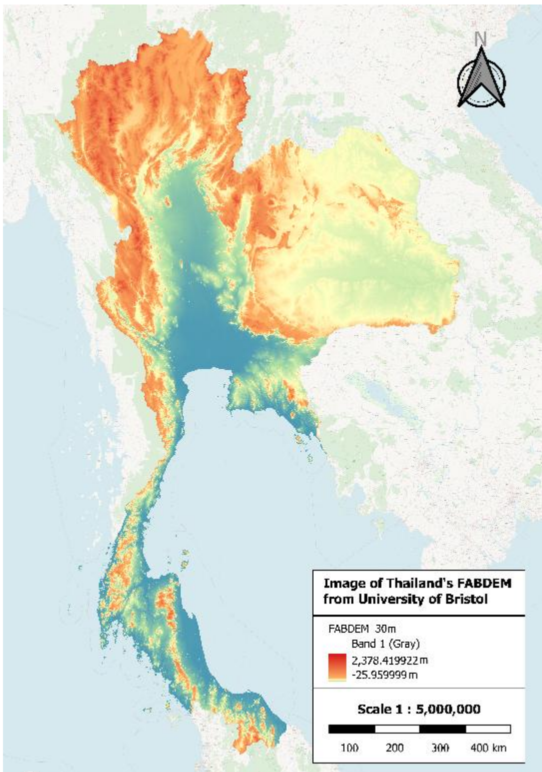

Figure 2. QGIS Visualization of Thailand's Elevation Based on a FABDEM File

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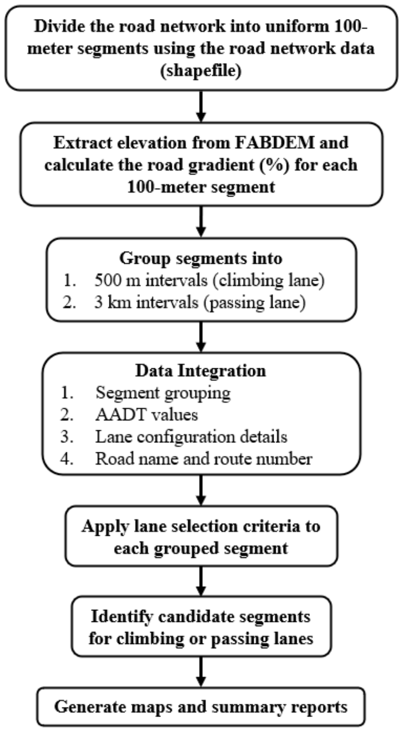

Figure 3. QGIS-Based Workflow for Segment Identification and Evaluation

3. Methodology

This section outlines the spatial analysis workflow used to evaluate highway segments for potential climbing and passing lane improvements, based on standardized preprocessing, segmentation, and HCM-based evaluation criteria.

The analysis began by importing the road network shapefile into the QGIS environment, the primary data layer for subsequent spatial operations. This shapefile contains geometric data of the road network. Then, the road network will be divided into fixed-length segments, each 100 meters long. This fine-grained segmentation is initially selected to allow flexible aggregation into longer intervals, facilitating more effective data management and multi-scale analysis.

(Before Segmentation)

(After Segmentation)

Figure 4. Comparison of Road Network Before and After 100-Meter Segmentation in QGIS

However, a key challenge arises from the structure of the GIS road dataset. Although each road segment includes information about its starting and ending position along the route, these values do not consistently begin from a standardized origin point, such as zero. In many cases, the starting position of each road is arbitrary, depending on how the data was initially recorded or segmented. This inconsistency prevents the application of uniform, fixed-interval segmentation across the entire network.

Additionally, there is a segment alignment mismatch issue, where the boundaries of existing segments do not align precisely with the desired segmentation intervals. As a result, specific segments may begin or end at positions that fall between standard intervals, leading to partial overlaps, gaps, or misaligned segments. These misalignments reduce the accuracy of segment-level grouping and can negatively impact gradient analysis, traffic volume calculations, and subsequent decision-making.

