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EVALUATION OF VEHICLE LATERAL POSITIONING FOR LANE-KEEPING PERFORMANCE ACROSS MULTIPLE SITES

Summary. This study investigates lateral lane-keeping behavior among human-driven passenger vehicles on Jordanian multi-lane roads. Using overhead video footage collected at five sites, 500 vehicles traveling alone in the leftmost lane under free-flow, daylight conditions were manually annotated for centerline deviation. The lateral position was analyzed using descriptive statistics, temporal trends, and spectral frequency analysis. Results show that 61% to 83% of vehicles remained within a ±0.5 m "safe zone" from the lane center. No vehicle exceeded the ±1.75 m legal lane boundary, and wheel position plots confirmed consistent lateral margins. Sites 1 and 2 exhibited a slight rightward bias, while Sites 3 through 5 showed a leftward tendency, especially Site 3, which had the highest variability (std dev = 0.43 m). Spectral analysis revealed consistent low-frequency oscillations (~0.01-0.02 Hz), indicating slow, smooth steering adjustments with no erratic corrections. The study confirms that under ideal conditions, drivers maintain stable lateral control within 3.5 m lane widths. These results provide valuable reference data for autonomous vehicle calibration, infrastructure planning, and future

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research into lane-keeping behavior under variable traffic and environmental conditions.

Keywords: lateral position, lane-keeping, autonomous vehicles, vehicle stability, lane departure, driving behavior patterns

1. INTRODUCTION

Maintaining strict lateral vehicle alignment is a critical parameter in roadway design and operational safety. Minor within-lane deviations may elevate collision likelihood, disrupt capacity, and reduce driver predictability. Among the governing variables influencing lateral trajectory is lane width. Broader lanes offer spatial freedom but tend to reduce steering precision and attentional focus. Narrow lanes restrict maneuverability, promoting centralized driving alignment. This relationship has been rigorously examined through naturalistic traffic observations, simulator environments, sensor-instrumented vehicles, and overhead video datasets. Pan et al. (2025) identified that excessive lane width undermines drivers' lane-centering sensitivity, increasing lateral drift susceptibility [1], [2]. Liu et al. (2016) found that reduced lane width correlates with lower travel speeds, explained by heightened driver alertness and visual confinement [3], [4]. Across various geometric and operational settings, lane width consistently governs lateral position variability.

In Jordan, these principles take on added urgency. The nation has witnessed an alarming surge in traffic incidents, with reported crashes increasing from 122,970 in 2020 to 190,175 in 2024, leading to 543 recorded deaths and over 18,000 injuries in that year alone [5], [6]. According to the Jordan Public Security Directorate, driver error was responsible for 97.1% of fatal crashes [7], with lane violations contributing to more than 29% of traffic-related deaths [8]. Additionally, failure to take precautionary action accounted for over 42% of traffic citations, placing lane discipline failures at the heart of Jordan's traffic safety dilemma. Amman, as the capital and most populous governorate, bears the brunt of this crisis. It alone accounts for approximately 41.7% of all reported road injuries in the country [9], and the region's traffic burden is compounded by its dense population, home to nearly 5 million people and over 45% of Jordan's entire vehicle fleet [10], [11].

Urban expansion in Amman continues to outpace infrastructure adaptation. From 2020 to 2024, vehicle registrations grew from 1.72 to nearly 2.0 million units, placing exceptional demand on a network originally designed for lower volumes [8], [12]. While newly rehabilitated corridors such as the Amman–Zarqa axis maintain 3.5-3.75 m lanes per international norms [13], a large share of the city's internal street system, including residential and collector roads, remains restricted to substandard widths near 3.0 m. Local engineering studies have proposed revisions, recommending the expansion of existing lanes to 3.6 m to align with AASHTO and regional policy frameworks [14]. The coexistence of narrow lanes, high vehicle density, inadequate shoulder delineation, and frequent signalized crossings collectively constrains drivers' lateral positioning precision, thereby heightening the risk of lane departure and conflict under real-time conditions [15], [16].

Despite the growing awareness, Jordanian road safety research has not kept pace with infrastructure development. National accident reports provide aggregate figures, but little empirical data exist on how drivers actually position their vehicles laterally during everyday travel. Current assessments rely heavily on crash post-analysis and police records, lacking direct measurement of lane-level behavior. This represents a serious knowledge gap, particularly as lane-related violations remain one of the most common causes of accidents.

Amman's mixed roadway system – comprising high-speed corridors, urban arterials, and substandard local roads – presents a complex and understudied setting for analyzing lateral positioning under varied geometric and operational conditions. Addressing this gap requires reliable, site-specific data on how real drivers respond to lane width, shoulder presence, and road alignment across different segments of the city's transport network.

The present study provides an empirical investigation of lane-keeping performance across multiple road sites in Amman under ideal free-flow, daylight conditions. By capturing overhead video footage and manually annotating vehicle centerline deviations for a sample of 500 passenger cars, the study quantifies the magnitude, direction, and variability of lateral positioning. Statistical, temporal, and frequency-domain analyses are used to evaluate lane centering stability. While the structure of this work mirrors existing international methods, its application in Amman offers an original contribution. No prior study has generated detailed, high-resolution lateral control data from Jordanian roadways. As such, the findings establish a baseline reference for driver behavior under standard geometric conditions and offer practical implications for lane width policy, design standards, and automated vehicle system calibration. The study's novelty lies in its methodological adaptation to a Jordanian urban context and its role in bridging the empirical gap in regional transport safety literature.

2. LITERATURE REVIEW

2.1 Lane width and lateral behavior

Lane width critically governs lateral vehicle dynamics. A percentile analysis established effective operational widths at 3.2 m (95th), 3.0 m (90th), and 2.8 m (85th), reflecting how spatial constraint sharpens lane discipline across urban corridors [17]. Simulation outcomes confirmed that 3.0 m lanes reduced private-vehicle oscillation by 12% under moderate traffic, suggesting improved centering precision in narrowed cross-sections [18], [19]. Recent design protocols follow suit. The NACTO 2023 guidance endorses 3.0 m lanes for urban streets, emphasizing their role in speed moderation and cross-modal integration [20], [21]. Empirical freeway data in China revealed that lateral displacement remains within ±0.10 m at sustained speeds over 100 km/h when the lane width is fixed at 3.25 m [22]. Driver-centric modeling by Chen et al. (2024) showed that passenger vehicles occupy 0.4-0.5 m more lateral bandwidth than heavy trucks; they recommend a 3.25-3.50 m minimum for car-only lanes [23]. Controlled tunnel-driving experiments demonstrated mean speeds of 60 km/h in 2.85 m lanes versus 88 km/h in 3.75 m lanes, with wider lanes yielding higher lateral variability [3]. Field studies on multi-lane roads observed consistent inward drift in outer lanes, attributed to edge aversion, while mid-lane vehicles exhibited greater deviation due to buffer perception [24]. Together, the evidence supports lateral stability thresholds of 2.9-3.3 m for urban networks and 3.25-3.50 m for high-speed zones, directly informing design calibration for Amman's varied cross-sections.

2.2 Effects of lane position and road geometry

Lane position significantly influences lateral stability. Simulator studies on urban expressways show that outer-lane drivers maintain an inward offset of 0.20-0.30 m to avoid close barriers, especially when lane widths are 2.85-3.00 m and shoulders are only 0.50 m wide [3], [25]. In contrast, center-lane drivers exhibit more stable, centered trajectories. In real-world settings, lane location also affects steering consistency. A field study on German freeways found that outer-lane vehicles showed 20-30% less lateral oscillation than center-lane vehicles at comparable speeds, indicating that edge lanes may promote more stable paths under free-flow conditions [26], [27]. Field data from two-lane mountain roads showed that curves with radii under 250 m caused lateral displacement to rise by 0.15-0.25 m, reflecting reduced lane stability. Tighter curvature increased within-lane deviation, elevating the likelihood of drift toward opposing lanes or shoulders [28]. Reducing shoulder width from 1.0 m to 0.5 m induces an average inward lateral vehicle shift of approximately 0.25-0.35 m, particularly pronounced on curved road segments. Drivers adapt to the diminished shoulder space by centering their vehicles more within the lane to maintain lateral clearance and perceived safety margins [29]. Analysis of 320 Utah arterials showed that wider lanes not only raised 85th percentile speeds by ~1 mph per foot but also increased injury crash odds by 38.3%, reinforcing the stabilizing role of narrower lanes in geometrically constrained settings [30].

