

Article

Mobile Mapping Systems for Road Tunnel Inspection: Influence of Acquisition Speed and Control Point Configuration on Geometric Reliability

Matteo Cappuccio ^{1,*} , Naser El-Sheimy ² , Maria Alessandra Tini ¹ , Luca Vittuari ¹  and Stefano Gandolfi ¹ 

¹ Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy; mariaalessandra.tini@unibo.it (M.A.T.); luca.vittuari@unibo.it (L.V.); stefano.gandolfi@unibo.it (S.G.)

² Department of Geomatics Engineering, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada; elsheimy@ucalgary.ca

* Correspondence: matteo.cappuccio@unibo.it

Highlights

What are the main findings?

- Tunnel cross-sectional shape, assessed after local best-fit registration of each section to the TLS reference, is preserved at the millimeter level across all configurations, despite meter-level global drift in GNSS-denied conditions.
- Substantial planimetric and longitudinal deformations occur at the global scale, with magnitudes strongly influenced by acquisition speed and GCP distribution.

What are the implications of the main findings?

- INS-based MMS surveys can provide reliable local shape information for tunnel inspection and modeling, even in GNSS-denied environments, provided that appropriate survey strategies are adopted; applications requiring absolute georeferencing still demand adequate ground control.
- The results enable the optimization of acquisition speed and GCP configuration, balancing survey efficiency and geometric accuracy.

Abstract

Mobile Mapping Systems (MMSs) are increasingly adopted for transport infrastructure inspection, where reliable characterization of global and local geometry is essential. This is critical in GNSS-denied environments such as road tunnels, where trajectory estimation relies on inertial navigation and drift degrades geometric accuracy. This study investigates the influence of acquisition speed and ground control point (GCP) configuration on trajectory accuracy and geometric consistency in a 2.3 km road tunnel. MMS data were acquired at 15, 30, and 50 km/h and processed under progressively denser, uniformly distributed GCP configurations, from unconstrained to fully constrained solutions. Post-processed forward–backward smoothed GNSS/INS trajectories were validated against a topographic control network, and cross-sectional geometry against terrestrial laser scanning (TLS). Without external constraints, planimetric errors at independent check points reached 16.5 m and global deformation reached 0.46% at low speed. Ground control markedly reduced trajectory errors, depending on both control density and acquisition speed. In contrast, locally registered cross-sections showed millimeter-level consistency with TLS in all configurations: median discrepancies of 4–5 mm, with 75–82% of values below 10 mm. Local cross-sectional shape is therefore preserved despite substantial global drift, supporting



Academic Editor: Marcelo Santos

Received: 27 August 2026

Revised: 29 September 2026

Accepted: 8 October 2026

Published: 10 October 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

MMS for shape-based tunnel inspection, while adequate ground control remains necessary for absolute georeferencing.

Keywords: mobile mapping system; road tunnel inspection; GNSS-denied environments; point cloud accuracy; point cloud density; geometric evaluation

1. Introduction

Mobile Mapping Systems (MMSs) [1,2] have become a key technology for the inspection and monitoring of transport infrastructures [3], enabling the rapid acquisition of high-density georeferenced data along road alignments. By integrating positioning sensors, typically based on Global Navigation Satellite Systems (GNSS) and Inertial Navigation Systems (INS) [4,5], with laser scanning technologies, MMSs allow the efficient generation of three-dimensional representations of the surveyed environment. Compared to traditional surveying approaches, MMSs markedly reduce acquisition time and operational complexity, making them particularly suitable for large-scale and time-critical applications.

In road tunnel environments, the advantages of MMS [6] are even more evident. Conventional survey methods, such as terrestrial laser scanning (TLS) [7] or total station measurements [8], often require static acquisitions, lane closures, or traffic interruptions, which may increase operational costs and expose survey personnel to safety risks. In contrast, MMSs enable data acquisition at traffic speed, minimizing disruption to road users and improving safety conditions for operators. These characteristics make MMS highly attractive for routine tunnel inspection and monitoring, where frequent and efficient data collection is required [9].

Despite these advantages, the reliability of MMS-derived data remains a critical issue, particularly in environments where GNSS signals are unavailable or severely degraded [10,11]. Road tunnels represent a typical GNSS-denied scenario, in which trajectory estimation relies primarily on inertial navigation. Under these conditions, the absence of GNSS updates leads to drift accumulation in the INS solution, potentially affecting both positioning accuracy and the geometric quality of the reconstructed data.

In GNSS-denied environments, acquisition speed introduces a relevant trade-off in MMS surveys. Lower speeds generally result in higher point cloud density and improved local geometric detail, but also increase acquisition time, potentially amplifying drift effects in INS-based trajectory estimation. Conversely, higher speeds reduce acquisition time and limit drift accumulation but may lead to lower point density and reduced geometric detail.

To mitigate these effects, external constraints such as ground control points (GCPs) are commonly introduced to adjust the trajectory and improve georeferencing accuracy [12]. However, the use of GCPs in tunnel environments requires additional field operations, including station setup and surveying of control points, which increase acquisition time and reduce the operational advantages of MMS. Minimizing or avoiding the use of GCPs would enhance survey efficiency and safety but requires a careful assessment of trajectory reliability in GNSS-denied conditions.

A considerable body of literature has investigated MMS performance, focusing on trajectory estimation, system calibration, and point cloud accuracy [13,14]. Other studies have addressed tunnel reconstruction from mobile mapping data, proposing advanced methods for geometric modeling and surface representation [15,16]. However, most existing works primarily evaluate point-wise accuracy or reconstruction quality, with limited attention to the preservation of geometric consistency under varying acquisition conditions [17].

In the context of infrastructure inspection and digital modeling, the availability of reliable geometric information is essential. Applications such as tunnel geometric documentation and structural assessment workflows rely on the consistency of point cloud data, highlighting the need to preserve key geometric properties when acquisition parameters change. For tunnel inspection purposes, geometric reliability extends beyond traditional accuracy metrics, requiring the assessment of whether relevant geometric features remain stable under different survey configurations [18].

In this context, the present study investigates the geometric consistency of road tunnel sections derived from MMS data under different operational conditions. Specifically, whereas previous studies have separately addressed MMS trajectory drift, trajectory correction using control points, and MMS/TLS point-cloud comparison, the relationship—and possible decoupling—between global trajectory degradation and the preservation of local cross-sectional geometry has, to the authors' knowledge, not yet been systematically quantified against an independent, survey-grade reference. This aspect constitutes the core contribution of the present work. The analysis considers multiple acquisition speeds and GCP configurations in a GNSS-denied environment, where in-tunnel trajectory estimation is based on INS data without additional aiding sources. Both trajectory-related accuracy and geometric indicators are evaluated, including planimetric and vertical errors, global deformation metrics, and cross-sectional consistency assessed through cloud-to-cloud comparison with a TLS reference dataset.

The main contributions of this work are: (i) the quantitative evaluation of the influence of acquisition speed and GCP distribution on trajectory accuracy and global deformation, (ii) the assessment of drift behavior under different operational configurations in a GNSS-denied scenario, and (iii) the analysis of the preservation of local cross-sectional shape through consistency metrics computed after local registration, explicitly distinguished from global georeferencing accuracy. The results provide practical guidelines for balancing acquisition efficiency, control point deployment, and geometric reliability, supporting the definition of optimized survey strategies for tunnel inspection using mobile mapping systems.

2. Materials and Methods

The study was conducted in the San Lorenzo tunnel, located in Forni di Sotto (46°24' N, 12°40' E), Udine, Italy (Figure 1). The tunnel extends for approximately 2.3 km and follows a curvilinear alignment in the east–west direction [19]. This configuration reflects typical road tunnel conditions and introduces realistic acquisition dynamics for mobile mapping systems.

Due to its underground setting, the environment is fully GNSS-denied, making it particularly suitable for evaluating the performance of mobile mapping systems under challenging positioning conditions. Moreover, the tunnel is located beneath an area affected by an active landslide, which is continuously monitored, further highlighting the relevance of accurate and reliable geometric data for infrastructure assessment.

2.1. Reference Dataset and Control Network

A high-accuracy reference dataset was established to evaluate the performance of the MMS acquisitions. The reference geometry was defined through the integration of a topographic control network and a terrestrial laser scanning (TLS) dataset, providing both discrete and continuous geometric references (Figure 2).

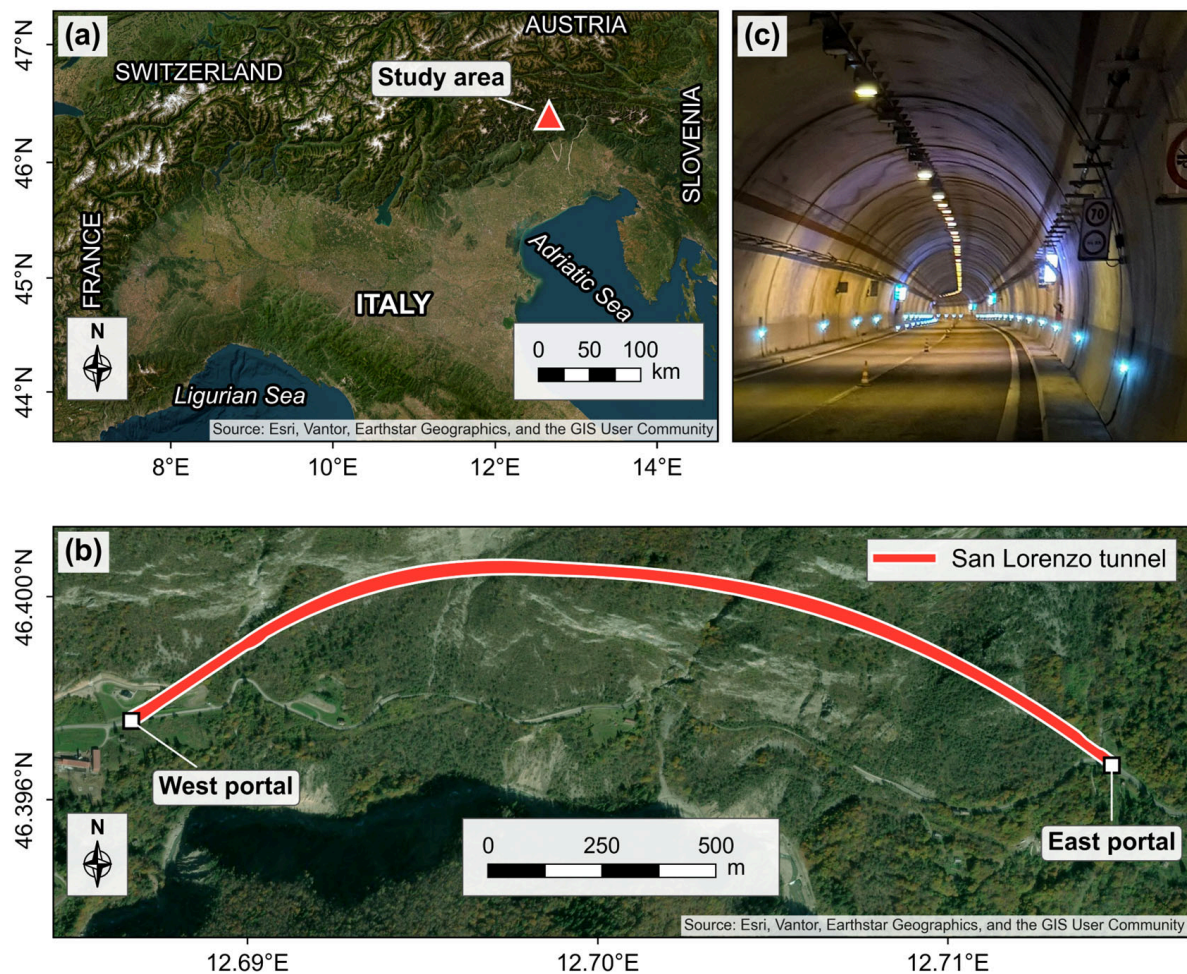


Figure 1. Study area overview. (a) Location of the investigated tunnel in Northern Italy (Forni di Sotto, Udine), indicated by the marker. (b) Detailed view of the tunnel alignment. (c) Representative view of the tunnel interior.