We first merged segments into continuous polylines based on route identifiers to resolve these issues. They were then re-referenced using a unified distance system that resets each route's starting point to zero. Figure 3 (bottom) shows that this enabled clean segmentation at fixed 100-meter intervals using QGIS tools. Any residual misalignments were corrected by snapping to standard breakpoints and combining small fragments with adjacent segments. This preprocessing ensured a spatially consistent segmentation structure suitable for slope computation and integration with traffic data.

Following segmentation, elevation values were extracted from the FABDEM raster dataset. These values correspond to the start and end points of each road segment and are used to calculate the segment-level slope. To align with evaluation guidelines from the Highway Capacity Manual (HCM), the segments were grouped by length into two categories: 500-meter segments for potential climbing lane improvements and 3-kilometer segments for potential passing lane improvements. The 500-meter grouping reflects HCM's recommendation for sustained upgrades where heavy vehicles experience significant speed reductions, while the 3-kilometer grouping captures overtaking behavior and vehicle platooning over longer segments.

Once grouped, each segment was evaluated based on criteria specific to the type of auxiliary lane being considered. These criteria, road gradient, the proportion of heavy vehicles, and Average Annual Daily Traffic (AADT), were derived from the Highway Capacity Manual, which provides quantitative thresholds for assessing the need for climbing and passing lanes on two-lane highways. Although the HCM also recommends considering overtaking-related crash history when evaluating passing lane candidates, this study excludes accident data due to its limited spatial resolution at the control-section level. As such, the analysis focused solely on the three primary factors that could be systematically integrated from available datasets. A summary of these criteria is presented in Table 1.

Criteria	Climbing Lane (≥ 500 m)	Passing Lane (≥ 3 km)
Gradient	≥ 3%	< 3%
Heavy Vehicle	≥ 10%	≥ 2%
AADT (vehicles/day)	≥ 5,000	≥ 5,000
Accident	Not required	≥ 1 recorded accident

Table 1. Criteria for Identifying Candidate Segments for Climbing and Passing Lanes Based on HCM Guidelines

The final set of candidate segments was visualized using QGIS to support spatial analysis and interpretation. Road segments identified as suitable for climbing or passing lane improvements were color-coded and overlaid on a topographic base map to assess their geographic distribution and proximity to critical terrain features. The results of this spatial visualization are presented in Section 4.

All spatial operations were performed using QGIS. Specific tools such as vector segmentation, raster sampling, attribute joins, and slope calculations were applied using standard QGIS processing tools and field calculator operations.

4. Results & Discussion

Tables 2 and 3, along with Figures 5 and 6, present representative highway segments identified as suitable for passing or climbing lane improvements. The passing lane example is from Bo Subdistrict, Mueang Nan District, while the climbing lane candidates are located in Tha Wang Pha Subdistrict, Tha Wang Pha District, both in Nan Province. Segment selection followed HCM thresholds for AADT, heavy vehicle proportion, and gradient. Additional attributes such as highway section codes and responsible district offices support design planning, field validation, and implementation. The accompanying figures further illustrate the geometric and traffic characteristics of the segments.

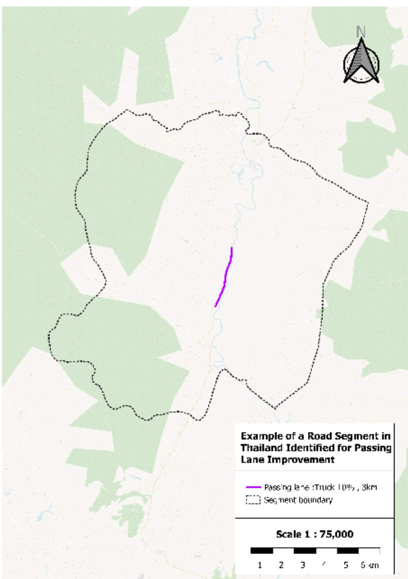

Figure 5. Example of a Candidate Segment for Passing Lane Improvement in Nan Province, Thailand

Segment	Highway Code	Control Code	AADT [veh/day]	Heavy Vehicle (%)	Gradient (%)
1	0101	0601	13282	13.462	2.19

Table 2. Attributes of a Candidate Segment for Passing Lane Improvement in Nan Province, Thailand