2.3 Methodologies: simulators vs field data

Driving behavior is studied using two main methods: simulations and field data. Simulations allow controlled changes, such as lane width or shoulder type. Field studies capture real-world behavior under natural conditions. Simulations offer control; field data offer realism. Both are essential for a full understanding of road safety.

Field data consistently show that narrower lanes raise lateral deviation and crash risk. On Italian mountain roads, 3.0-3.2 m lanes caused 30% more lateral wandering and 8% lower speed than 3.5 m lanes

By contrast, naturalistic and instrumented-vehicle studies capture real driving in traffic. Like using UAV video on freeways to measure vehicles' lateral distances during overtakes [31]. Chen *et al.* (2024) analyzed trajectories from instrumented cars in Chinese expressways [32]. Field studies of vehicle lateral positioning and lane-keeping behavior corroborate findings from driving simulator research, demonstrating that trucks tend to maintain greater lateral clearance from lane edges than passenger cars [33], [34], and that available overtaking gaps significantly constrain lateral spacing between vehicles [35], [36]. Unlike simulators, real-world data captures large sample sizes of naturalistic driving behavior [37], including driver responses to unpredictable traffic events such as oncoming vehicles. These dynamic interactions often force drivers to adjust their lateral position within the lane, frequently pushing them toward one side to maintain safety margins.

2.4 Global and regional perspectives

Road authorities worldwide recognize lane width as a crucial design parameter. In the United States, the AASHTO Green Book mandates 3.66 m lanes on high-speed roadways, while urban arterials may utilize 2.7-3.6 m widths depending on context [38], [39]. European standards vary: Germany recommends 3.5-3.75 m lanes, and the UK's Design Manual for Roads and Bridges specifies 3.65-3.7 m [30]. Australia follows with 3.3-3.5 m lane widths for arterial roads [40].

Field research in Sweden has measured lateral positioning on two-lane rural roads, finding standard deviation of lateral wander between 0.19-0.46 m, depending on lane width and roadside design [41]. No Jordanian-specific studies of lane-keeping were found in the literature. In summary, although many countries default to 3.5-3.75 m, field evidence supports narrower lanes – 3.2-3.5 m – for effective speed control and consistent lane behavior. Where geometric flexibility is limited, maintaining lane widths above 3.2 m offers a balance of capacity and safety, validated by both simulator and field data.

2.5 Knowledge gaps and research needs

Although the relationship between lane width, speed, and lateral control is well-established, several critical gaps remain. First, most existing research neglects the impact of mixed traffic conditions, particularly the interaction of motorcycles, cyclists, and passenger cars in congested urban settings. How these dynamics influence lateral behavior in narrow lanes is insufficiently understood. Second, current evidence is largely drawn from controlled simulation environments, which fail to capture real-world variability in speed choice and lane-keeping. Naturalistic driving studies are needed to examine how drivers simultaneously adjust speed and lateral position across diverse road geometries.

Third, regional variations in driving behavior are underexplored. In cities like Amman, where informal lane discipline and high traffic heterogeneity prevail, it remains unclear whether global findings on lane width apply. There is a need for empirical studies grounded in Middle Eastern contexts to test the generalizability of established design assumptions.

Finally, the impact of advanced driver-assistance systems (ADAS), particularly lane-keeping assistance, under nonstandard lane widths and degraded markings warrants investigation. As these technologies are increasingly deployed in Jordan, understanding their compatibility with existing infrastructure is essential.

Key research questions include:

- How does mixed traffic in urban centers like Amman affect the relationship between lane width and lateral control?
- To what extent do speed and lane width interact under naturalistic driving conditions?
- How transferable are international findings to regional driving cultures?
- How do ADAS systems perform in narrow or irregular lanes commonly found in Amman?

3. DATA AND METHODOLOGY

3.1 Study site and data collection

This study was conducted on selected segments of Jordanian roads, predominantly featuring two or three lanes per direction, and a posted speed limit ranging from 60-80km/h. These roads, which serve as interurban connectors, were chosen for their representative geometric and traffic characteristics. Data collection focused on straight, level road sections in order to eliminate confounding effects from curvature, elevation changes, or merging zones.

Vehicle observations were recorded using a fixed camera mounted orthogonally on an overpass. Although the exact height of the bridge is not specified, it adheres to standard clearance regulations designed to accommodate heavy vehicles. The camera setup ensured minimal perspective distortion and provided a clear top-down view of passing vehicles. The footage was captured during daylight hours under clear weather conditions to maintain consistency in visibility and lighting. Traffic was observed to be in free-flow conditions, with no signs of congestion or abnormal vehicular interactions.

3.2 Sample selection and annotation

From the collected video footage, a total of 500 human-driven passenger cars were manually annotated. To ensure high precision and eliminate behavioral artifacts, only vehicles traveling alone in the leftmost (fastest) lane were included. Vehicles were excluded from the study if they were partially obscured, in the process of changing lanes, or traveling adjacent to another vehicle. This filtering process aimed to isolate undisturbed lane-keeping behavior under normal driving conditions.

Manual annotation was carried out by a team of five trained observers. Each vehicle's lateral position was recorded as the distance from the geometric center of the vehicle to the centerline of the lane it occupied. While no formal camera calibration was applied, the lateral offset was estimated visually, and values were averaged across observers to reduce subjective bias. This approach yielded a practical estimate of lateral position with an approximate accuracy tolerance informed by observer consensus.

Kinovea motion analysis software was employed to assist in the manual annotation process. The software's gridline overlay was activated to provide consistent spatial referencing, with the spacing between consecutive gridline ticks calibrated to represent 17.5 cm in the field. This ensured uniform measurement scaling across all frames and enhanced the accuracy of lateral position estimation by allowing observers to align vehicle features precisely relative to the lane centerline, as shown in Fig. 1.

Fig. 1. Gridline overlay in Kinovea showing 17.5 cm spacing between ticks for lateral position measurement

3.3 Lane geometry

The lane width was assumed to be 3.5 meters, based on national road design guidelines and corroborated by official roadway documentation for the studied road segments. Only the leftmost travel lane was considered for analysis to reduce variability introduced by lane function as shown in Fig. 2.

3.4 Data processing and statistical methods

The evaluation of lateral positioning data followed a structured methodology to ensure accuracy, reproducibility, and consistency with the study objectives (see Fig. 3). All analyses were conducted in Python using pandas for data handling, numpy for numerical operations, matplotlib and seaborn for visualization, and scipy for basic statistical computations.

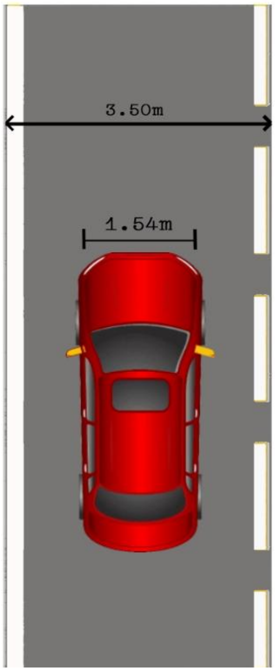


Fig. 2. Vehicle and lane geometry reference for lateral positioning measurements

Data pre-processing

Annotated measurements from five independent observers were compiled into a single dataset. For each vehicle, the lateral offset from the lane centerline was averaged across observers to reduce inter-rater variability. Only records meeting the predefined criteria – human-driven passenger cars traveling alone in the leftmost lane during daylight, under free-flow conditions, and without occlusion or adjacent vehicles – were included. This filtering ensured the dataset represented undisturbed lane-keeping behavior.

Descriptive statistical analysis

For each observation site, measures of central tendency (mean, median) and dispersion (standard deviation, interquartile range, minimum, maximum) were calculated. Distributional characteristics were examined through histograms, boxplots, and kernel density estimates (KDEs) to visualize lane-keeping behavior and identify directional biases.

Safety and performance classification

Lateral deviations were classified according to predefined thresholds:

- Central Zone: within ±0.50 m of the lane centerline,
- Lateral Deviation Zones: left or right offsets within lane boundaries (±1.75 m from the centerline).