The control network was established using a closed traverse, measured with a Leica TS30 total station (Leica Geosystems AG, Heerbrugg, Switzerland), extending along the entire tunnel alignment. The traverse was adjusted as a closed loop, ensuring internal consistency and limiting error propagation over the longitudinal extent of the tunnel. The network was constrained at both tunnel portals through GNSS observations acquired with Stonex S900 receivers (Stonex S.r.l., Paderno Dugnano, Italy) on four reference stations (two at the eastern portal and two at the western portal). The GNSS data were processed using both differential positioning and Precise Point Positioning (PPP) [20,21], providing a reliable absolute georeferencing of the control network.

A total of 85 control points were derived from the closed traverse and distributed along both sides of the tunnel, ensuring homogeneous spatial coverage. The adjusted control network achieved millimeter-level planimetric precision, with median 95% confidence ellipse axes of approximately 10 mm and 5 mm for the semi-major and semi-minor axes, respectively, while the vertical component remained below approximately 20 mm at the 95% confidence level, providing a robust reference framework for subsequent analyses.

Ground control points (GCPs) were defined using clearly identifiable pre-existing features along the tunnel walls, specifically the upper-right corners of progressive distance markers installed along the tunnel. These features provide well-defined and stable geometric references that can be consistently identified in both MMS data and reference

measurements, supporting robust trajectory adjustment and ensuring repeatability of the experiment, as well as enabling potential multi-epoch analyses.

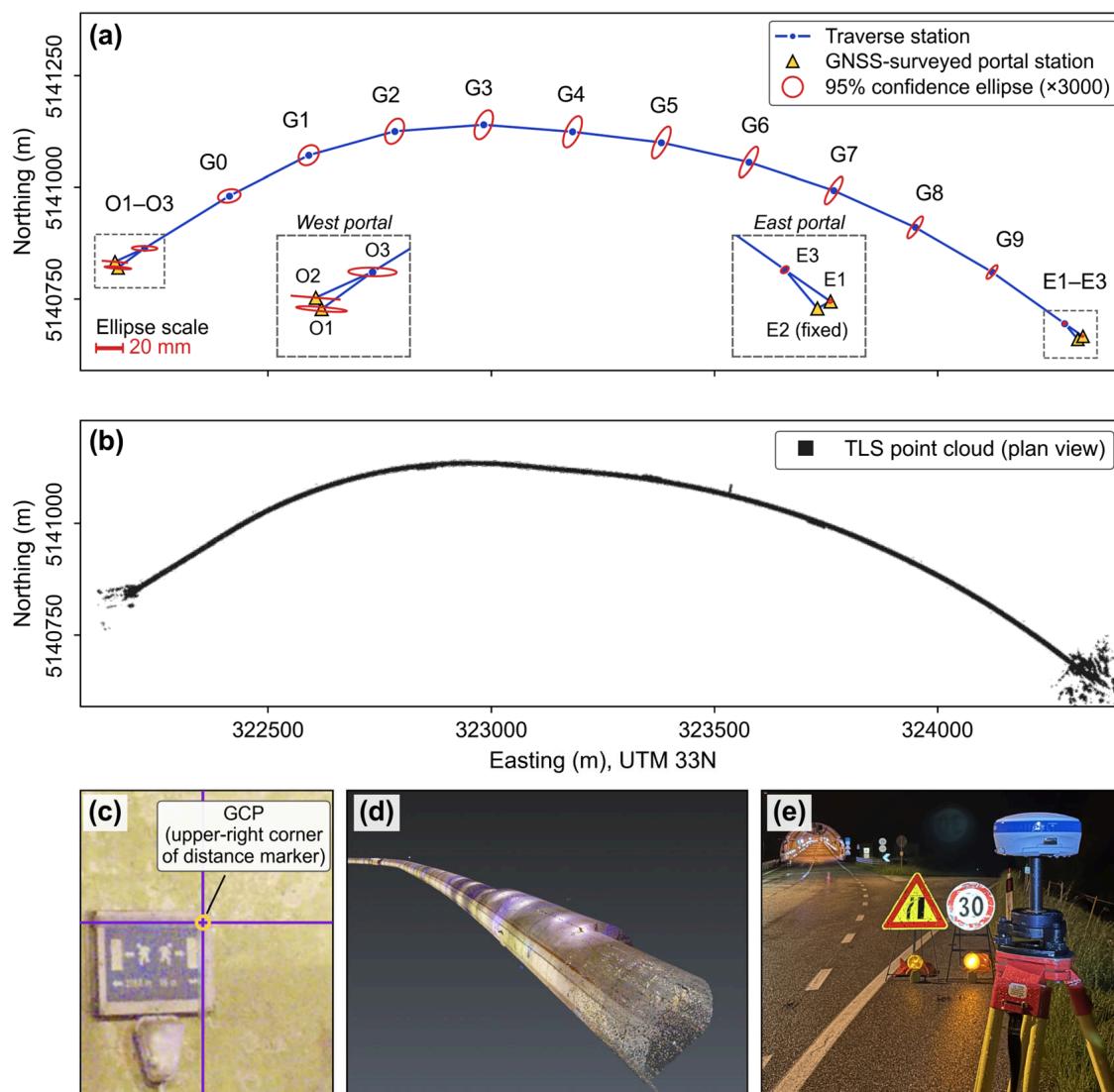


Figure 2. Study framework for the reference geometric characterization. (a) Closed traverse established along the tunnel, with associated 95% confidence ellipses, used as reference network for the determination of ground control point (GCP) coordinates. (b) Reference geometry derived from TLS point cloud, used as benchmark for accuracy and consistency analyses. (c) Example of a ground control point (GCP) employed for trajectory adjustment and validation. (d) TLS-based 3D reconstruction of the tunnel environment. (e) GNSS Survey setup during field acquisition.

In addition to the control network, a high-resolution TLS survey was performed with a Leica RTC360 laser scanner (Leica Geosystems AG, Heerbrugg, Switzerland) to acquire a dense point cloud of the tunnel environment. The TLS dataset was registered and georeferenced within the same reference system defined by the control network, providing a continuous geometric representation of the tunnel.

The integrated use of the control network and the TLS dataset provides a reliable geometric reference for the validation of both the MMS trajectory and the derived point cloud under GNSS-denied conditions.

2.2. Mobile Mapping System Survey

The Mobile Mapping System (MMS) data were acquired using a Leica Pegasus TRK100 platform (Leica Geosystems AG, Heerbrugg, Switzerland; product datasheet 982592, July 2023), which integrates LiDAR sensors with a positioning unit based on GNSS and inertial navigation. The main system specifications are summarized in Table 1. The positioning unit is based on a tactical-grade MEMS inertial measurement unit (NovAtel SPAN μ IMU-IC) [22]. According to the manufacturer’s datasheet, the system provides a post-processed absolute accuracy of 19 mm (horizontal) and 11 mm (vertical) under continuous GNSS coverage, degrading to 39 mm and 16 mm, respectively, after a 60 s GNSS outage (1σ values, quoted with odometer aiding, which was not used in this study).

Table 1. Main specifications of the Leica Pegasus TRK100 mobile mapping system used in this study.

	Component	Specification
Positioning	GNSS	Multi-GNSS, multi-frequency, 555 channels
	IMU	NovAtel SPAN μ IMU-IC
Mapping	LiDAR sensors	2 $\times$ Velodyne
	LiDAR meas. rate	0.6 MHz
	LiDAR Scan Freq.	20 Hz per scanner
	LiDAR Range Acc.	≤ 10 mm
	LiDAR FOV	$30^\circ (\pm 15^\circ)$
	LiDAR channels	2 $\times$ 16 channels
	Camera System	360° panoramic
	Image Resolutions	24 MP

Trajectory estimation was performed through post-processing using a forward–backward smoothing approach, implemented in Inertial Explorer software v9.0 (NovAtel Inc., Calgary, AB, Canada; <https://novatel.com/products/waypoint-post-processing-software/inertial-explorer>, accessed on 6 June 2026), combining GNSS and inertial measurements where available. GNSS observations were acquired only in the approach sections outside the tunnel, where a reference station was established approximately 150 m before the portal (Figure 2e) and processed in differential mode. These observations provide initial and terminal constraints for the trajectory, enabling GNSS reinitialization at both tunnel portals. It should be emphasized that, although no GNSS observations are available inside the tunnel, the forward–backward smoothing allows the in-tunnel solution to benefit retrospectively from the GNSS constraints at both portals. The trajectories analyzed in this study are therefore post-processed, smoothed GNSS/INS solutions subject to a GNSS outage across the tunnel, rather than purely unaided real-time INS propagations, and the drift magnitudes reported hereafter are correspondingly smaller than those expected from free-inertial navigation.

The adopted system does not include additional aiding sources, such as SLAM-based solutions, wheel odometry, or other sensor fusion approaches [23]. As a result, the trajectory is fully driven by the inertial navigation system within the tunnel, making it particularly sensitive to drift accumulation. This configuration represents a challenging but controlled scenario for assessing MMS performance in GNSS-denied environments.

To investigate the influence of operational parameters, three acquisitions were conducted at nominal vehicle speeds of 15, 30, and 50 km/h, one run per speed, corresponding to GNSS-denied intervals of approximately 9, 5, and 3 min, respectively, over the 2.3 km tunnel. These values represent typical survey conditions in road tunnels and directly affect both trajectory estimation and point cloud sampling. As illustrated in Figure 3, increasing vehicle speed leads to a progressive reduction in point density along the trajectory.

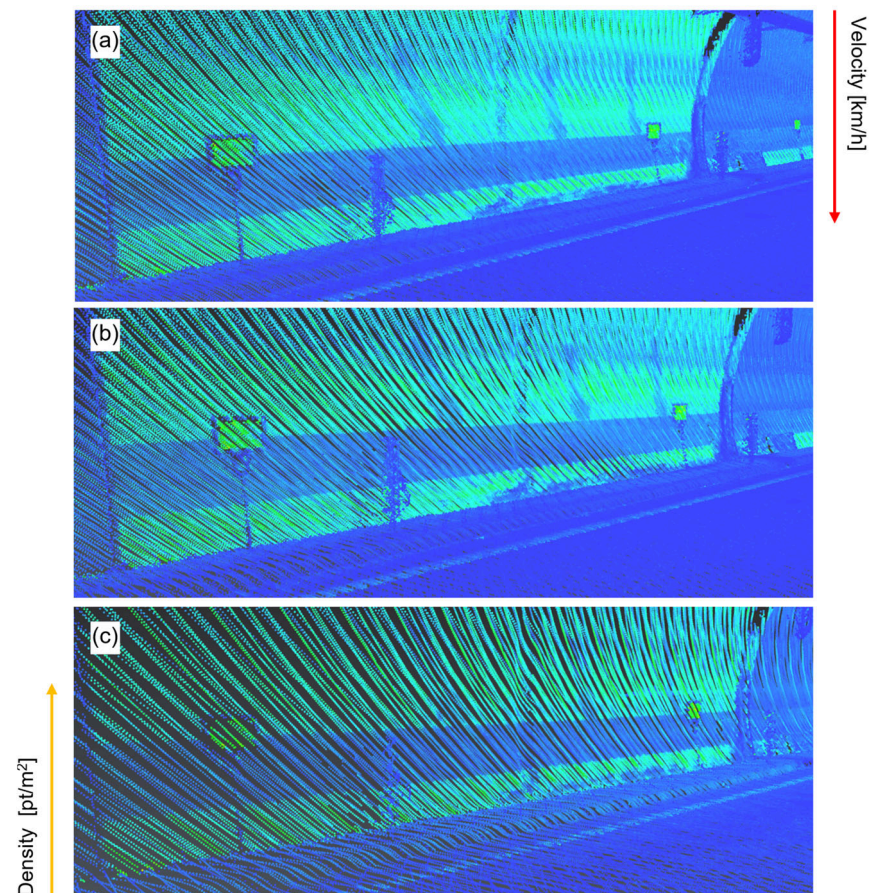


Figure 3. Mobile mapping point clouds of the road tunnel at (a) 15 km/h, (b) 30 km/h, and (c) 50 km/h, colored by intensity.