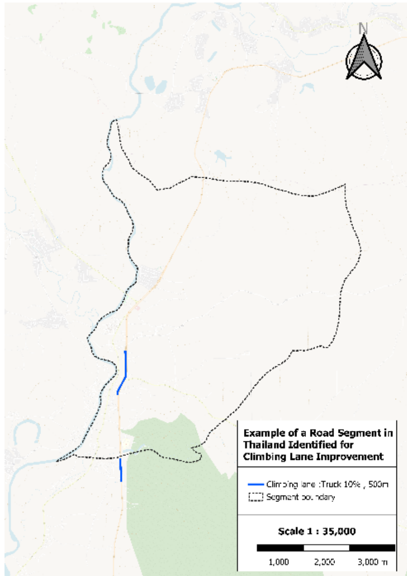

Figure 6. Example of a Candidate Segment for Climbing Lane Improvement in Nan Province, Thailand

Segment	Highway Code	Control Code	AADT [veh/day]	Heavy Vehicle (%)	Gradient (%)
1	0101	0601	13282	13.462	3.11
2	0101	0601	13282	13.462	3.34
3	0101	0601	13282	13.462	3.16

Table 3. Attributes of a Candidate Segment for Climbing Lane Improvement in Nan Province, Thailand

All qualifying segments across Thailand are spatially visualized in Figures 7 and 8, with distinct color codes indicating whether each segment is classified as a climbing or passing lane candidate. These maps provide a comprehensive geographic overview of the improvement needs throughout the country's highway network.

