Road pavement rut detection using mobile and static terrestrial laser scanning

Article *in* Applied Geomatics · September 2021

DOI: 10.1007/s12518-021-00400-4

3 authors:

Nawras Shatnawi
Al-Balqa' Applied University
28 PUBLICATIONS **303** CITATIONS
SEE PROFILE

Mohammed Taleb Obaidat
Jordan University of Science and Technology; Jadara University
99 PUBLICATIONS **376** CITATIONS
SEE PROFILE

Bara W. Al-Mestarehi
Jordan University of Science and Technology
32 PUBLICATIONS **62** CITATIONS
SEE PROFILE

Applied Geomatics
https://doi.org/10.1007/s12518-021-00400-4

ORIGINAL PAPER

Road pavement rut detection using mobile and static terrestrial laser scanning

Nawras Shatnawi[1] · **Mohammed Taleb Obaidat**[2,3] · **Bara' Al-Mistarehi**[2]

Received: 21 January 2021 / Accepted: 27 August 2021

Abstract

This research work was anticipated to quantify pavement rut depths for one of the main roads in Jordan. New techniques using mobile and terrestrial laser scanning systems were used in order to detect, assess, and evaluate the surface measured rutting values. A study area located to the south of Amman, the capital city of Jordan, was used for data collection purpose. Accuracy assessment was carried out with reference to ground measurements using differential global position system (GPS). GPS static measurements were used to have accurate and precise rutting locations and depths. Captured images were rectified, enhanced, and processed using threshold values and noise removal filters. Pavement rut depths were measured for different severity levels for the three mentioned different methods using digital surface models (DSM) extracted from the mobile and terrestrial laser scanning systems point clouds. Statistical analysis of the extracted surfaces showed that the mean difference of measured rut depths between mobile laser scanning and GPS was 24 mm, while it was 45 mm for the terrestrial laser scanning system. Results showed consistent accuracy and preference for terrestrial laser scanner measurements associated with least commission errors; however, mobile laser scanning system had lowest omission errors, whereas the potential accuracy measured in terms of root mean square error (RMSE) was 74 mm for the mobile laser scanning system and 93 mm of the static terrestrial laser scanner system, respectively. On the other hand, the consistency of accuracy of measurements was slightly better for the static terrestrial laser system with a mean average error (MAE) of 66 mm, while it was 97 mm for the mobile system. High correlation does exist between mobile laser scanner and GPS measurements with R^2 of 0.92, while it was 0.89 between static terrestrial laser system and GPS systems. These results and potential accuracies of rut depth measurements of the new used techniques would open the door to adapt them in different micro and macro measurements in numerous transportation engineering applications.

Keywords Pavement rut depth · Mobile laser scanner · Static terrestrial laser system · Surface measurements · Image processing · Digital surface model

Introduction and literature review

Roads are one of the most important elements in the civilized communities. They play vital role in connecting villages, cities, districts, states, production lines, and even countries together. Due to frequent and high load of vehicles on roads, it is normal to have failures in the top surface (pavement) of the roads. Standard failures of pavement are called distresses, which are divided into several types that affect the performance of the road. These distresses can be categorized as follows: cracking which is the major distress type in main roads, while in secondary roads, potholes, patches, and rutting are often found (Oliveira 2013; Obaidat et al. 1997; Al-Suleiman et al. 2000; and Shahin 2005). Mainly, nineteen distresses do exist in flexible pavement.

✉ Mohammed Taleb Obaidat
mobaidat@just.edu.jo; mobaidat@jadara.edu.jo

Nawras Shatnawi
nnshatnawi@bau.edu.jo

Bara' Al-Mistarehi
bwmistarehi@just.edu.jo

[1] Department of Surveying and Geomatics Engineering, Al-Balqa Applied University, Al-Salt 19117, Jordan

[2] Department of Civil Engineering, Jordan University of Science and Technology (JUST), 3030 Irbid, Jordan

[3] Present Address: Jadara University, Irbid-Amman Highway, Nuaymah Interchange, Irbid, Jordan

However, this study will focus on rutting evaluation and assessment.

In order to maintain good performing roads, proper maintenance should be followed frequently based on accurate pavement inspections and surveys. This kind of inspections can be done by specialists who can monitor, acquire images, collect data, and assess roads distresses. This traditional way of data collection has many drawbacks such as labor-intensive, time-consuming, and dangerous especially in highways and prone to subjectivity (Meignen et al. 1997; and Obaidat et al. 1997, Cheng and Miyojim 1998, Beraldin et al. 2010 and Subirats et al. 2004). Therefore, automatic distress data collection using digital imaging technology has been used by many researchers since more than 50 years. This method reduces disturbance to the public traffic and road hazard to human inspectors during the survey (Wang 2000, and Zhou et al. 2005). Zhang et al. (2016) used neural networks to detect road pavements cracks, while Zhang et al. (2014) with the application of high-speed complementary metal–oxide–semiconductor (CMOS) industrial cameras automatically detected cracks in a subway tunnel using morphological image processing techniques and thresholding operations. Shatnawi (2018) used image processing techniques and neural network to detect pavement cracks in secondary roads, based on images acquired by drones. Fuentes et al. (2017) used computer vision techniques to study and detect pavement cracks over several past years and showed how deep learning based method could affect using different parameters.