For a fixed scanning geometry, higher vehicle speeds result in increased spacing between consecutive scan lines in the along-track direction. In the considered configurations, the average spacing is approximately 3.5 cm at 15 km/h, 7 cm at 30 km/h, and 11.5 cm at 50 km/h. These values refer to the lateral tunnel walls in regions not affected by overlap between the two LiDAR sensors, and up to a height of approximately 3.5 m, thus representing a conservative sampling condition corresponding to the least favorable acquisition geometry.

In other areas of the tunnel cross-section, the two LiDAR sensors provide overlapping coverage, resulting in a denser and more redundant sampling of the surface. This cross-overlap configuration improves the effective point density and geometric robustness of the acquired data. The spatial distribution of point density and the effect of acquisition speed are clearly illustrated in Figure 3. All datasets were collected under comparable environmental and operational conditions, ensuring consistency and enabling a controlled evaluation of the impact of acquisition parameters on the quality and reliability of MMS-derived data.

2.3. Experimental Design

The experimental design considered two main factors: vehicle speed, as described in Section 2.2, and GCP configuration.

Five configurations were considered: the default solution without GCPs (NoGCP), three reduced configurations with 6, 13, and 21 GCPs, and a full configuration including all available control points. The NoGCP configuration represents the default MMS trajectory solution, as described in Section 2.2.

The GCP configurations were defined to ensure an approximately uniform spatial distribution along the tunnel axis, with the aim of minimizing the distance between consecutive control points. Although perfectly regular spacing was not always achievable due to visibility constraints and the use of pre-existing features, the adopted configurations reflect realistic survey conditions and ensure a consistent and representative assessment of control point distribution effects. Whenever possible, control points were selected on both sides of the tunnel (Figure 4) to improve the geometric strength of the configuration, particularly for constraining trajectory orientation.

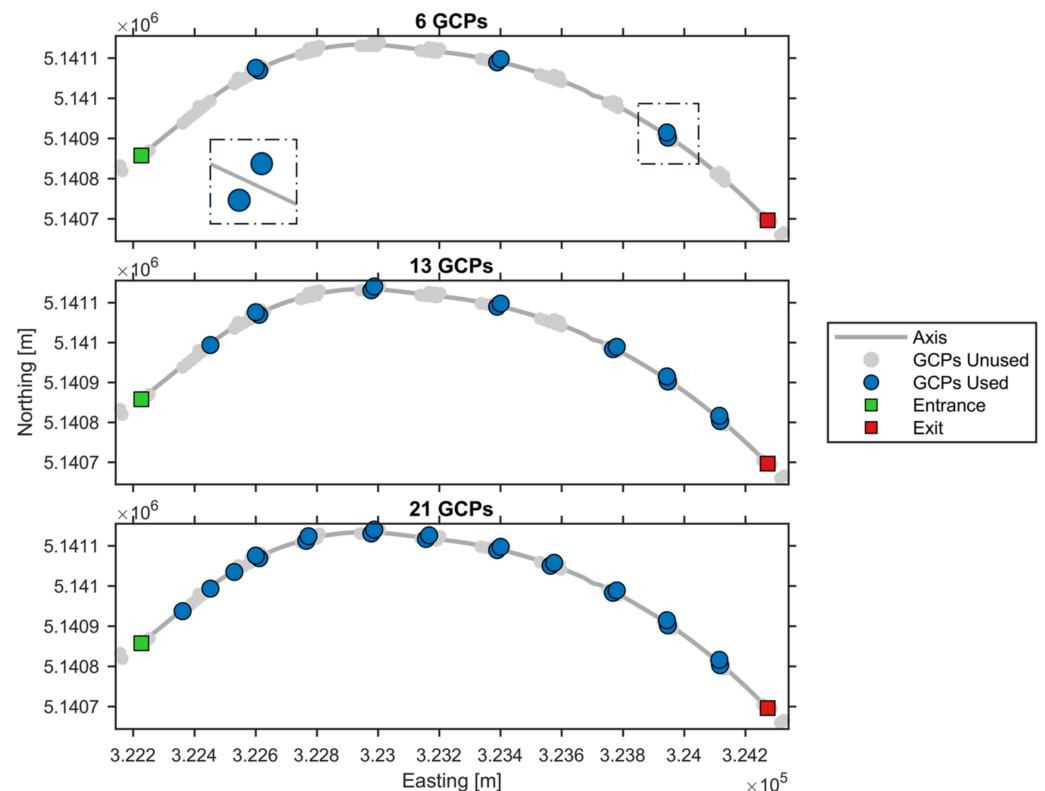


Figure 4. Spatial distribution of ground control points (GCPs) along the tunnel axis for configurations with 6, 13, and 21 GCPs, showing the selection of control points used for trajectory adjustment.

The experimental setup was designed to address three main objectives: (i) to quantify the effect of GCP distribution on trajectory accuracy and geometric reconstruction, (ii) to evaluate the influence of vehicle speed on both trajectory estimation and point cloud characteristics, and (iii) to assess the geometric accuracy and consistency of MMS-derived data with respect to the reference dataset.

2.4. Data Processing and Analysis Methods

The MMS trajectories described in Section 2.2 were used as the basis for all subsequent analyses. For each acquisition speed and GCP configuration, a specific trajectory solution was computed by applying the corresponding set of control points within the post-processing workflow. This approach allows the effect of control point distribution on trajectory accuracy and geometric consistency to be isolated. In each configuration, the GCPs are introduced in the trajectory post-processing as position updates: the coordinates of each control point, identified in the MMS point cloud, are compared with their reference values, and the resulting corrections are applied to the smoothed trajectory at the corresponding epochs, with stochastic weights consistent with the precision of the reference control network (approximately 1 cm planimetric and 2 cm vertical at the 95% confidence

level). The lever-arm and boresight parameters of the system are those resulting from the manufacturer’s calibration and were held fixed across all processing runs.

Trajectory accuracy was assessed by comparing the MMS-derived positions of the control points with their reference coordinates. Only control points clearly identifiable within the MMS point clouds were considered, ensuring a consistent evaluation across all configurations and acquisition speeds. For the reduced configurations (G6, G13, G21), the control points employed in the trajectory adjustment represent only a subset of the identified points, so that the remaining reference points, which are not used in the adjustment, act as independent check points for external validation (Section 3.2, Table 2). Of the 85 control points surveyed, 67 satisfied this criterion and were retained for the analysis. All check-point statistics reported in Table 2 are computed exclusively on the points not used as constraints in the corresponding configuration.

Table 2. Check-point errors for each acquisition speed and GCP configuration, reported as N, median (Q1–Q3), RMSE, and maximum absolute error for the planimetric (2D) and vertical (Z) components (m). For G6, G13, and G21, only independent points excluded from the adjustment are considered. Full values represent control-point residuals.

Speed [km/h]	Config.	N	2D Median (Q1–Q3) [m]	2D RMSE [m]	2D Max [m]	Z Median (Q1–Q3) [m]	Z RMSE [m]	Z Max [m]
15	NoGCP	67	10.520 (4.415–14.317)	10.789	16.486	0.748 (0.267–1.090)	0.811	1.316
	G6	61	3.124 (0.625–4.208)	7.921	22.509	0.120 (0.050–0.319)	0.233	0.742
	G13	54	0.268 (0.152–0.959)	1.421	4.214	0.044 (0.015–0.080)	0.066	0.164
	G21	46	0.071 (0.044–0.122)	0.197	0.794	0.026 (0.015–0.045)	0.038	0.088
	Full	67	0.009 (0.000–0.021)	0.019	0.055	0.001 (0.000–0.006)	0.017	0.104
30	NoGCP	67	1.533 (0.738–3.914)	2.915	5.613	0.318 (0.119–0.573)	0.425	0.724
	G6	61	0.728 (0.221–1.551)	1.619	4.488	0.064 (0.026–0.172)	0.129	0.281
	G13	54	0.213 (0.116–0.914)	0.692	1.426	0.024 (0.011–0.056)	0.050	0.150
	G21	46	0.033 (0.017–0.071)	0.096	0.314	0.013 (0.006–0.024)	0.037	0.132
	Full	67	0.012 (0.000–0.026)	0.024	0.073	0.002 (0.000–0.011)	0.015	0.054
50	NoGCP	67	0.759 (0.373–1.277)	0.963	1.536	0.168 (0.129–0.200)	0.171	0.279
	G6	61	0.074 (0.045–0.109)	0.094	0.185	0.029 (0.013–0.067)	0.057	0.152
	G13	54	0.036 (0.012–0.058)	0.055	0.133	0.020 (0.005–0.052)	0.044	0.161
	G21	46	0.032 (0.012–0.049)	0.039	0.099	0.014 (0.004–0.023)	0.030	0.115
	Full	67	0.026 (0.004–0.048)	0.038	0.111	0.010 (0.000–0.023)	0.023	0.087

To characterize drift behavior, each trajectory was compared with a reference solution obtained using the full GCP configuration. Differences were evaluated along the trajectory, considering both planimetric and vertical components and their evolution. This relative comparison reflects realistic operating conditions in road surveys, where no predefined

path constraints (such as rail tracks in railway applications) are available. It should be noted, however, that the comparison against the full-GCP solution quantifies internal consistency with respect to the best available constrained solution rather than external accuracy; the latter is assessed independently through the check-point analysis reported in Table 2.

In addition to positional discrepancies, vehicle orientation was evaluated by comparing the heading, pitch, and roll angles with respect to the reference solution. Angular differences were computed component-wise along the trajectory, using the attitude outputs provided directly by the post-processing software, each tested solution being differenced against the corresponding full-GCP solution epoch by epoch. Heading differences were wrapped to the interval $[-180^\circ, 180^\circ]$ before taking their absolute value, so as to account correctly for the circular $0^\circ/360^\circ$ convention, while pitch and roll differences were computed directly, as no angular discontinuities occur in the analyzed trajectories. A component-wise formulation was adopted, rather than a combined three-dimensional attitude-error metric, because the purpose of the comparison is to characterize the individual attitude components released by the processing software, and it allows the assessment of orientation differences and their dependence on acquisition speed and GCP configuration.