The proportion of vehicles in each category was computed to evaluate lane-keeping accuracy.

Temporal analysis

To assess stability over the observation period, deviations were plotted sequentially by vehicle index and smoothed using a 10-point rolling mean. This approach was used to detect potential drift or changes in positioning behavior across the dataset.

Vehicle envelope analysis

Wheel positions were estimated by offsetting the vehicle center position by ±0.75 m (half the assumed vehicle width). These positions were compared with lane boundaries (±1.75 m from the centerline) to evaluate spatial margins and verify lane compliance.

Frequency-domain analysis

Lateral deviation time series were analyzed in the frequency domain using the Fast Fourier Transform (FFT) to identify dominant oscillation frequencies and characterize the periodicity of steering adjustments.

This combination of descriptive, temporal, spatial, and spectral analyses provided a comprehensive basis for interpreting lane-keeping performance across the observation sites.

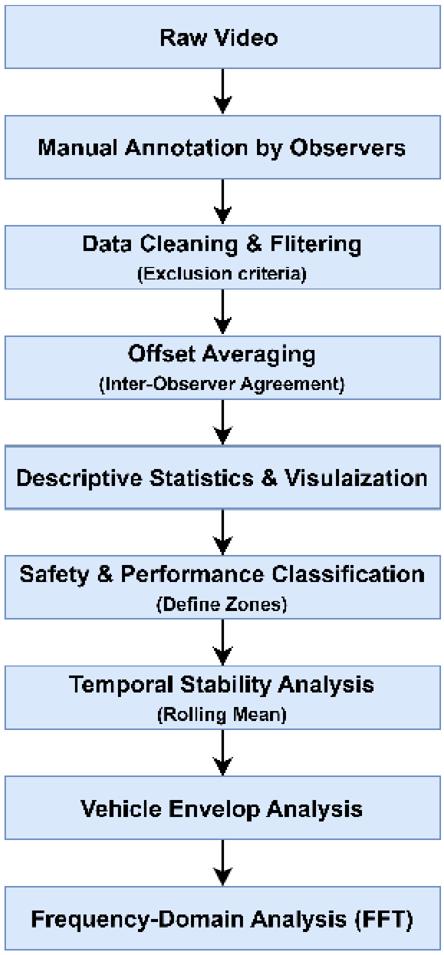


Fig. 3. Flowchart illustrating the sequential data processing and statistical analysis steps used in the evaluation of vehicle lateral positioning

4. RESULTS

This section presents the lane-keeping performance of human-driven passenger vehicles across five observation sites located on Jordanian multi-lane roads. Each site was characterized by straight road geometry, standard 3.5-meter lane widths, and consistent conditions (daytime, clear weather, free-flowing traffic). Only vehicles traveling alone in the leftmost (fastest) lane were analyzed to isolate undisturbed lane-keeping behavior.

4.1 Lateral position summary statistics

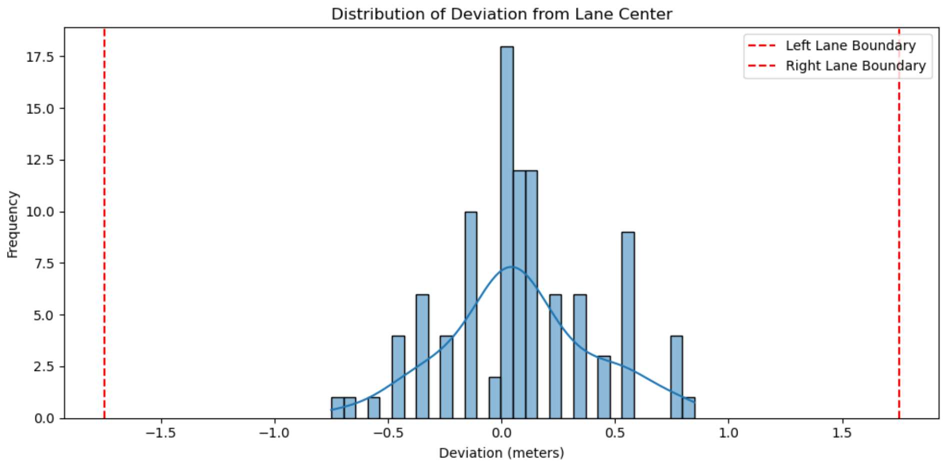
Descriptive analysis was conducted to evaluate the distribution of vehicle centerline deviations from the lane center. Tab. 1 summarizes the mean, standard deviation, and spread of lateral position across all sites.

Tab. 1

Descriptive statistics of lateral position deviation (in meters)

Site	N	Mean	Std Dev	Min	25%	Median	75%	Max
1	100	+0.079	0.325	–0.750	–0.150	+0.050	+0.250	+0.750
2	100	+0.081	0.318	–0.740	–0.140	+0.055	+0.245	+0.740
3	100	–0.172	0.430	–0.850	–0.550	0.000	0.000	+0.750
4	100	–0.051	0.359	–0.850	–0.310	–0.030	+0.240	+0.630
5	100	–0.069	0.370	–0.850	–0.350	–0.040	+0.260	+0.630

Sites 1 and 2 showed a slight rightward deviation, while Sites 3, 4, and 5 revealed a modest leftward bias. The standard deviation ranged between 0.318 and 0.430 meters, indicating relatively stable lane-keeping with some inter-site variability. As shown in Fig. 4, the distributions of lateral position vary modestly across sites. Sites 1 and 2 are slightly right-skewed, while Sites 3, 4, and 5 show a leftward shift, especially pronounced at Site 3.



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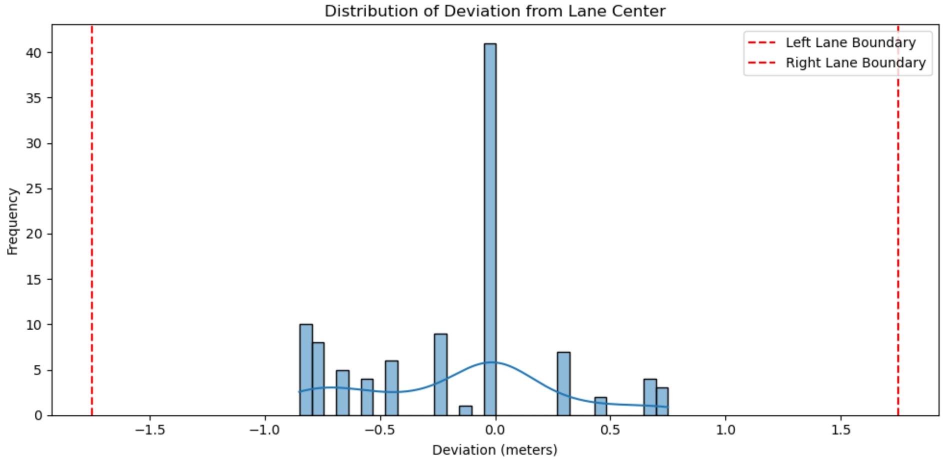
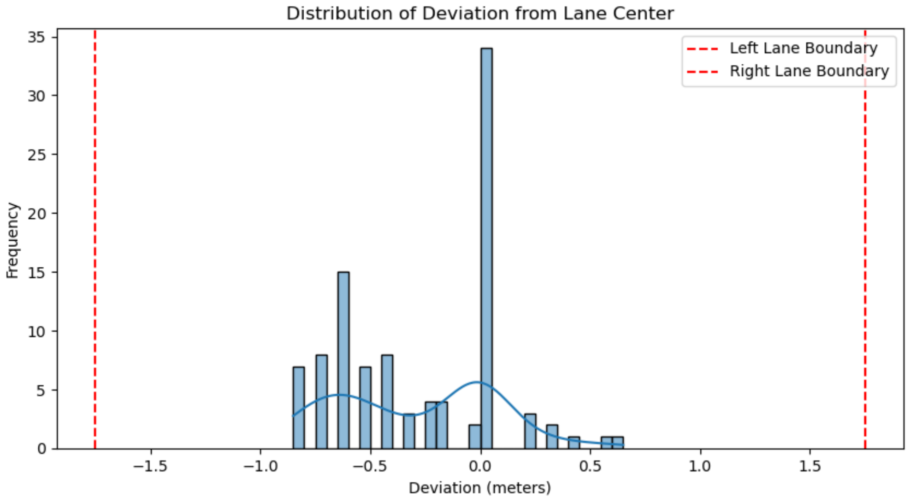
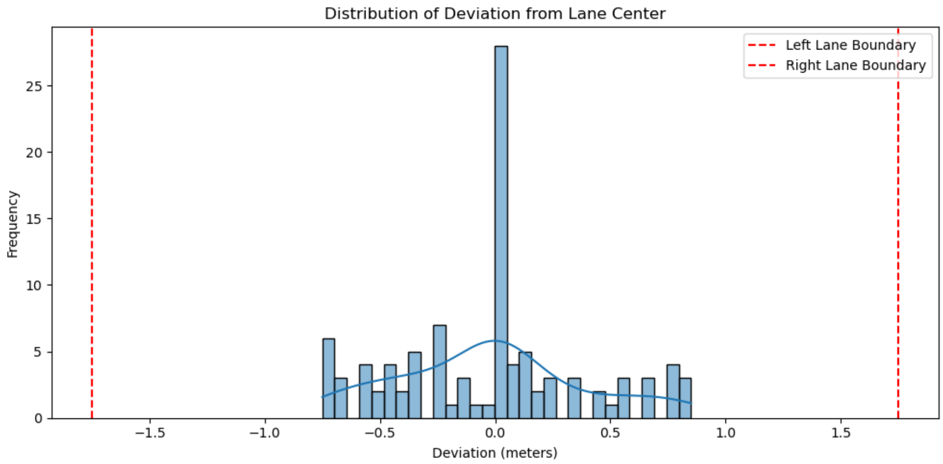