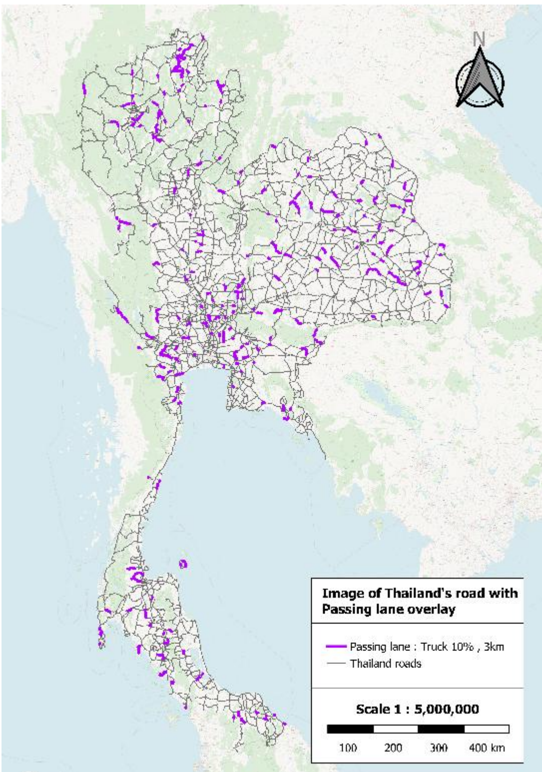

Figure 7. Identified Candidate Segments for Passing Lanes across Thailand

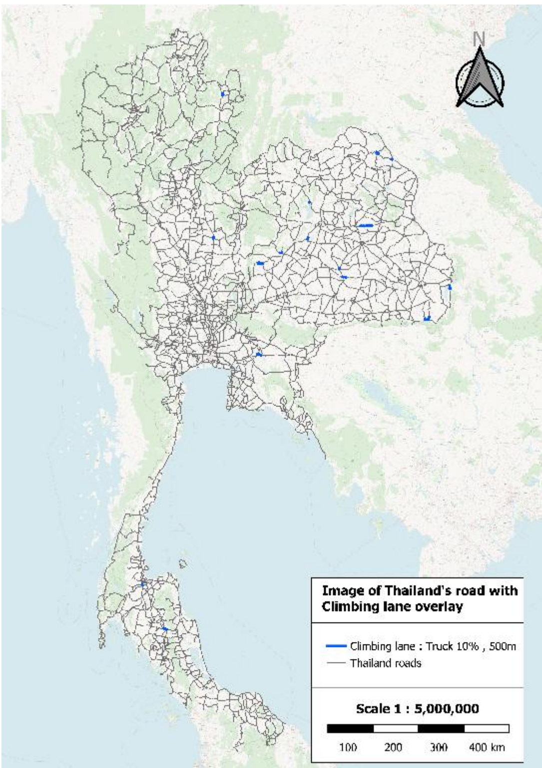

Figure 8. Identified Candidate Segments for Climbing Lanes across Thailand

4.1 Passing Lane Results

As illustrated in Figure 7, candidate segments for passing lanes are distributed across all regions of Thailand, with noticeable clusters in the western, central, and southern areas. Dense concentrations are particularly observed in the central plains and along mountainous corridors in the north and west. These areas tend to have high traffic volumes and moderate terrain, resulting in frequent vehicle platooning and limited opportunities for overtaking.

Based on filtering criteria, including minimum traffic volume, truck proportion, and road geometry, approximately 1,935 kilometers of roadway met the requirements for passing lane improvements. It accounts for roughly 3.7% of Thailand's two-lane highway network, which totals around 52,969 kilometers. The widespread presence of eligible segments suggests a broad operational benefit from implementing passing lanes, especially in flatter but heavily trafficked corridors.

4.2 Climbing Lane Results

In contrast, the distribution of climbing lane candidates, shown in Figure 8, is much more limited and concentrated primarily in Thailand's northern and northeastern regions. These areas are characterized by steep gradients and a high proportion of heavy vehicles, which slow down significantly on upgrades and can disrupt traffic flow.

Using filtering thresholds related to slope and heavy vehicle proportion, the total length of eligible segments for climbing lane improvements was calculated at approximately 141.7 kilometers, or just 0.27% of the entire two-lane highway network. This small percentage underscores that climbing lanes are geographically specific and only applicable in areas with challenging terrain.

4.3 Interpretation and Implications

The spatial distribution patterns provide essential insights into the varying operational challenges across Thailand's highway network. The higher density of passing lane candidates in flatter central and southern regions aligns with corridors experiencing higher traffic volumes but fewer geometric challenges. In these areas, overtaking slower vehicles is difficult due to continuous traffic flow and limited lane availability.

In contrast, the limited but strategically important distribution of climbing lane candidates highlights segments where steep terrain and slow-moving heavy vehicles pose substantial safety and operational challenges. These results align with established highway design guidelines, affirming that climbing lanes should be selectively implemented in areas where they can deliver the most significant safety and performance benefits.

4.4 Limitations and Future Work

While the method demonstrated strong capabilities in identifying potential improvement areas using spatial data and engineering thresholds, several limitations warrant consideration. The analysis relied on static datasets, such as AADT and elevation, which do not fully capture dynamic traffic conditions or seasonal variations. Moreover, the selection criteria did not account for practical implementation constraints, including land acquisition feasibility, construction costs, or adjacent urban development.

Although accident risk data from the Department of Highways is available, it is typically aggregated over long road sections (e.g., control-section level). It lacks the spatial granularity required for segment-level analysis. As a result, while accident history was applied as a binary filter in passing lane identification, the framework could not prioritize segments based on relative crash risk. Future work should investigate the disaggregation of national crash data or the development of a traffic-weighted safety index that incorporates traffic exposure, gradient severity, and crash frequency. Such an index could improve segment-level risk prioritization and safety impact assessment.

Another limitation concerns the resolution of the elevation data used. The study utilized the FABDEM dataset, which has a 30-meter spatial resolution, to compute longitudinal gradients for each 100-meter road segment. These gradients were then aggregated to 500 meters and 3 kilometers for analysis of climbing and passing lanes, respectively. While this resolution is generally appropriate for capturing average terrain characteristics at the segment scale, it may underrepresent localized variations in road geometry, particularly in steep, curved, or terraced areas. Additionally, raster-based slope estimation may not fully reflect the actual road alignment when the roadway meanders within a 30-meter grid. Future studies could benefit from incorporating higher-resolution DEMs (e.g., LiDAR or drone-based surveys) or field-based elevation validation to enhance gradient accuracy and support design-stage planning.