Global planimetric deformation was quantified by comparing the cumulative length of each trajectory with that of the reference solution. A deformation coefficient C was defined as the ratio between the cumulative lengths of the analyzed and reference trajectories (Equation (1)).

$$C = \frac{\sum_{i=1}^n \|\mathbf{x}_i^{\text{config}} - \mathbf{x}_{i-1}^{\text{config}}\|}{\sum_{i=1}^n \|\mathbf{x}_i^{\text{ref}} - \mathbf{x}_{i-1}^{\text{ref}}\|}, \quad (1)$$

where $\mathbf{x}_i^{\text{config}}$ and $\mathbf{x}_i^{\text{ref}}$ are the two-dimensional planimetric position vectors at sample i for the analyzed configuration and the Full-GCP reference solution, respectively, and n is the number of trajectory intervals.

From this coefficient, both percentage deformation and absolute length differences were derived. Values of $C > 1$ indicate elongation, while $C < 1$ denotes compression relative to the reference.

To further investigate drift dynamics, a threshold-based analysis was introduced. For a set of increasing error thresholds, the time and distance required to exceed each threshold were computed. This approach provides a quantitative description of drift accumulation under different configurations and acquisition conditions.

Finally, geometric consistency was evaluated through cross-sectional analysis using Leica Cyclone 3DR 2026.0 (Leica Geosystems AG, Heerbrugg, Switzerland; <https://leica-geosystems.com/products/laser-scanners/software/leica-cyclone/leica-cyclone-3dr>, accessed on 22 June 2026). Ten representative cross-sections were extracted at regular intervals of approximately 200 m along the tunnel axis, ensuring spatial comparability across all datasets.

For each configuration, the corresponding MMS-derived sections were locally aligned to the TLS reference through a rigid best-fit registration, removing translational and rotational offsets and isolating cross-sectional shape differences from global trajectory errors. The TLS is used here as an independent validation reference; without such a reference, local section geometry can still be analysed, but the millimetre-level accuracy reported here cannot be independently verified.

3. Results

This section presents the results of the MMS performance assessment under varying acquisition speeds and GCP configurations in a tunnel environment. The analysis highlights a clear contrast between global trajectory accuracy and local geometric reliability.

Global deformation and drift are first evaluated to characterize large-scale trajectory errors, followed by an assessment of cross-sectional consistency to quantify the preservation of local tunnel geometry.

3.1. Global Geometric Deformation of the Tunnel

Deformation is computed from the MMS trajectory and, since the point cloud is geo-referenced through it, directly reflects the large-scale distortions affecting the reconstructed tunnel geometry.

Figure 5 reports the planimetric deformation as a function of GCP configuration and acquisition speed, expressed in terms of the deformation coefficient defined in Equation (1) and the corresponding planimetric length difference (ΔL_{plan}). The latter represents the difference between the trajectory length computed for each configuration and the corresponding reference length.

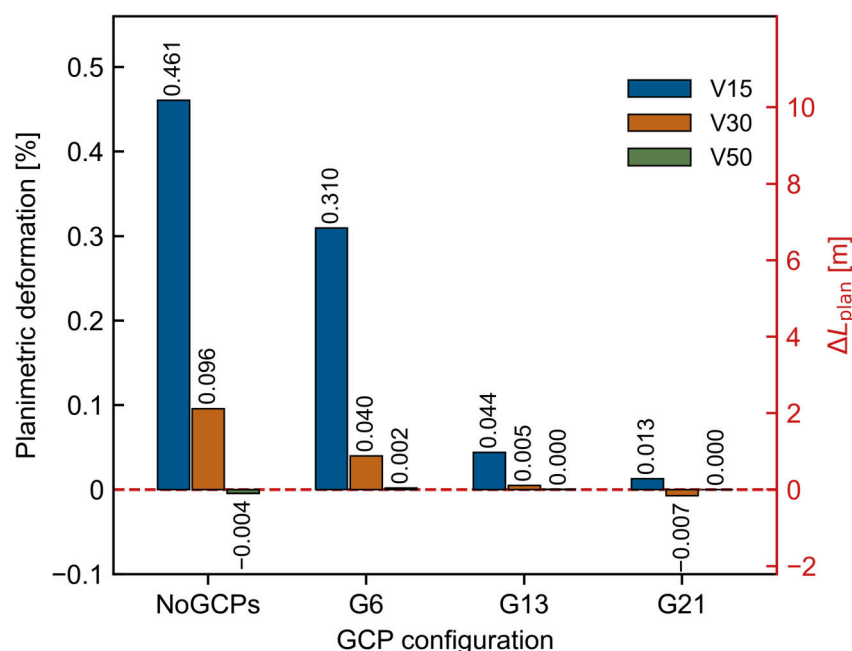


Figure 5. Planimetric deformation as a function of GCP configuration and acquisition speed. Bars represent deformation percentages (left axis), with corresponding planimetric length differences ΔL_{plan} reported on the right axis.

For all acquisition speeds, the highest deformation values are observed in the NoGCP configuration, corresponding to the default inertial solution without external constraints. In this case, the deformation reaches approximately 0.46% at 15 km/h, with a corresponding planimetric length difference of approximately 10 m.

The introduction of control points markedly reduces deformation across all configurations. In the G6 configuration, deformation values decrease compared to the NoGCP case, while further reductions are observed for G13 and G21 configurations. The lowest deformation values are consistently obtained for the highest number of GCPs, approaching negligible levels.

A consistent trend is observed across acquisition speeds, with deformation values generally decreasing from 15 km/h to 50 km/h. At the highest speed, deformation remains close to zero for all GCP configurations, with ΔL_{plan} values below 0.1 m in magnitude.

Overall, the results highlight a clear dependence of global geometric deformation on both acquisition speed and GCP configuration, with the combined effect of higher

speeds and increased control point density leading to a substantial reduction of large-scale distortions.

3.2. Drift Analysis

The drift behavior of the MMS trajectories was evaluated through the analysis of planimetric and vertical errors across different acquisition speeds and GCP configurations. Figure 6 summarizes the distribution of errors using boxplots, providing a global overview of trajectory deviations with respect to the reference solution.

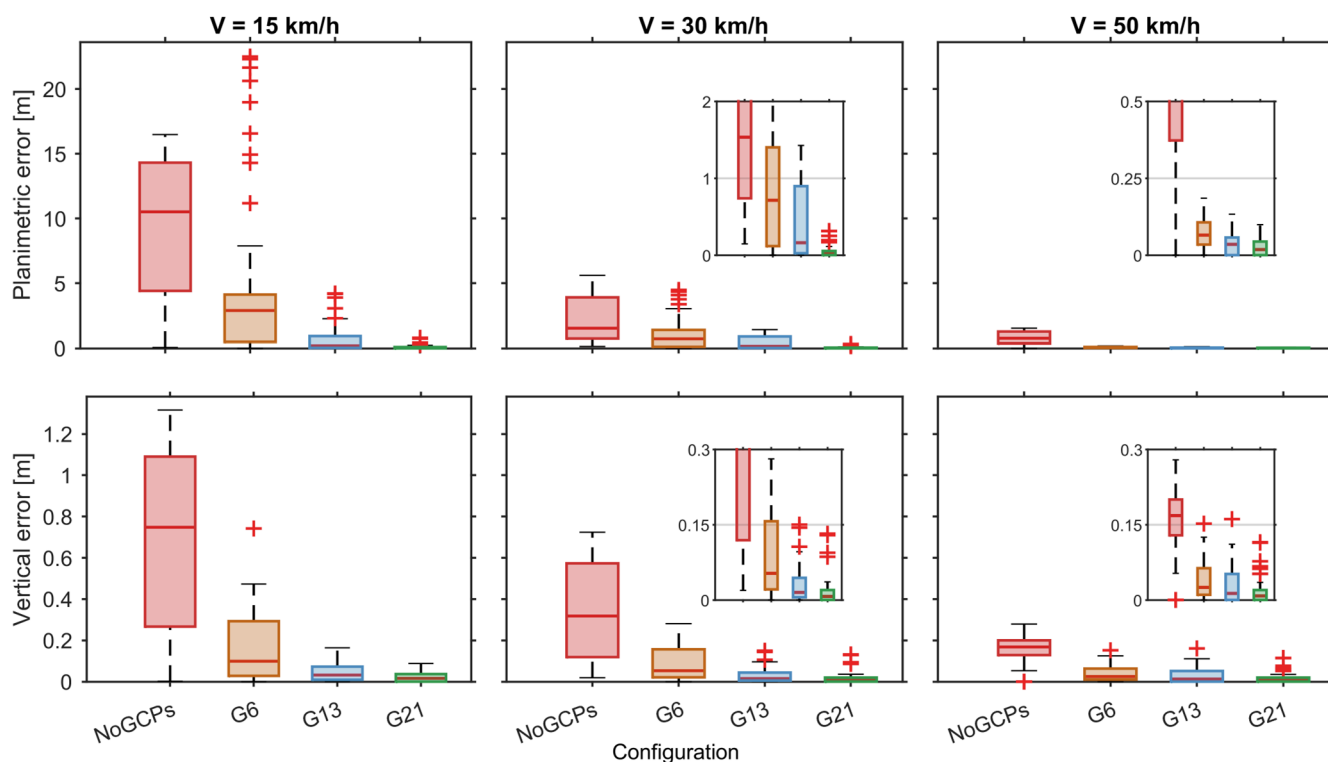


Figure 6. Distribution of planimetric (top) and vertical (bottom) errors for different acquisition speeds (15, 30, and 50 km/h) and GCP configurations (NoGCP, G6, G13, G21). Boxplots summarize the variability of errors; “+” symbols denote outliers beyond 1.5 times the interquartile range. Inset plots provide a detailed view of lower error ranges.

Overall, the NoGCP configuration shows the largest trajectory deviations, although the independent check-point statistics in Table 2 reveal a localized exception at 15 km/h, where G6 reaches a maximum planimetric error of 22.5 m compared with 16.5 m for NoGCP. The introduction of control points generally leads to a marked reduction in both the magnitude and variability of errors. In the G6 configuration, planimetric errors decrease to the metric range, while further reductions are observed for G13 and G21 configurations. In particular, the inset plots highlight that, for G13 and G21, planimetric errors are generally confined below 0.1–0.2 m, with vertical errors reaching the centimeter level.

A consistent trend is also observed with respect to acquisition speed. Error magnitudes and variability decrease from 15 km/h to 50 km/h, with the highest speed showing limited dispersion and reduced error ranges across all configurations. In particular, at 50 km/h, errors are largely confined within the sub-decimeter range, with only minor variability across different GCP configurations.

To complement the boxplot representation with quantitative measures, and to provide an external accuracy assessment independent of the full-GCP reference solution, Table 2 reports summary statistics (sample size, median, first and third quartiles, RMSE, and maximum error) of the errors measured at the reference points identified in each MMS

point cloud (Section 2.4). For the constrained configurations (G6, G13, G21), the statistics are computed exclusively on the points not used as constraints in the corresponding adjustment, which therefore act as fully independent check points; in the NoGCP configuration, all identified points are independent by construction. Because in the Full configuration every identified point is used as a constraint, the corresponding values represent control-point residuals of the adjustment rather than independent check-point errors, and are reported for completeness only. The joint reading of medians, quartiles, RMSE, and maxima also characterizes the shape of the error distributions: the gap between median and RMSE reveals heavy upper tails (e.g., for G13 at 15 km/h the planimetric median is 0.27 m, but the RMSE reaches approximately 1.4 m with a maximum of 4.2 m), reflecting localized trajectory deformation between control points. The check-point statistics confirm the trends discussed above, but also show that, at the lowest acquisition speed, external errors remain larger than the internal consistency with respect to the full-GCP solution would suggest. Sub-decimeter external accuracy (in terms of RMSE) is achieved with 21 GCPs at 30 km/h and with all GCP-constrained configurations at 50 km/h.