Distribution of Deviation from Lane Center
Left Lane Boundary
Right Lane Boundary
Frequency
Deviation (meters)

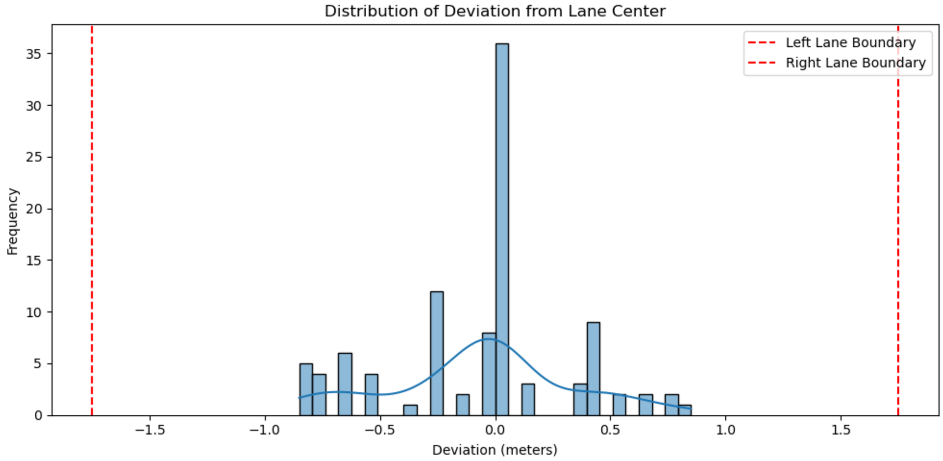
(b)


Distribution of Deviation from Lane Center
Left Lane Boundary
Right Lane Boundary
Frequency
Deviation (meters)

(c)


Distribution of Deviation from Lane Center
Left Lane Boundary
Right Lane Boundary
Frequency
Deviation (meters)

(d)



(e)

Fig. 4. Histograms and kernel density estimates (KDEs) of vehicle lateral position deviation across Sites 1 to 5

4.2 Lane-keeping accuracy and safety

The percentage of vehicles that remained within a ±0.5 m deviation from the lane centerline, referred to as the safe zones, ranged from 61%-83% at all sites (see Tab. 2).

No vehicles in any site crossed the lane boundaries (±1.75 m from the lane center), and all vehicles maintained both left and right wheels within the legal lane limits.

Tab. 2

Lane-keeping performance by site

Site	Analysis Summary				
	Safe Zone Coverage	Left Bias %	Right Bias %	Lane Center %	Lane Departure %
Site 1	83%	53%	29%	18%	0%
Site 2	66%	16%	43%	41%	0%
Site 3	61%	8%	58%	34%	0%
Site 4	74%	33%	39%	28%	0%
Site 5	74%	22%	42%	36%	0%

Figure 5Fig. **5** presents boxplots comparing the central tendency and dispersion of lateral deviation across all five sites. The figure confirms that median values were close to zero at most sites, with greater variance observed at Site 3.

4.3 Distribution patterns and lateral bias

Histograms and kernel density estimates (KDE) revealed that:

- Sites 1 and 2 had unimodal distributions centered slightly to the right of lane center (positive deviation).

- Sites 3 to 5 had distributions centered slightly to the left, with Site 3 showing the widest spread and the clearest leftward skew.

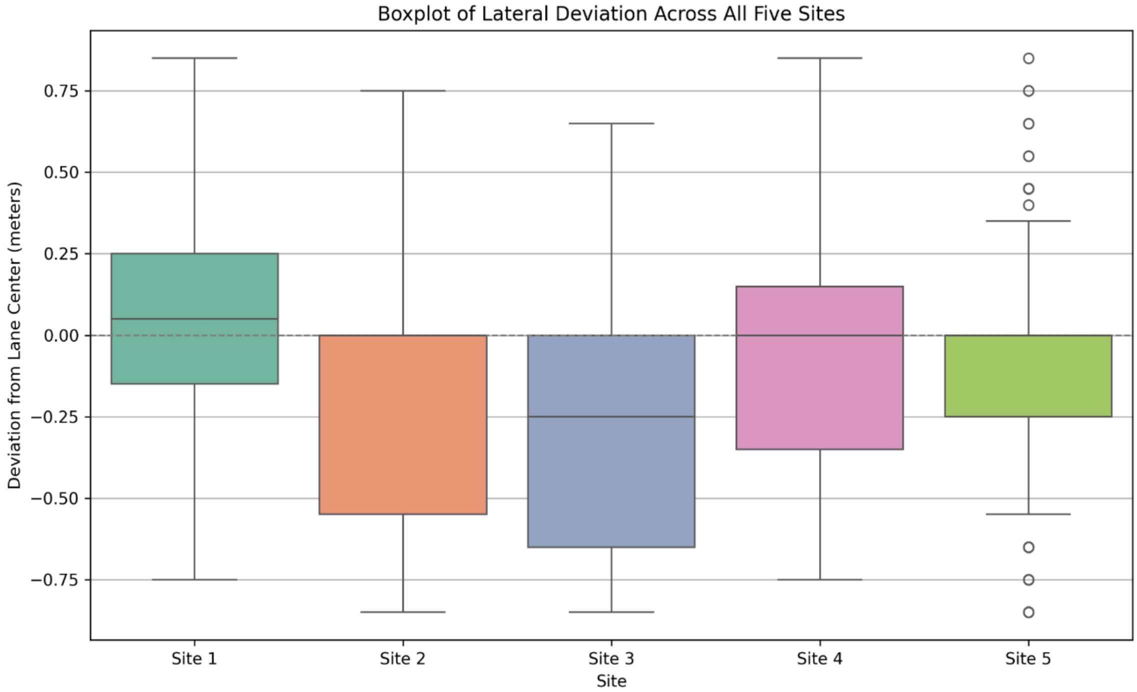


Fig. 5. Boxplot of lateral deviation across all five sites

These findings are consistent with the descriptive statistics and suggest possible influences from site-specific road geometry or driver behavior tendencies. This pattern is further supported by the histograms and KDEs shown in Fig. 4.
Fig. **4**

4.4 Temporal consistency and rolling averages

For all sites, plots of lateral deviation over vehicle index showed no systematic drift over time. Rolling mean plots indicated stable driving patterns throughout the data collection sessions. This supports the reliability of the observational protocol, and the uniformity of the traffic flow conditions across all sites. As shown in Fig. 6, the rolling average of deviation over vehicle index was consistent across time, with no drift or trending, indicating data quality and driver consistency.