Additionally, future research could further enhance the framework by integrating real-time traffic data, crash severity indicators, benefit–cost evaluations, and field validation. Incorporating these elements would improve both the analytical robustness and practical applicability of the methodology, ultimately supporting more effective infrastructure investment decisions.

5. Conclusion

This study introduced a scalable, replicable, and open-source GIS-based framework for identifying highway segments suitable for passing and climbing lane improvements. By integrating QGIS tools with national-scale datasets, including FABDEM elevation, AADT, and road geometry, and applying Highway Capacity Manual (HCM) thresholds, the method enables objective, data-driven prioritization of auxiliary lane investments. The framework processed over 52,000 kilometers of Thailand's two-lane highway network, identifying over 2,000 candidate segments and visualizing results through thematic maps and structured tables. These outputs facilitate transparent and evidence-based planning decisions, particularly valuable for resource-constrained transportation agencies.

A key contribution of the study lies in its adaptability to other geographic and planning contexts. By relying on publicly available data and open-source tools, the approach is accessible and cost-effective, offering a practical alternative to simulation-heavy or field-intensive methods. Aligning spatial analytics with established engineering standards also ensures consistency and credibility in the evaluation process.

Future work should focus on enhancing the analytical robustness and practical relevance of the framework by incorporating crash severity data, real-time traffic and weather conditions, and benefit–cost evaluations. Field validation of candidate segments is also recommended to account for local conditions not captured in geospatial datasets. These enhancements would support more resilient, safe, and efficient road infrastructure planning, particularly in mountainous or topographically diverse regions.

References

American Association of State, H., Transportation, O. 2018. *A Policy on Geometric Design of Highways and Streets* (7th ed.). American Association of State Highway and Transportation Officials.

Arizona Department of Transportation. 2015. Climbing and Passing Lane Prioritization Study. https://apps.azdot.gov/adotlibrary/Multimodal_Planning_Division/Studies/Climb_Pass_Lane-FR-1502.pdf

Arpriyanita, V., Tjahjono, T. 2022, 04/01. Design of climbing lane on provincial road study case in Magetan Districts East Java. *IOP Conference Series: Earth and Environmental Science, 1000*, 012032. doi.org/10.1088/1755-1315/1000/1/012032

Bolstad, P. 2012. *GIS fundamentals* (Vol. 4). Eider Press White Bear Lake, MN.

Mutabazi, M., Russell, E. R., Stokes, R. W. 1999. Review of the Effectiveness, Location, and Safety of Passing Lanes in Kansas. https://rosap.ntl.bts.gov/view/dot/33832

National Academies of Sciences, E., and Medicine. 2022. *Highway Capacity Manual (HCM), 7th Edition: A Guide for Multimodal Mobility Analysis*. The National Academies Press. https://nap.nationalacademies.org/catalog/26432/highway-capacity-manual-7th-edition-a-guide-for-multimodal-mobility

Organization, W. H. 2023. Global status report on road safety 2023. https://www.who.int/publications/i/item/9789240086517

Sapsin, S., Tangsongsuwan, R., Suntornnak, C., Chansutham, T. 2025, 2025/05/28. *Guidelines for Implementing Special Traffic Lanes: Passing Lanes and Climbing Lanes* Proceedings of the 30th National Convention on Civil Engineering, Prachuap Khiri Khan, Thailand.

Solutions, D. L. 2023. GIS Explained: Comprehensive Guide to Its Impact. Dynamic Link Solutions. Retrieved April 1 from https://redpeopleartist.com/gis-explained-comprehensive-guide-to-its-impact/

Thailand, T. A. o. 2020, 2025/04/21. History & Geography & Geology. https://www.tourismthailand.org/About-Thailand/Geography

Wooldridge, M. D., Messer, C. J., Heard, B. D., Raghupathy, S., Parham, A. H., Brewer, M. A., Lee, S. 2001. Design Guidelines for Passing Lanes on Two-Lane Roadways (Super 2).

Zhang, H., Zhang, M., Zhang, C., Hou, L. 2021, 2021/07/01/. Formulating a GIS-based geometric design quality assessment model for Mountain highways. *Accident Analysis & Prevention, 157*, 106172. doi.org/https://doi.org/10.1016/j.aap.2021.106172