The temporal evolution of drift along the trajectory is further illustrated in Figure 7, where planimetric and vertical errors are reported as a function of the progressive distance.

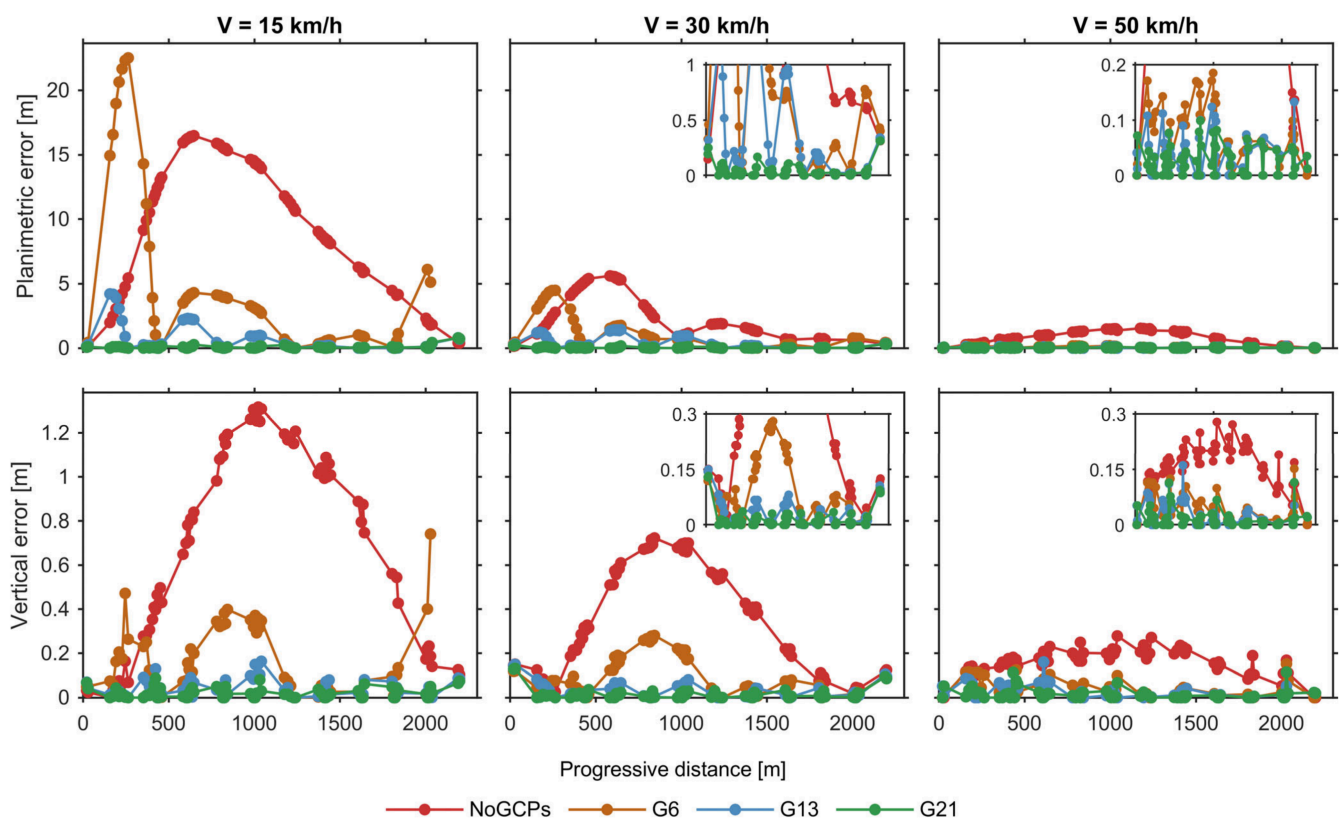


Figure 7. Spatial distribution of planimetric (**top row**) and vertical (**bottom row**) errors along the trajectory (progressive distance [m]) for different acquisition speeds (15, 30, and 50 km/h) and GCP configurations. Insets provide a detailed view of lower error intervals.

For the NoGCP configuration, errors exhibit a progressive increase along the trajectory, highlighting the accumulation of inertial drift over time. This behavior is particularly evident at 15 km/h, where planimetric and vertical errors peak at approximately 650 m and 1000 m, respectively, before decreasing towards the exit portal.

The presence of control points mitigates this effect, limiting both the growth and variability of errors. For the G6 configuration, drift accumulation is reduced but still observable. In addition, localized increases in planimetric error are observed at 15 km/h,

where a pronounced peak is visible along the trajectory. This behavior indicates localized deformation effects affecting specific segments, followed by a subsequent reduction of the error towards values comparable to the NoGCP configuration.

For G13 and G21 configurations, error profiles remain close to centimeter level along the entire trajectory, with only minor fluctuations.

At higher acquisition speeds, the temporal evolution of errors becomes less pronounced, with reduced drift accumulation and more stable profiles across all configurations.

A threshold-based analysis was further conducted to quantify the temporal and spatial evolution of trajectory errors. Figure 8 reports the time and distance required to exceed increasing error thresholds for different acquisition speeds and GCP configurations.

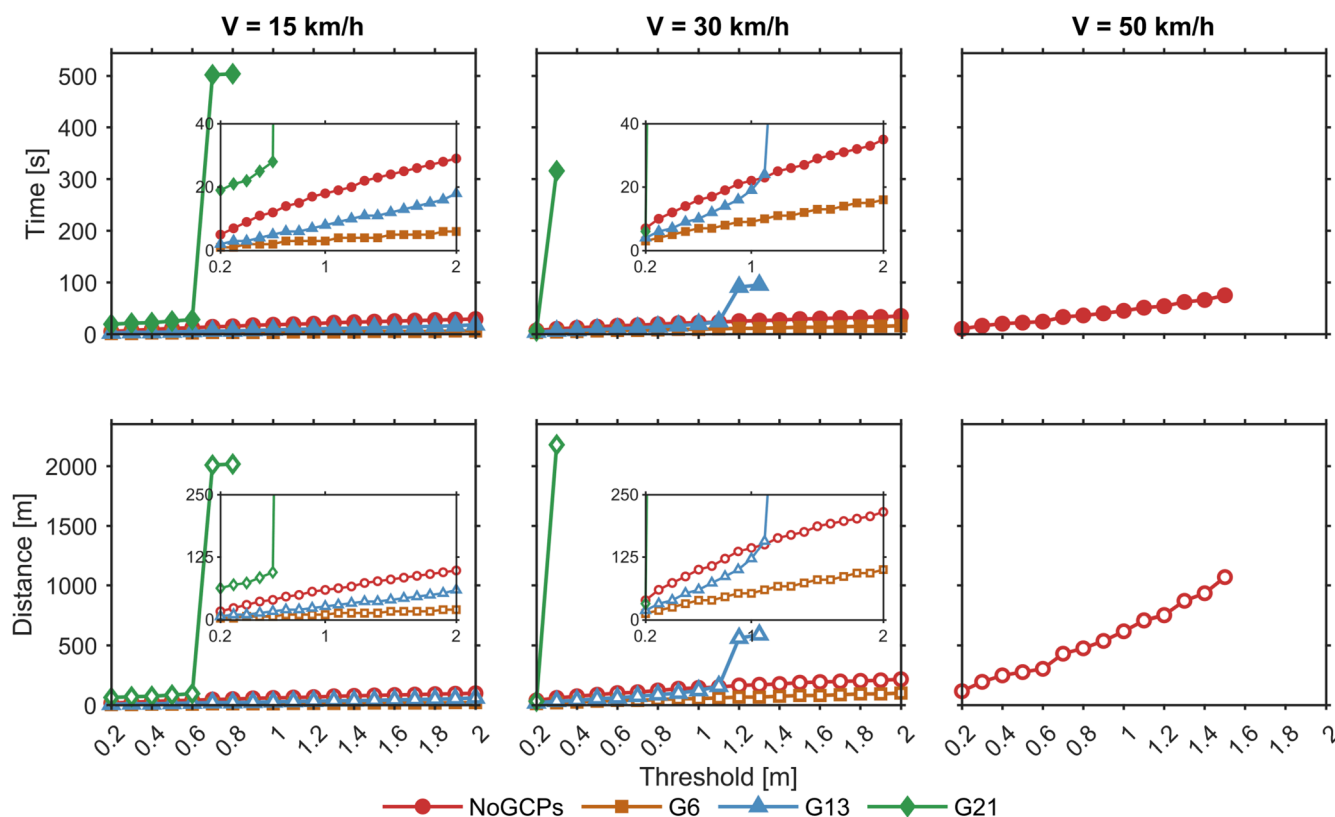


Figure 8. Threshold-based drift analysis showing the time (top row) and distance (bottom row) required to exceed increasing error thresholds for different acquisition speeds (15, 30, and 50 km/h) and GCP configurations. Insets highlight the behavior at low threshold values.

For the NoGCP configuration, error thresholds are reached rapidly, particularly at lower speeds, indicating a fast accumulation of drift. At 15 km/h, thresholds exceeding 1 m are reached within a short time interval, while higher thresholds are progressively exceeded along the trajectory.

The introduction of control points markedly delays the exceedance of the same thresholds. In the G6 configuration, threshold values are reached more gradually, while for G13 and G21 configurations, threshold exceedance is strongly limited, with only low error thresholds being reached within the analyzed trajectory length.

A clear dependence on acquisition speed is observed. At higher speeds, the time and distance required to exceed a given threshold increase, indicating a reduced rate of drift accumulation. In particular, at 50 km/h, threshold values remain limited across all configurations, with a more stable and controlled error behavior.

From an operational perspective, the threshold-based analysis provides a direct estimate of the maximum trajectory length or acquisition time that can be tolerated before

exceeding a given accuracy level. For instance, in the NoGCP configuration at 15 km/h, meter-level errors are reached within a relatively short portion of the trajectory, whereas configurations with 13 or more GCPs maintain sub-decimeter deviations with respect to the fully constrained solution over substantially longer distances. This representation is particularly relevant for survey planning, as it enables the definition of maximum admissible acquisition lengths based on target accuracy thresholds, rather than relying solely on global error statistics.

In addition to positional discrepancies, the consistency of trajectory orientation was evaluated by analyzing the differences in heading, pitch, and roll with respect to the reference solution obtained from the full GCP configuration, over the GNSS-denied segment of each acquisition. Figure 9 summarizes the distribution of absolute angular differences for the different acquisition speeds and GCP configurations. In marked contrast with the positional errors, all angular differences remain below 0.2° : median values range from 0.0002° to 0.078° , and the largest single discrepancy over the entire dataset is 0.18° . These values must be read against the internal precision of the attitude solution itself, which over the same GNSS-denied segments is approximately 0.015° for heading and 0.003° for pitch and roll (1σ , as reported by the post-processing software).