4.5 Vehicle wheel position vs. lane boundaries

To evaluate safety margins, the positions of the left and right wheels (inferred from the center position ±0.75 m) were plotted against lane boundaries. At no point did either wheel cross the lane edge, and a comfortable margin from both boundaries was consistently observed, Fig. 7 visualizes left and right wheel positions relative to the lane boundaries. All vehicles stayed within ±1.75 m of the centerline, with no contact or crossing of lane edges.

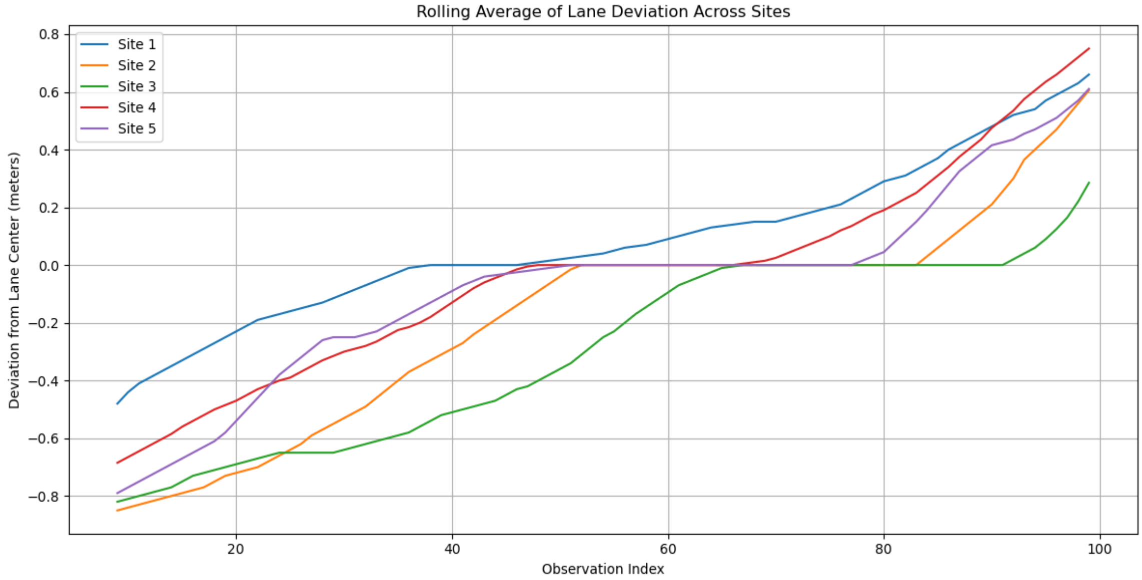
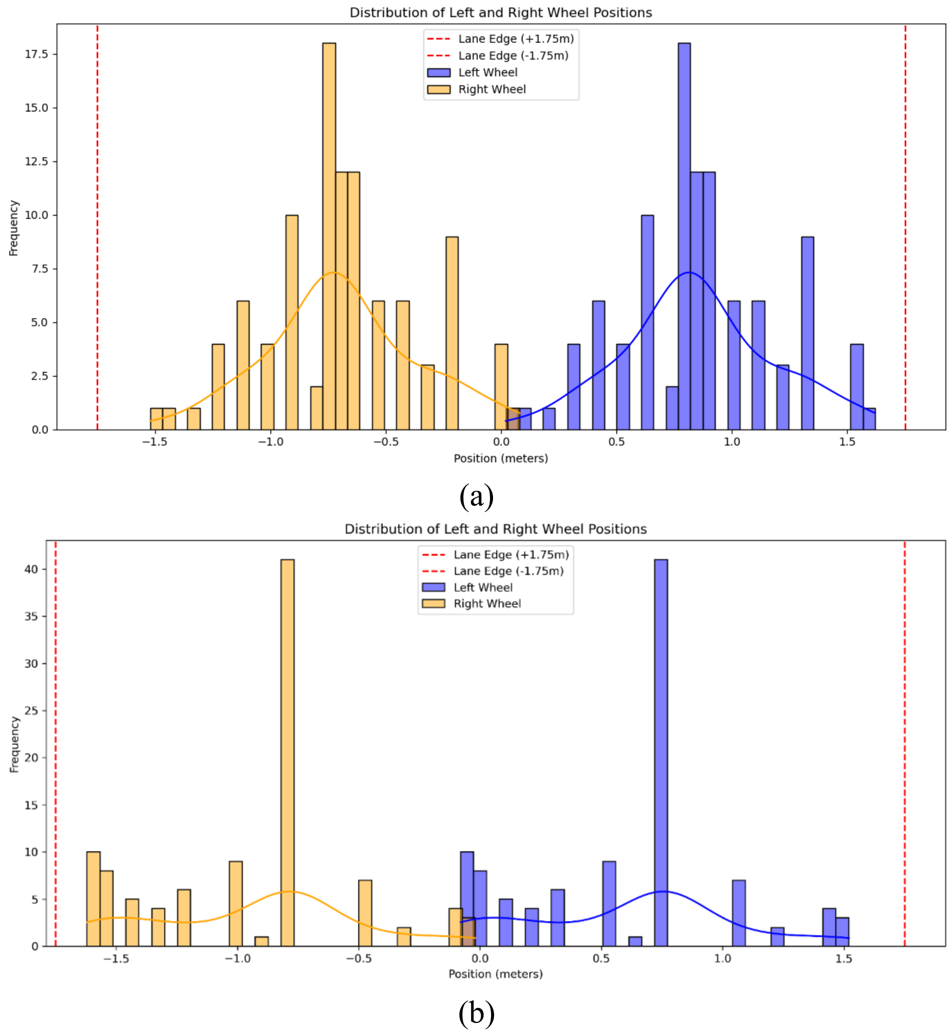
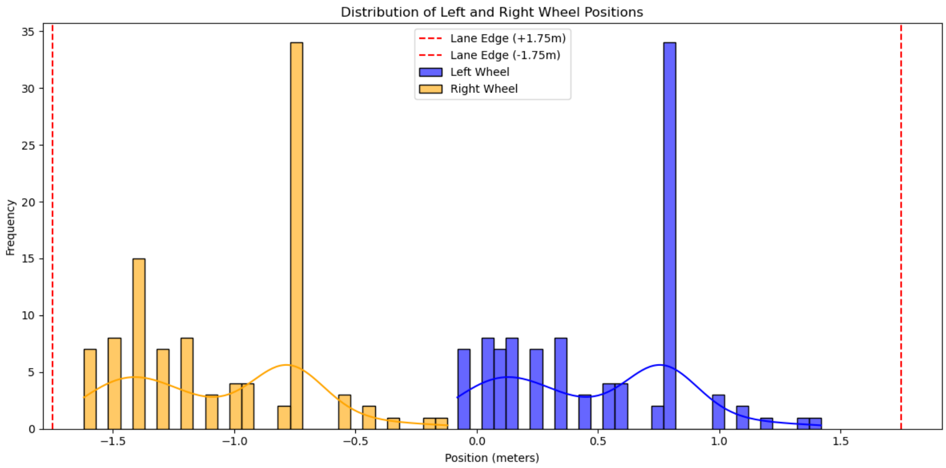


Fig. 6. Rolling average of lateral position deviation across all vehicle indices at Sites 1 through 5





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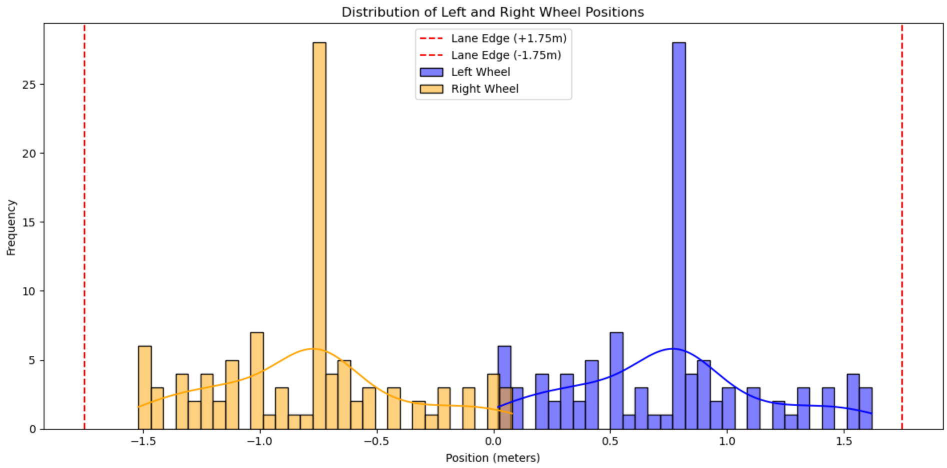