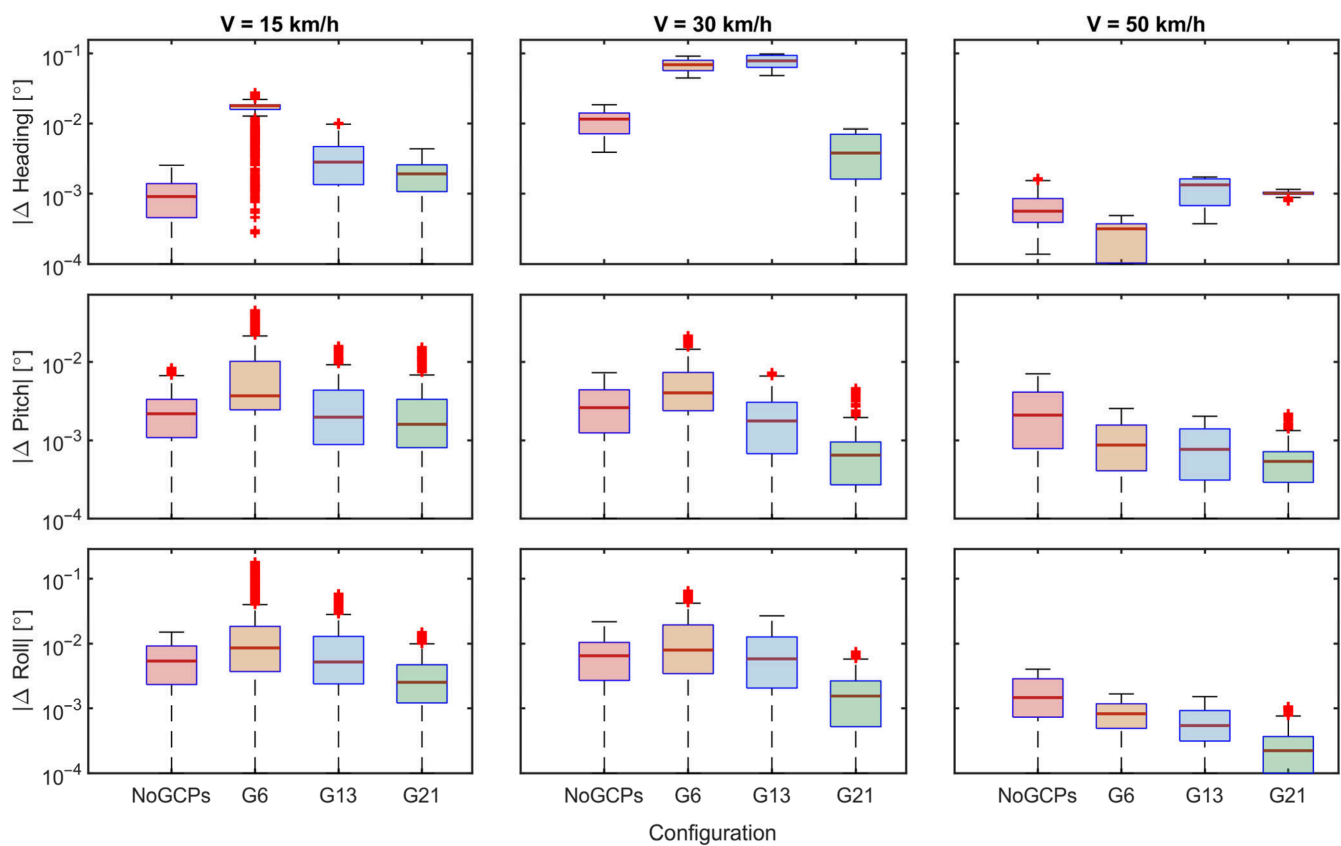


Figure 9. Distribution of absolute angular differences in heading, pitch, and roll with respect to the reference solution, for different acquisition speeds (15, 30, and 50 km/h) and GCP configurations (NoGCP, G6, G13, G21). Differences are computed over the GNSS-denied segment of each acquisition. Note the logarithmic vertical scale: all values remain below 0.2° .

Pitch and roll show median differences below 0.01° in every configuration and at every speed, corresponding to between about 0.2 and 3.5 times their own 1σ precision. Heading spans a wider relative range, from 0.1σ to about 5σ , and produces the largest excursions of the three components, with medians of 0.069° and 0.078° for the G6 and G13 configurations at 30 km/h. This is consistent with roll and pitch remaining continuously observable

during a GNSS outage through the gravity vector sensed by the accelerometers, whereas heading has no equivalent observable at this IMU grade and is constrained only indirectly, through the position updates. The differences do not decrease monotonically with control density: sparse configurations occasionally exceed the unconstrained solution, indicating that position updates redistribute small attitude corrections rather than systematically improving orientation. The dispersion visible in Figure 9 for the sparse configurations is not randomly distributed along the trajectory: at 15 km/h with six control points, the values falling outside the interquartile range are confined to the first 500 m of the transit, where the alignment reaches its smallest curvature radius (approximately 980 m, against 1500–4300 m elsewhere), and the median $|\Delta\text{Roll}|$ rises there to 0.13° against 0.002 – 0.012° over the remainder of the tunnel. This is the same segment that hosts the localized planimetric error peak discussed in Section 4.2, showing that the largest attitude discrepancies and the localized planimetric error occur within the same high-curvature portion of the alignment.

A reduction with acquisition speed is also observed: at 50 km/h no median difference exceeds 0.0021° and no single value exceeds 0.008° . Taken together, these results show that, in the tested configurations, the differences between the tested trajectory solutions are expressed predominantly in position rather than in attitude: the unconstrained and the fully constrained solutions remain very similar in orientation, with median differences at or close to the precision of the attitude solution, even where their positions differ by more than 16 m.

To contextualize the geometric implications of these angular discrepancies, the largest observed angular difference of 0.18° , applied at a representative scanner-to-wall distance of approximately 3.5 m, would correspond to a boundary displacement of about 11 mm at the tunnel section perimeter. For pitch and roll, median differences below 0.01° correspond to sub-millimeter displacements at the same representative distance, whereas the largest heading medians, of 0.069° and 0.078° , correspond to displacements of a few millimeters. The implications of these angular differences for cross-sectional geometry are examined in Section 3.3.

3.3. Geometric Consistency of Tunnel Cross-Sections

In contrast to trajectory-related metrics, cross-sectional analysis reveals a high level of geometric consistency across all configurations.

The geometric consistency of tunnel cross-sections was evaluated using the C2C comparison approach described in Section 2.4. Preliminary analyses showed negligible differences among GCP configurations, with variations on the order of 10^{-4} m in terms of cross-sectional discrepancies.

Figure 10 summarizes the distribution of C2C distances for the three acquisition speeds using boxplots. The results indicate a high level of geometric consistency across all configurations, with median values consistently around 4–5 mm. The interquartile ranges remain limited, generally within the millimeter-to-centimeter range, while whiskers extend up to approximately 20 mm, indicating the presence of localized deviations, as further illustrated in Figure 11. No appreciable dependence on acquisition speed is observed in terms of median values and dispersion, as all configurations exhibit comparable distributions. It should be noted that, with a single run per speed, these comparisons rely on descriptive statistics (medians, interquartile ranges, and percentiles) rather than on formal hypothesis testing. Minor differences in the boxplots are related to variations in point density and the number of points per section.

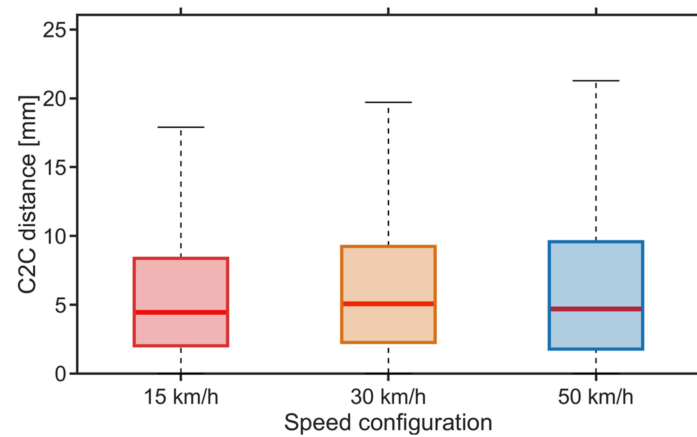


Figure 10. Boxplot distribution of cloud-to-cloud (C2C) distances between MMS-derived cross-sections and the TLS reference for different acquisition speeds (15, 30, and 50 km/h).

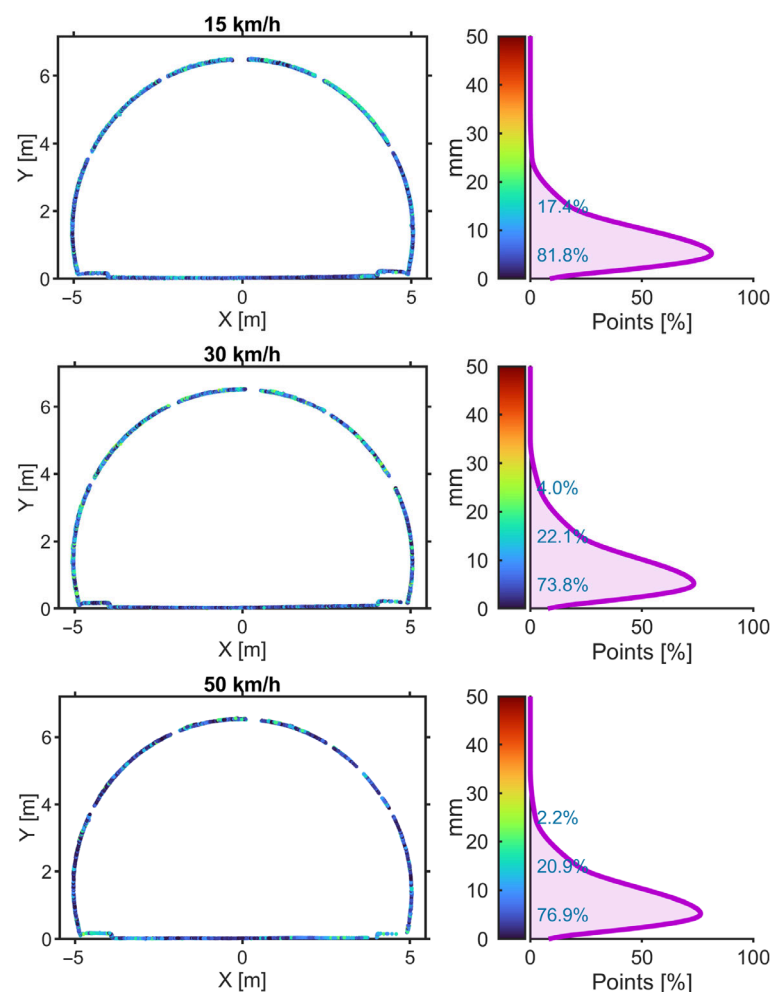


Figure 11. Representative tunnel cross-sections and corresponding cloud-to-cloud (C2C) distance maps with respect to the TLS reference, for acquisition speeds of 15, 30, and 50 km/h.

Figure 11 provides a detailed view of representative cross-sections and the corresponding distribution of C2C distances. The spatial distribution of errors confirms that deviations are generally small and uniformly distributed along the section profiles. Quantitatively, 75–82% of points, depending on the acquisition speed, exhibit discrepancies below 10 mm, while only a limited fraction exceeds 20 mm.

Overall, the results demonstrate that the shape of the tunnel cross-sections is preserved with millimeter-level consistency across all acquisition speeds, once translational and rotational offsets are removed by the local registration. These findings highlight a decoupling between global trajectory accuracy and local shape consistency, indicating that substantial drift does not necessarily compromise the preservation of cross-sectional shape.

4. Discussion

The results of this study provide quantitative evidence on the performance of Mobile Mapping Systems in road tunnels, with direct implications for survey planning, infrastructure inspection workflows, and the definition of minimum control requirements.