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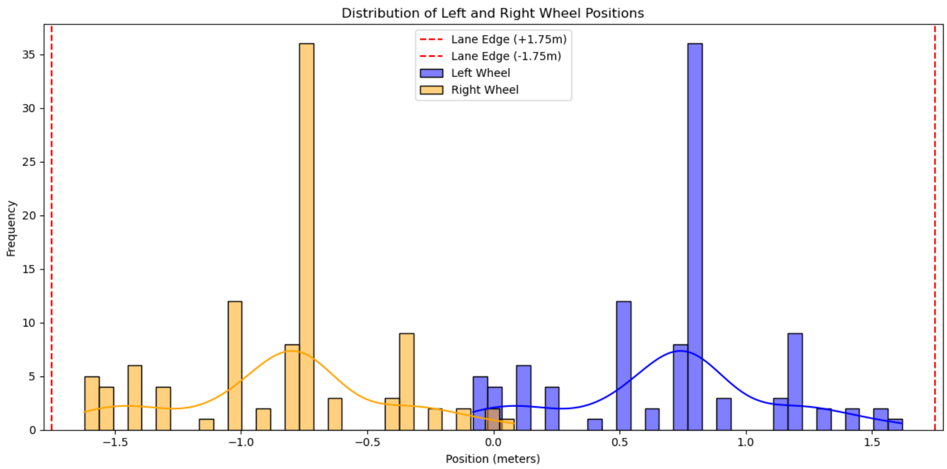

(e)

Fig. 7. Left and right wheel positions relative to lane boundaries (±1.75 m from lane centerline)

As shown in Fig. 8. All sites demonstrated good lane-keeping, with over 60% of vehicles within the ±0.5 m range.

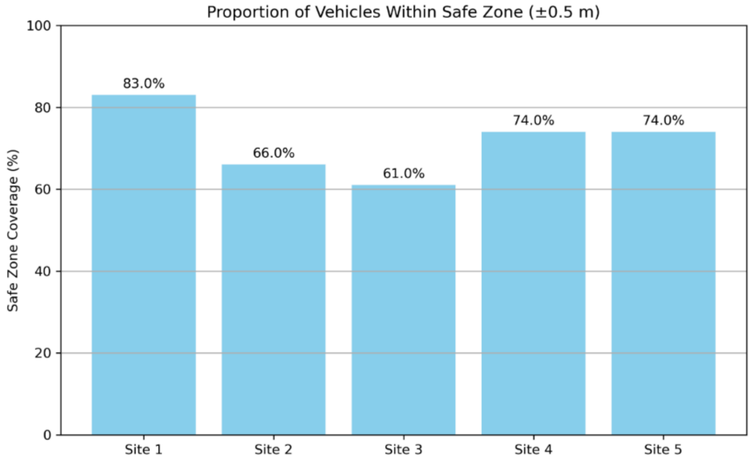

Fig. 8. Proportion of vehicles within the safe zone (±0.5 m from lane center) across all sites

4.6 Frequency and stability analysis

Figure 9 displays the overlaid frequency spectra of lateral deviations for all five sites. Across all sites, a dominant low-frequency component was observed near 0.01 to 0.02 Hz. This corresponds to slow, periodic lateral corrections occurring approximately every 50 to 100 seconds. The consistent peak shape and magnitude across sites suggest that drivers performed smooth, long-period steering adjustments irrespective of location.

Notably, Site 3 exhibited the highest amplitude near 0 Hz, indicating a larger average deviation from the lane center and possible persistent lateral offset. In contrast, Sites 1 and 2 displayed similar, slightly lower peak magnitudes, confirming more centered and stable driving behavior. The lack of high-frequency components (>0.1 Hz) across all sites reflects the absence of erratic or high-frequency corrections, underscoring the stable driving dynamics under free-flow, ideal road conditions.

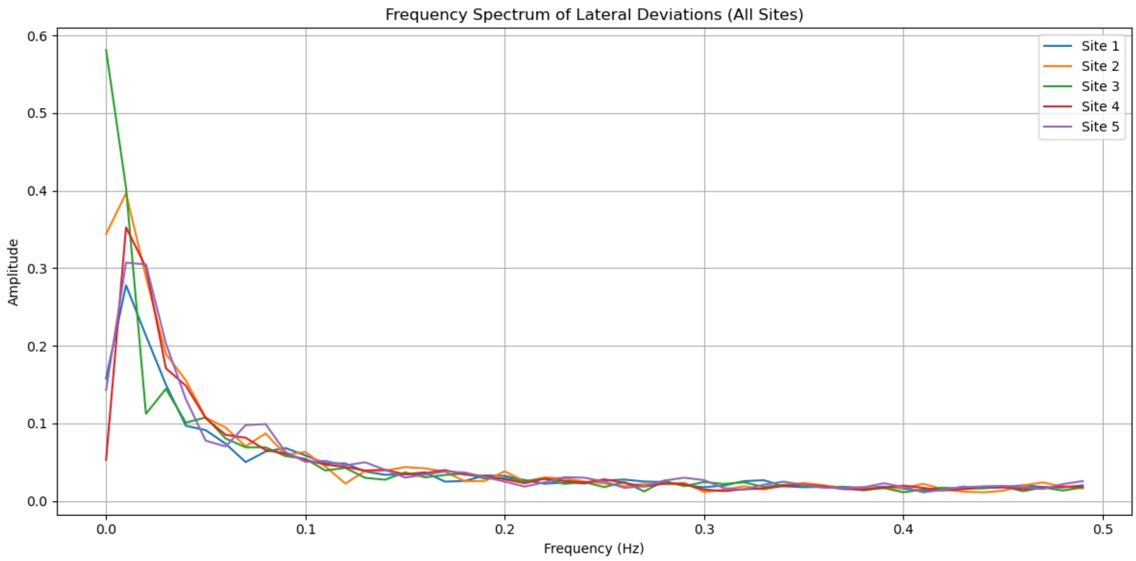

Fig. 9. Frequency spectrum of lateral deviations across all five sites

5. DISCUSSION

This study presents an empirical evaluation of lane-keeping behavior among human drivers under free-flow road conditions across five sites in Jordan. The results reinforce the existing body of literature that indicates drivers tend to maintain a reasonably centered lateral position within standard lane widths, particularly under low-stress, ideal conditions.

Descriptive statistics showed that mean deviations were close to the lane center at most sites, ranging between +0.079 m and –0.172 m. While Sites 1 and 2 exhibited a mild rightward bias, Sites 3 through 5 showed a modest leftward deviation, especially Site 3. This could indicate subtle influences from site-specific features such as pavement marking visibility, roadside geometry, or background scenery, which are known to affect perceptual lane width and driver comfort. The increased spread in lateral deviation at Site 3 (standard deviation of 0.43 m) further supports this hypothesis.

Lane-keeping accuracy was robust across all sites, with 61–83% of vehicles maintaining a position within ±0.5 m from the lane center, confirming good control under favorable conditions. Notably, no vehicle at any site approached or crossed the lane boundaries, as evidenced by wheel position plots and deviation limits. This finding affirms that a 3.5 m lane width offers sufficient space for safe lateral maneuvering without over-constraining driver behavior.

Temporal analysis showed no drift in mean deviation over time, suggesting stable behavior throughout the observation period and confirming the reliability of the camera-based data collection method. Rolling averages reinforced the consistency of vehicle tracking, even without formal calibration. Additionally, the inferred wheel position analysis demonstrated that vehicles consistently maintained a safe margin from lane boundaries.

Perhaps most revealing was the frequency spectrum analysis. All five sites showed a dominant peak in the 0.01-0.02 Hz range, corresponding to periodic lateral shifts every 50 to 100 seconds. These slow, smooth oscillations suggest that lateral deviations are primarily the result of subtle, infrequent corrections rather than abrupt maneuvers. The uniform spectral patterns across all sites, with low high-frequency content, provide strong evidence of stable, attentive lane-keeping under ideal conditions. The elevated zero-frequency amplitude at Site 3 further supports the notion of a persistent leftward offset unique to that site.