4.1. Global Trajectory Accuracy and the Role of Acquisition Speed

In the absence of external constraints, the inertial drift observed in this study reaches values that would be unacceptable for applications requiring absolute georeferencing or longitudinal consistency over the full tunnel extent. At 15 km/h, planimetric errors at independent check points reach 16.5 m and global deformation approaches 0.46%, with a corresponding planimetric length discrepancy of approximately 10 m. These values are consistent with known drift characteristics of tactical-grade IMU systems operating in GNSS-denied conditions [4], and confirm that unconstrained solutions driven by inertial propagation through the tunnel cannot be relied upon for applications where global geometric fidelity is required.

A practically relevant finding is that acquisition speed acts as an effective lever for controlling drift accumulation, independently of GCP availability. At 50 km/h, global deformation remains very limited across all GCP configurations, not exceeding 0.004% in magnitude even in the unconstrained case. This behavior is explained by the time-dependent nature of inertial errors: higher speeds reduce the duration of the GNSS-denied segment, thereby limiting the integration interval over which drift accumulates [24]. It must be stressed, however, that a single acquisition was available at each speed: the observed differences therefore combine the effect of the outage duration with run-to-run variability related to vehicle dynamics, IMU initialization, and terminal GNSS reacquisition. Repeated runs would be required to isolate the speed effect statistically; consequently, the observed trends should be interpreted as case-study evidence rather than as statistically generalizable performance relationships. With this caveat, the results suggest that survey speed should be regarded as a relevant accuracy parameter in tunnel MMS campaigns, not merely as a productivity factor. In contexts where deploying GCPs is logistically constrained, for example in long tunnels under active traffic, increasing acquisition speed may offer a viable means of improving global geometric consistency without additional field operations.

The reduction of global deformation at higher speeds should not, however, be read as a general improvement of survey quality, because speed and point cloud density trade off against each other. At 50 km/h, the along-track spacing between consecutive scan lines reaches approximately 11.5 cm, compared to 3.5 cm at 15 km/h. While this difference does not appear to affect cross-sectional geometric consistency in the present study, it may become relevant in applications requiring the detection of fine surface features, cracks, or localized defects at the millimeter scale [25]. Survey planners should therefore balance the reduction in global drift achievable at higher acquisition speeds against the corresponding decrease in point cloud density and the sampling requirements of the specific inspection task.

4.2. Ground Control Point Configuration: Effects of Control Density and Acquisition Speed

The introduction of GCPs reduces both trajectory drift and global deformation across all acquisition speeds, but the benefit of sparse control is neither uniform nor guaranteed. The G6 configuration, corresponding to approximately one control point every 380 m, lowers the planimetric RMSE at the independent check points from 10.8 to 7.9 m at 15 km/h and from 2.9 to 1.6 m at 30 km/h, yet at 15 km/h it raises the maximum check-point error from 16.5 to 22.5 m (Table 2). Sparse control therefore redistributes the accumulated drift rather than removing it, and sub-meter external accuracy is reached only at 50 km/h [26]. In the G6 configuration at 15 km/h, this effect is localized in the highest-curvature portion of the tunnel. This is likely related to the stronger vehicle dynamics during turning, where small heading and roll errors can produce larger cross-track position deviations; with sparse position constraints, the smoother may therefore redistribute the accumulated drift non-uniformly between consecutive GCPs. The operational implication is that a minimal investment in field control cannot be assumed to deliver a proportionate gain in geometric quality: its effectiveness depends on acquisition speed and on where the control points fall relative to the trajectory geometry.

The effect of increasing GCP density varies across acquisition speeds. At 15 and 30 km/h, substantial improvements are still observed when moving from intermediate to denser control configurations, whereas at 50 km/h even the G6 configuration provides high external accuracy. In particular, the independent check-point planimetric RMSE decreases from 1.421 to 0.197 m between G13 and G21 at 15 km/h and from 0.692 to 0.096 m at 30 km/h, while at 50 km/h the G6 configuration already achieves an RMSE below 0.10 m. These results indicate that the control density required to achieve a given level of accuracy depends strongly on acquisition speed and target accuracy, rather than following a single general trend as GCP density increases.

A practical implication is that intermediate configurations, corresponding to a control point spacing of roughly 110–180 m (13 to 21 GCPs over the 2.3 km considered here), represent a well-balanced operational choice for routine inspection campaigns. Since the appropriate control density is expected to scale with tunnel length, IMU grade, target accuracy, and acquisition speed, this recommendation should be read primarily in terms of spacing rather than absolute number of points, and should not be generalized beyond the tested configuration without verification. At this density, trajectory errors relative to the fully constrained solution are reduced to the centimeter-to-decimeter range while limiting the field time associated with control point surveying, whereas the independent check-point analysis (Table 2) indicates that external accuracy at the lowest speed can remain at the decimeter-to-meter level. For single-epoch applications where only local geometric information is needed, the results suggest that GCPs may be entirely dispensed with at all tested acquisition speeds, since cross-sectional shape consistency showed no appreciable dependence on speed (Section 3.3); acquisition speed should then be selected according to the point density required by the specific inspection task (Section 4.1).

One aspect requiring careful attention in practice is the spatial distribution of GCPs relative to the tunnel geometry. The localized planimetric error peak observed in the G6 configuration at 15 km/h occurs in the higher curvature segments of the tunnel, indicating that trajectory deformation is strongly influenced by the underlying geometry. In such conditions, uneven or sub-optimal placement of control points may lead to non-uniform adjustments along the trajectory. These results suggest that GCP deployment should be guided not only by their number or nominal spacing, but also by the geometric characteristics of the tunnel alignment, with particular attention to curved sections. Future work will further investigate the relationship between curvature radius and drift behavior, as well as the contribution of different error sources to the observed trajectory deformation.

4.3. Local Geometric Reliability and Implications for Tunnel Inspection

The most operationally relevant finding of this study is the high level of cross-sectional shape consistency, assessed after local best-fit registration, maintained across all tested configurations, including the fully unconstrained solution at the lowest acquisition speed. Median cloud-to-cloud distances with respect to the TLS reference remain in the 4–5 mm range regardless of speed or GCP configuration, with 75–82% of points exhibiting discrepancies below 10 mm. Considering a representative tunnel diameter of approximately 7 m, this corresponds to a relative geometric error below 0.15% for 75–82% of the compared points. Whether this level is sufficient depends on the tolerance adopted by the specific inspection protocol and should be verified case by case; applications involving multi-epoch deformation monitoring, as discussed below, additionally require a stable external reference frame [27].

This decoupling between global trajectory accuracy and local geometric reliability has direct and important consequences for the practical use of MMS in infrastructure inspection. It implies that even surveys conducted without GCPs and at low speeds—configurations that would produce unacceptable global positional errors—can still provide geometrically reliable cross-sectional data for a wide range of inspection tasks. These include the assessment of clearance profiles, the identification of geometric anomalies, and the generation of cross-sectional models for structural analysis. Applications based on cross-epoch comparisons, such as convergence and deformation monitoring of tunnel linings, additionally require a stable common reference frame and reliable registration between epochs [28]; since each section is here registered independently to the TLS reference, the present single-epoch experiment does not by itself demonstrate that an unconstrained MMS survey can detect millimeter-level temporal deformation, and adequate ground control remains necessary for such tasks. The physical explanation for this behavior lies in the different spatial scales of the error sources involved. Inertial drift manifests as a low-frequency, slowly varying distortion of the trajectory, affecting the absolute position and orientation of the scanner over distances of tens to hundreds of meters. In contrast, the relative geometry of individual scan lines, which determines the shape of cross-sections, is governed by the short-term stability of the IMU and the angular accuracy of the LiDAR sensors, both of which remain largely unaffected by cumulative drift. As a result, the shape of tunnel cross-sections is faithfully captured even when their absolute position in space is subject to substantial error.

It should be noted that the orientation analysis presented in Section 3.2 shows that angular differences between the unconstrained and the fully constrained solutions remain at the milli-degree level, at or close to the 1σ precision of the attitude solution. Expressed as a boundary displacement at a representative scanner-to-wall distance of approximately 3.5 m, the largest of these differences corresponds to about 11 mm, and the median pitch and roll differences to sub-millimeter effects. This supports the interpretation proposed here: across the tested configurations, the differences between trajectory solutions appear predominantly as a slowly varying translation, while the attitude that governs the reconstruction of each cross-section changes comparatively little. Accordingly, the C2C analysis reflects local section-shape fidelity rather than absolute positioning accuracy. This is the quantity that matters for the target applications of tunnel inspection and geometric documentation, where the shape of the lining profile, rather than its absolute position, is the primary information of interest.

4.4. Operational Recommendations and Limitations

Based on the results presented, the following practical recommendations can be derived for MMS/INS-based road tunnel inspection campaigns. In the present case study,

configurations with approximately 13 to 21 uniformly distributed GCPs, corresponding to an inter-GCP spacing of roughly 110 to 180 m for a tunnel of this length, provided substantial improvements in global trajectory consistency. The recommended spacing is expected to decrease for longer GNSS-denied intervals, lower-grade IMUs, or strongly curved alignments, whereas shorter tunnels, higher-grade inertial sensors, and straighter trajectories may allow wider GCP spacing. Therefore, the 110–180 m range should be interpreted as case-specific rather than as a universal design criterion. In terms of field operations, establishing this number of control points requires additional survey effort, including traverse setup and target measurement, and may require partial traffic management depending on site-specific safety and operational constraints. Combined with an acquisition speed of 30 km/h or higher, these configurations achieve sub-decimeter internal consistency with respect to the fully constrained solution. Sub-decimeter external accuracy at independent check points, in contrast, was obtained only with 21 GCPs at 30 km/h and with all GCP-constrained configurations at 50 km/h, while at 15 km/h the external RMSE remained at the decimeter level even with 21 GCPs (Table 2).

It is important to contextualize these recommendations within the experimental conditions of this study. The MMS platform adopted here operates, inside the tunnel, purely on inertial navigation, without wheel odometry, SLAM-based loop closure, or any other aiding source beyond the GNSS constraints available at the two portals, which are exploited retrospectively by the forward–backward smoother. This represents a deliberately conservative setup for the conditions investigated in this study. Additional aiding sources, such as wheel odometry or SLAM-based solutions, can provide velocity or relative-pose constraints during GNSS outages, limiting inertial drift accumulation and potentially reducing the density of external GCPs required to achieve comparable trajectory accuracy [29]. The GCP densities and acquisition speeds reported here should therefore be interpreted as conservative reference values. Surveys conducted with more advanced MMS platforms, or in shorter tunnels where drift accumulation is inherently reduced, may achieve comparable or improved geometric performance under less demanding control conditions. Although the present study is based on a single tunnel, a single MMS platform and IMU, and a single acquisition per speed, the adopted configuration represents a deliberately constrained operational scenario, allowing the reported results to provide practical reference indications for GNSS-denied tunnel mapping applications; nevertheless, tunnel geometry, vehicle dynamics, IMU quality, tunnel length, and trajectory curvature can markedly influence inertial drift, and the reported values should be transferred to other scenarios with caution.

5. Conclusions

This study investigated the performance of Mobile Mapping Systems for road tunnel inspection, with a systematic analysis of the effects of acquisition speed and ground control point (GCP) configuration on both trajectory accuracy and geometric reliability. The experimental campaign, conducted in a 2.3 km road tunnel using an MMS platform relying solely on inertial navigation inside the tunnel and validated against a high-accuracy TLS reference dataset, provides three main findings with direct operational implications.

First, acquisition speed emerges as a relevant and controllable factor affecting global trajectory accuracy in GNSS-denied environments, independently of the availability of external constraints, although with a single run per speed the observed trend cannot be fully separated from run-to-run variability. Higher speeds reduce the duration of the inertial-only segment and therefore limit drift accumulation, with the 50 km/h configuration achieving near-zero global deformation even in the absence of GCPs. This result highlights acquisition speed as a controllable parameter that should be explicitly considered in survey

design, particularly in long tunnels or in scenarios where the deployment of control points is constrained by operational conditions.

Second, ground control markedly improves global geometric consistency, but the required density is governed by acquisition speed and target accuracy rather than by a single general trend. Sparse control lowers the median error while leaving, at the lowest speed, maximum errors larger than those of the unconstrained solution, whereas the step from 13 to 21 points reduces the check-point planimetric RMSE by roughly a factor of seven at both 15 and 30 km/h. Configurations with a control point spacing of approximately 110–180 m (13–21 uniformly distributed points for the 2.3 km tunnel considered here) represent an effective compromise between global accuracy and operational efficiency; expressed in terms of spacing, this indication is expected to scale with tunnel length, IMU grade, target accuracy, and acquisition speed, and should not be read as a universal point count. Survey effort is more effectively directed towards a balanced spatial distribution, with particular attention to curved segments, than towards simply increasing the number of points.

Third, from an application-oriented perspective, tunnel cross-sectional shape was preserved with millimeter-level consistency across all tested configurations, including fully unconstrained solutions. Median cloud-to-cloud discrepancies with respect to the TLS reference remained within 4–5 mm, with the majority of points below 10 mm, regardless of acquisition speed or GCP configuration. These results support the use of INS-based MMS for local geometric characterization tasks, including clearance analysis, as-built documentation, and geometric quality assessment. Taken together, these results confirm that Mobile Mapping Systems, even when operating in a conservative configuration without in-tunnel aiding sensors, provide a reliable and efficient solution for road tunnel geometric characterization. The findings establish a quantitative basis for optimizing survey strategies by balancing acquisition speed, control point deployment, and required geometric accuracy. Future work extending the analysis to tunnels with different geometries, to MMS platforms integrating additional aiding sources, and to repeated acquisitions per configuration, enabling formal statistical testing, will further support the definition of robust and standardized workflows for underground infrastructure mapping.

Author Contributions: Conceptualization, M.C. and S.G.; methodology, M.C.; software, M.C. and M.A.T.; validation, S.G. and L.V.; writing—original draft preparation, M.C. and S.G.; writing—review and editing, M.A.T., L.V. and N.E.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data may be requested from the corresponding author solely for scientific purposes.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MMS	Mobile Mapping System
GNSS	Global Navigation Satellite System
INS	Inertial Navigation System
PPP	Precise Point Positioning
TLS	Terrestrial Laser Scanning

IMU	Inertial Measurement Unit
C2C	Cloud to Cloud
GCP	Ground Control Point
LiDAR	Light Detection and Ranging
RMSE	Root Mean Square Error
SLAM	Simultaneous Localization and Mapping

References

1. Puente, I.; González-Jorge, H.; Martínez-Sánchez, J.; Arias, P. Review of Mobile Mapping and Surveying Technologies. *Measurement* **2013**, *46*, 2127–2145. [\[CrossRef\]](#)
2. Elhashash, M.; Albanwan, H.; Qin, R. A Review of Mobile Mapping Systems: From Sensors to Applications. *Sensors* **2022**, *22*, 4262. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Scolamiero, V.; Boccardo, P.; La Riccia, L. Mobile Mapping System for Urban Infrastructure Monitoring: Digital Twin Implementation in Road Asset Management. *Land* **2025**, *14*, 597. [\[CrossRef\]](#)
4. El-Sheimy, N.; Youssef, A. Inertial Sensors Technologies for Navigation Applications: State of the Art and Future Trends. *Satell. Navig.* **2020**, *1*, 2. [\[CrossRef\]](#)
5. Zhuang, Y.; Sun, X.; Li, Y.; Huai, J.; Hua, L.; Yang, X.; Cao, X.; Zhang, P.; Cao, Y.; Qi, L.; et al. Multi-Sensor Integrated Navigation/Positioning Systems Using Data Fusion: From Analytics-Based to Learning-Based Approaches. *Inf. Fusion* **2023**, *95*, 62–90. [\[CrossRef\]](#)
6. Belloni, V.; Sjölander, A.; Nascetti, A. Data Collection Using Mobile Mapping Systems for Automated Tunnel Inspections. In *Tunnelling into a Sustainable Future—Methods and Technologies*; CRC Press: London, UK, 2025; pp. 4133–4139.
7. Wang, W.; Zhao, W.; Huang, L.; Vimarlund, V.; Wang, Z. Applications of Terrestrial Laser Scanning for Tunnels: A Review. *J. Traffic Transp. Eng. (Engl. Ed.)* **2014**, *1*, 325–337. [\[CrossRef\]](#)
8. Walker, J.; Awange, J. Total Station: Measurements and Computations. In *Surveying for Civil and Mine Engineers*; Springer International Publishing: Cham, Switzerland, 2020; pp. 77–99.
9. Sun, H.; Xu, Z.; Yao, L.; Zhong, R.; Du, L.; Wu, H. Tunnel Monitoring and Measuring System Using Mobile Laser Scanning: Design and Deployment. *Remote Sens.* **2020**, *12*, 730. [\[CrossRef\]](#)
10. Chiang, K.-W.; Tsai, S.; Huang, C.-H.; Lu, Y.-E.; Srinara, S.; Tsai, M.-L.; El-Sheimy, N.; Ai, M. Navigation Error Characteristics of LIO-, VIO-, and RIMU-Assisted INS/GNSS Multi-Sensor Fusion Schemes in a GNSS-Denied Environment. *Sensors* **2026**, *26*, 2068. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Boguspayev, N.; Akhmedov, D.; Raskaliyev, A.; Kim, A.; Sukhenko, A. A Comprehensive Review of GNSS/INS Integration Techniques for Land and Air Vehicle Applications. *Appl. Sci.* **2023**, *13*, 4819. [\[CrossRef\]](#)
12. Wang, Q.; Tang, C.; Dong, C.; Mao, Q.; Tang, F.; Chen, J.; Hou, H.; Xiong, Y. Absolute Positioning and Orientation of MLSS in a Subway Tunnel Based on Sparse Point-Assisted DR. *Sensors* **2020**, *20*, 645. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Muhojoki, J.; Hakala, T.; Kukko, A.; Kaartinen, H.; Hyypä, J. Comparing Positioning Accuracy of Mobile Laser Scanning Systems under a Forest Canopy. *Sci. Remote Sens.* **2024**, *9*, 100121. [\[CrossRef\]](#)
14. Li, Z.; Tan, J.; Liu, H. Rigorous Boresight Self-Calibration of Mobile and UAV LiDAR Scanning Systems by Strip Adjustment. *Remote Sens.* **2019**, *11*, 442. [\[CrossRef\]](#)
15. Cao, Z.; Chen, D.; Peethambaran, J.; Zhang, Z.; Xia, S.; Zhang, L. Tunnel Reconstruction With Block Level Precision by Combining Data-Driven Segmentation and Model-Driven Assembly. *IEEE Trans. Geosci. Remote Sens.* **2021**, *59*, 8853–8872. [\[CrossRef\]](#)
16. Camara, M.; Wang, L.; You, Z. Tunnel Cross-Section Deformation Monitoring Based on Mobile Laser Scanning Point Cloud. *Sensors* **2024**, *24*, 7192. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Cui, H.; Li, J.; Hu, Q.; He, L.; Tao, Y.; Xu, L.; Mao, Q. TTM: A Concise yet Effective Surface Reconstruction Approach for Tunnel Point Cloud from Mobile Mapping System. *Tunn. Undergr. Space Technol.* **2026**, *171*, 107411. [\[CrossRef\]](#)
18. Bruno, S.; De Amicis, A.; Loprencipe, G.; Orlandini, S.; Rotondi, G.; Vita, L. Advancing Road Infrastructure: Cross-Slope Analysis of Road Sections Using a Mobile Mapping System (MMS). *Transp. Res. Procedia* **2025**, *90*, 456–463. [\[CrossRef\]](#)
19. Ballaera, A.; Festi, P.; Borgatti, L.; Bossi, G.; Marcato, G. Investigation and Monitoring for Ever-Updating Engineering Geological Models: The Example of the Passo Della Morte Landslide System. *Geosciences* **2024**, *14*, 94. [\[CrossRef\]](#)
20. Cappuccio, M.; Tavasci, L.; Poluzzi, L.; Gandolfi, S. Study on the Accuracy of Multi-GNSS PPP for Different Observing Sessions Time Spans Using PRIDE PPP-AR Open-Source Software Package. *Appl. Geomat.* **2026**, *18*, 24. [\[CrossRef\]](#)
21. Poluzzi, L.; Tavasci, L.; Vecchi, E.; Gandolfi, S. Impact of Multiconstellation on Relative Static GNSS Positioning. *J. Surv. Eng.* **2021**, *147*, 04021005. [\[CrossRef\]](#)
22. Suvorkin, V.; Garcia-Fernandez, M.; González-Casado, G.; Li, M.; Rovira-Garcia, A. Assessment of Noise of MEMS IMU Sensors of Different Grades for GNSS/IMU Navigation. *Sensors* **2024**, *24*, 1953. [\[CrossRef\]](#) [\[PubMed\]](#)

23. Zhang, Y.; Dong, F.; Sun, Q.; Song, W. Laser SLAM Matching Localization Method for Subway Tunnel Point Clouds. *Sensors* **2025**, *25*, 3681. [[CrossRef](#)] [[PubMed](#)]
24. Groves, P.D. *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*, 2nd ed.; Artech House: Norwood, MA, USA, 2013.
25. Huang, H.; Liu, S.; Zhou, M.; Shao, H.; Li, Q.; Thansirichaisree, P. Automated 3D Defect Inspection in Shield Tunnel Linings through Integration of Image and Point Cloud Data. *AI Civ. Eng.* **2025**, *4*, 12. [[CrossRef](#)]
26. Běloch, L.; Pavelka, K. Optimizing Mobile Laser Scanning Accuracy for Urban Applications: A Comparison by Strategy of Different Measured Ground Points. *Appl. Sci.* **2024**, *14*, 3387. [[CrossRef](#)]
27. Gall, V.E.; Mleczko, W.; Robert, F.; Angerer, W.; Salmi, J.; Ye, Z.; Grasmick, J.; Rives, M.; Aldrian, W.; Dohmen, P.; et al. ITA-AITES—BIM in Tunnelling—Guideline for Mechanised and Conventional Tunnels. *Tunn. Undergr. Space Technol.* **2026**, *168*, 106714. [[CrossRef](#)]
28. Camara, M.; Wang, L.; You, Z. Three-Dimensional Point Cloud Displacement Analysis for Tunnel Deformation Detection Using Mobile Laser Scanning. *Appl. Sci.* **2025**, *15*, 625. [[CrossRef](#)]
29. Li, Z.; Wu, X.; Cui, J.; Xu, Y.; Liu, R.; Tu, R.; Jiang, W. Tunnel-SLAM: Low-Cost LiDAR/Vision/RTK/Inertial Integration on Vehicles for Roadway Tunnels. *Electronics* **2026**, *15*, 1101. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.