Taken together, these results demonstrate that under controlled, free-flowing conditions, human drivers on Jordanian roads exhibit stable, centered lateral positioning with predictable correction patterns. The combined use of spatial distribution, temporal smoothing, and spectral analysis offers a holistic view of driver behavior and highlights the utility of low-cost, observational methods for road safety assessment.

6. IMPLICATIONS OF THE STUDY

The findings of this research offer several key implications for transportation infrastructure, vehicle automation, driver modeling, and traffic safety policy.

1) Road Design and Lane Width Standard

The results confirm that under ideal driving conditions – free-flow traffic, dry pavement, and daylight – passenger vehicles are consistently able to maintain lateral positions well within ±0.5 m of the lane center. No vehicle approached or exceeded the ±1.75 m lane boundaries. These observations validate the adequacy of current road design standards that prescribe 3.5 m lane widths for motorways. In space-constrained environments, this data could support re-evaluation of lane width requirements, particularly on low-speed or urban segments where narrower lanes may improve multimodal accommodation without compromising safety.

2) Human Driver Behavior Modeling

The consistent low-frequency oscillations (0.01-0.02 Hz) in lateral deviation reflect natural, smooth steering adjustments by human drivers. These spectral patterns can inform the calibration of microscopic traffic simulation tools, which often lack empirical lateral dynamics inputs. Incorporating these metrics – such as deviation amplitude, frequency, and temporal stability – would allow for more accurate representation of human steering behavior in virtual environments and traffic modeling software.

3) Autonomous Vehicle (AV) and Advanced Driver Assistance System (ADAS) Calibration

The study provides a benchmark for what constitutes stable human lane-keeping performance. These benchmarks can be used to evaluate the lateral control algorithms of AVs and ADAS-equipped vehicles. Lane-centering systems that match or exceed human-level lateral deviation control and swaying frequency would be considered safe and acceptable by behavioral standards. Additionally, the results may guide the definition of warning thresholds for lane departure systems.

4) Real-Time Roadway Monitoring and Safety Alerts

Given that significant lateral instability was not observed in the study, any deviation from these patterns – such as high-frequency swaying or lane edge encroachment – may indicate driver impairment, distraction, or deteriorating environmental conditions. These anomalies could be used in the future to trigger infrastructure-based safety alerts or real-time monitoring systems designed to detect at-risk driving behavior.

5) Policy and Risk Assessment Applications

By establishing baseline lateral behavior under optimal conditions, this study enables more informed traffic safety audits and risk analyses. The absence of erratic deviations or boundary violations supports the use of current design standards on modern roads but also provides a reference against which behavior in adverse conditions (e.g., nighttime, congestion, rain) can be meaningfully compared.

6) Methodological Validation and Data Science Potential

Finally, the study demonstrates the value of overhead camera systems and signal analysis techniques for extracting and analyzing driver behavior in a non-intrusive, scalable way. This lays the groundwork for broader applications of computer vision, traffic data analytics, and behavioral modeling in transportation research, including cross-national studies and longitudinal safety assessments.

7. CONCLUSION

This study evaluated the lateral positioning behavior of 500 passenger vehicles across five road segments in Jordan. Through visual annotations and advanced signal analysis, it was determined that the majority of vehicles (61% to 83%) remained within a ±0.5 m range of the lane center. No instances of lane departure were recorded, and both left and right wheel paths stayed comfortably within the ±1.75 m lane boundaries.

The analysis revealed subtle spatial biases, with Sites 1 and 2 showing mild rightward deviation and Sites 3 to 5 showing a leftward tendency. Site 3 had the highest variability, indicating potential local design or perceptual influences. Spectral analysis confirmed that lateral adjustments occurred smoothly and periodically, primarily around 0.01-0.02 Hz, and no rapid corrective behaviors were observed.

These findings affirm that a 3.5 m lane width is sufficient to support safe, comfortable driving behavior under optimal conditions. The results provide a valuable behavioral benchmark for calibrating lane-keeping assistance systems, informing road design policies, and guiding future studies that incorporate adverse conditions, driver distraction, or mixed traffic.

8. LIMITATIONS AND FUTURE WORK

While this study provides a detailed assessment of lateral vehicle behavior under ideal conditions, several limitations must be acknowledged. First, the data collection was restricted to clear, dry daylight periods and free-flowing traffic, which excludes the influence of adverse environmental conditions (e.g., rain, fog, darkness) or traffic congestion. These factors are known to affect both lane-keeping behavior and driver attentiveness and should be considered in future evaluations.

Second, the study focused exclusively on passenger vehicles traveling alone in the leftmost lane. While this controlled for confounding influences such as lane-changing, following distance, or side-by-side interactions, it also limits the generalizability of the findings to multilane interactions or commercial vehicles. The lateral dynamics of larger vehicles, such as trucks and buses, are likely to differ due to width, driver visibility, and lane occupancy behavior.

Third, the study relied on manually annotated video frames from fixed overhead cameras. Although this method proved effective and repeatable, it may introduce minor human error in annotation and limits the temporal resolution of vehicle motion. Automated tracking systems with high-frequency data (e.g., LiDAR or drone-based photogrammetry) could provide more continuous and precise position data for dynamic movement analysis.

Additionally, the study did not incorporate contextual information such as pavement markings, roadside features, or visual obstructions—all of which may influence driver lane perception. Nor did it assess driver demographics, vehicle type, or automation level, which could affect behavior.

Future research should address these gaps by:

- Expanding the dataset to include nighttime, inclement weather, and congested traffic conditions;
- Incorporating commercial vehicles and mixed-traffic interactions;
- Using automated, high-resolution tracking tools for real-time analysis;
- Examining the impact of road geometry, signage, and lane markings on lateral control;
- Comparing human-driven behavior with assisted or autonomous lane-keeping systems;
- Exploring cross-cultural and geographic variations in lane-use behavior.

Such extensions would support more robust modeling of driver behavior and inform the design of inclusive, adaptive transportation systems that reflect the diversity of road users and operating environments.

References

1. Pan C., Y. Zhang, H. Zhang, and J. Xu. 2025. "Lateral Displacement and Distance of Vehicles in Freeway Overtaking Scenario Based on Naturalistic Driving Data". *Applied Sciences* 15(5): 2370. DOI: 10.3390/APP15052370.
2. Haitham A.H., G. Schuchmann. 2022. "Relationship between Critical Gap and Certain Geometrical Parameters in Roundabouts". *Periodica Polytechnica Civil Engineering* 66(3): 922-929. DOI: 10.3311/PPCI.18628.
3. Liu S., J. Wang, T. Fu. 2016. "Effects of Lane Width, Lane Position and Edge Shoulder Width on Driving Behavior in Underground Urban Expressways: A Driving Simulator Study". *International Journal of Environmental Research and Public Health* 13(10): 1010. DOI: 10.3390/IJERPH13101010.
4. Al Hasanat H.A., D. Alothman, O. AlHarasees. 2025. "Capacity of Single-lane Roundabouts in Hungary". *Periodica Polytechnica Transportation Engineering* 2025. DOI: 10.3311/PPTR.37534.
5. "Traffic accidents surge in 2024, resulting in 543 deaths, 18,275 injuries – HPC". 2025. *The Jordan Times*. Available at: https://jordantimes.com/news/local/traffic-accidents-surge-2024-resulting-543-deaths-18275-injuries-%E2%80%94-hpc.
6. Alharasees O., H.A. Al Hasanat, D. Alothman. 2024. "Public Perception of Autonomous and Shared Autonomous Vehicles: Case Study of Amman". *2024 2nd International Conference on Technology Innovation and Its Applications (ICTIIA).* 1-5, Sep. 2024. DOI: 10.1109/ICTIIA61827.2024.10761581.
7. Alharasees O., H.A. Al Hasanat, R. Al-Matarneh. 2025. "A Comprehensive Human Factors Approach to Pedestrian Accidents Analysis in Urban Environments". *2025 2nd International Conference on Advanced Innovations in Smart Cities, ICAISC 2025*. DOI: 10.1109/ICAISC64594.2025.10959468.
8. Al-Tammemi B., et al. 2024. "Navigating Road Traffic Accidents in Jordan: ARetrospective Exploration of the Health andEconomic Impacts". *Cureus* 16(5). DOI: 10.7759/cureus.60497.
9. "Traffic Department: Wrong Lane Usage Caused 29.3% of Road Fatalities in 2024". 2024. *Jordan News.* Available at: https://www.jordannews.jo/Section-109/News/Traffic-Department-Wrong-Lane-Usage-Caused-29-3-of-Road-Fatalities-in-2024-42943.
10. DOS. "Population Estimates at the End of 2024". Amman, Jan. 2025.
11. "Jordan Registered Motor Vehicles, 2005-2024". CEIC Data. Available at: https://www.ceicdata.com/en/indicator/jordan/motor-vehicle-registered.
12. MOT. "Ministry of Transport Transport Sector Strategic Plan (2024-2028)". Amman, 2024.
13. GAM. "Transport and Mobility Master Plan for Amman Final Report". Amman, Apr. 2010. Available: http://www.ammanbrt.jo/Studies?l=en
14. Jrew B., N. Hussein, R. Al-Kouz. 2018. "Management of Multi-Lane Highways in Jordan (Case Study)". *Jordan Journal of Civil Engineering* 12(1).
15. Msallam M. 2019. "Evaluation and improvement in the level of service of multi-lane highways in Jordan". *Elektronički časopis građevinskog fakulteta Osijek* 10(18):71-81. DOI: 10.13167/2019.18.7.
16. Jrew B., M. Msallam, E. Mosab Naser. 2010. "Analysis, Evaluation and Improvement the Level of Service of Two-Lane Highways in Jordan (Case Study/Jordan)".

17. Shima H., et al. "A national investigation on the impacts of lane width on traffic safety: narrowing travel lanes as an opportunity to promote biking and pedestrian facilities within the existing roadway infrastructure". Report. Nov. 2023.
18. Liu J., Z. Guo, D. Shan, X. Liu. 2024. "Effective lane width for cars considering lateral oscillation characteristics based on high-precision field data". *International Journal of Transportation Science and Technology*16: 18-33. DOI: 10.1016/J.IJTST.2023.10.007.
19. Al Hasanat H., J. Juhasz. 2022. "The Influence of Circulating and Entering Flows on Critical Gaps Value in Roundabouts". *International Journal For Traffic And Transport Engineering* 12(3). DOI: 10.7708/IJTTE2022.12(3).03.
20. "Lane Width - NACTO". Available at: https://nacto.org/publication/urban-street-design-guide/street-design-elements/lane-width/.
21. Al Hasanat H.A., J. Juhász. 2023. "Development of Empirical Models to Predict Gap Acceptance Parameter Based on the Geometrical and Operational Parameters of Different Roundabouts". *Periodica Polytechnica Civil Engineering* 67(2): 349-356. DOI: 10.3311/PPCI.20883.
22. Tang J., et al. 2024. "Study on the Deviation Characteristics of Driving Trajectories for Autonomous Vehicles and the Design of Dedicated Lane Widths". *Sustainability* 16(21): 9155. DOI: 10.3390/SU16219155.
23. Chen Z., S. Wu, Z. Dai, Z. Chen, C. Pan, J. Xu. 2024. "A study of vehicle lateral position characteristics and passenger cars' special lane width on expressways". *Engineering Reports* 6(4): p. e12753. DOI: 10.1002/ENG2.12753.
24. Wu S.F., Z.W. Chen, G.F. Zhang, Q. Chen, J. Xu. 2023. "Investigation on Trajectory Deviation and Lane Lateral Margin of Passenger Cars on Freeways Based on Field Driving Data". *China Journal of Highway and Transport* 36(5): 197-209. DOI: 10.19721/J.CNKI.1001-7372.2023.05.017.
25. Milstead R., et al. 2011. "Procedures for Setting Advisory Speeds on Curves FHWA Safety Program". New Jersey, Jun. 2011. Available at: http://safety.fhwa.dot.gov.
26. Ding R., C. Pan, Z. Dai, J. Xu. 2022. "Lateral Oscillation Characteristics of Vehicle Trajectories on the Straight Sections of Freeways". *Applied Sciences* 12(22): 11498. DOI: 10.3390/APP122211498.
27. Al Hasanat H., G. Schuchmann. 2022. "Critical Gap in Roundabouts – A Short Comparison of Estimation Methods". *Periodica Polytechnica Transportation Engineering* 50(3): 273-278. DOI: 10.3311/PPTR.18632.
28. Han L., Z. Du. 2025. "Research status, challenges and trends of curve driving safety: A bibliometric analysis and critical review". *Journal of Traffic and Transportation Engineering* 12(4): 723-751. DOI: 10.1016/J.JTTE.2024.04.010.
29. Mecheri S., F. Rosey, R. Lobjois. 2017. "The effects of lane width, shoulder width, and road cross-sectional reallocation on drivers' behavioral adaptations". *Accid Anal Prev* 104: 65-73. DOI: 10.1016/J.AAP.2017.04.019.
30. Azin B., R. Ewing, W. Yang, N.S. Promy, H.A. Kalantari, N. Tabassum. 2025. "Urban Arterial Lane Width Versus Speed and Crash Rates: A Comprehensive Study of Road Safety". *Sustainability* 17(2): 628. DOI: 10.3390/SU17020628.
31. Pan C., Z. Dai, Y. Zhang, H. Zhang, M. Fan, J. Xu. 2025. "An approach for accurately extracting vehicle trajectory from aerial videos based on computer vision". *Measurement* 242: 116212. DOI: 10.1016/J.MEASUREMENT.2024.116212.
32. Chen Z., S. Wu, Z. Dai, Z. Chen, C. Pan, J. Xu. 2024. "A study of vehicle lateral position characteristics and passenger cars' special lane width on expressways". *Engineering Reports* 6(4). DOI: 10.1002/ENG2.12753.

33. Das V.R., M. Jayashree, S. Rahul. 2016. "Lateral Placement of Vehicles on Horizontal Curves". *Transportation Research Procedia* 17: 43-51. DOI: 10.1016/J.TRPRO.2016.11.059.
34. Al Hasanat H.A., O. Alharasees, D. Alothman. 2024. "Connected Automated Vehicles Entry Capacity on Roundabouts - Case Study Hungary". *Proceedings - 2024 2nd International Conference on Technology Innovation and Its Applications, ICTIIA 2024*. DOI: 10.1109/ICTIIA61827.2024.10761405.
35. Faiz R.U., N. Mashros, S.A. Hassan. 2022. "Speed Behavior of Heterogeneous Traffic on Two-Lane Rural Roads in Malaysia". *Sustainability* 14(23): 16144. DOI: 10.3390/SU142316144.
36. Russo F., S. Fric, S.A. Biancardo, D. Gavran. 2015. "Driver Speed Behavior on Circular Curves of Undivided Two-Lane Rural Roads". *Transp Res Rec* 2472: 117-128. DOI: 10.3141/2472-14.
37. Dingus T.A., et al. 2016. "Driver crash risk factors and prevalence evaluation using naturalistic driving data". *Proceedings of the National Academy of Sciences of the United States of America* 113(10): 2636-2641. DOI: 10.1073/pnas.1513271113.
38. Hancock M.W., P. Secretary. 2013. "A Policy on Geometric Design of Highways and Streets". 6th Edition, 2011 - November 2013 Errata. Washington, DC. Available at: http://downloads.transportation.org/GDHS-6-Errata.pdf.
39. Desmon S. 2023. "How Narrower Traffic Lanes Could Help Reduce Crashes. Narrower streets with room for bike lanes and sidewalks could pay dividends for health and safety". Bloomberg School of Public Health. Available at: https://publichealth.jhu.edu/2023/narrower-lanes-safer-streets?utm_source=chatgpt.com.
40. "Narrow roads. Bike-friendly communities". Bicycle Network. Available at: https://bicyclenetwork.com.au/tips-resources/bike-friendly-communities/narrow-roads/.
41. McGarvey T. 2016. "Vehicle lateral position depending on road type and lane width : vehicle position surveys carried out on the Swedish road network". VTI Rapport. Available at: https://urn.kb.se/resolve?urn=urn:nbn:se:vti:diva-10747.

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