Laser scanning is, in contrast to image-based approaches, an automatic, direct measurement of 3D points (Hoffmeister 2020). In terms of sensors, mobile mapping system (MMS) is normally categorized as image-based and laser-based mapping (Shan and Toth 2018). Image-based mobile mapping has a major impact on conventional transportation surveying and mapping, such as modelling and estimation of road boundaries in road safety assistance (Tao and Li 2007; Dickmanns and Mysliwetz 1992). This significant impact exists because images contain rich color and texture information, which benefits road extraction and automated distress detection. A large range, with several usages and applications, exploit automated mobile mapping acquisition systems. Some of these applications are utilized for highway distress rating and estimation, pavement distress and airport runway distress, tunnels, and bridge fields. Al-Durgham et al. (2021) introduced an automated framework for the accuracy assessment and quality inspection of point cloud data collected by MMS operating with lightweight laser scanners and consumer grade microelectromechanical systems (MEMS) sensors. The results of the study showed high range of accuracy which can be used for the accuracy assessment of mobile mapping systems.

Commercial image-based road extraction systems have been widely available (Liu et al. 2013). However, image-based mobile mapping are incapable of dealing with situations where road features such as lane markings are missing and visibly restricted due to weather conditions (Tsogas et al. 2011). The technology of 3D laser scanning has emerged and further been fueled to a wide variety of transportation applications, such as model-based road design, monitoring, and automated detection of road distresses.

Compared to photogrammetry and field surveys, laser scanners capture very highly accurate 3D point clouds with a high point density in a relatively short amount of time (Haala et al. 2008). Besides collecting explicit highly accurate elevation information, mobile laser scanner systems also provide other implicit information, such as intensity, rutting and potholes depth, scanning patterns, and pulse information, all of which contribute to road information extraction.

Utilization of LIDAR data has increased during the past few years in many fields of applications, for example, in road environment monitoring and road damages. The detection of rut depths, slopes, and drainage is possible from the high point density LIDAR data sets (Tsai et al. 2014). LIDAR point cloud is possible to color by slopes, which may give some information about rut locations even from lower point density data sets. Mobile laser scanning technology can accurately and effectively conduct network-level rutting measurements at different highway speeds (Campbell et al. 2013). Obaidat et al. (2020) used precise positioning system (RTK) and cellular phone for rutting measurements in minor roads in northern part of Jordan, in addition to develop rutting and lateral displacement models using different parameters such as annual average daily traffic (AADT), truck percent, lane width, pavement age, and pavement thickness. The study showed that the used methods produced accurate and reliable results compared with the manual method based on root mean square error (RMSE).

Working with laser technologies on highways is more efficient with medium to low traffic, because moving objects such as cars and large vehicles have direct effect on the acquisition quality by increasing laser pulse distortion. Therefore, it is not recommended to use such technologies during rush hours. From economical point of view, it is obvious that laser scanning technologies are more efficient and practical for rut depth measurement compared with manual methods. However, these methods reduce time and risk in the site. In addition to that, the methodology presented in this study is safe, fast, and potentially accurate.

This research work will investigate the potential of mobile and terrestrial laser scanning systems in measuring rut depth for flexible pavement of one of the major highways in Jordan. Image processing techniques will be incorporated within the proposed scheme of rut depth measurements.

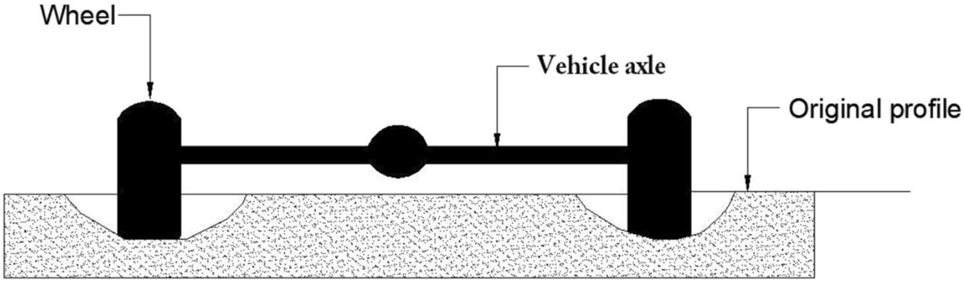


Fig. 1 Pavement rutting under the wheel path

Pavement rutting

Rutting, a main distress accomplished in asphalt pavements, is highly associated to the mixture's resistance to shear deformation (McGhee 2004). In general, it is a perpetual deformation (surface depression) under the wheel paths in the pavement as shown in Fig. 1.

Considerable rutting can lead to main structural failure of the pavement. It occurs under the wheel paths in the pavement. The causes of rutting are as follows: improper asphalt density, weak subgrade, high temperature (heat), lack of or improper compaction, and traffic loading (Young-Chan et al. 2011). The mean rut depth is calculated by laying a straightedge across the rut, measuring its depth, and then using measurements taken along the length of the rut to compute its mean depth in inches as shown in Fig. 2 (Mcghee 2004).

Severity levels of the rutting which is highly dependent on the road class, traffic, and road authority decisions are based on the mean rut depth as shown in Table 1.

Description of study area

A 4.4-km length segment of highway was mapped in this study. This segment is a part of a divided highway with two lanes in each direction, linking Amman with Aqaba Portal city. The road is known as desert highway because it passes through the Jordanian desert in the southern part of Jordan. Figure 3 shows the location of the study area. Due to excessive amount of equivalent single axle loads (ESALs) on the road, many serious distresses appeared on its surface such as rut and cracks. Future maintenance and rehabilitation are necessary for this highway. The suggested methods will facilitate the distresses assessment and quantity surveying, especially with the presence of heavy traffic all the time.

Fig. 2 Example to compute mean rut depth

Description of the used system

Mobile mapping is a process for geospatial data collection by means of moving vehicle. This vehicle is fitted with a photographic, radar, laser, LIDAR, or any number of remote sensing systems along with navigation and positioning sensors such as a global positioning system (GPS) and inertial devices such as an inertial measurement unit (IMU) (Tao and Li 2007). Mobile mapping technology involves the dynamic digitization at very high spatial resolution of complex environments (mainly urban environments) using a mobile terrestrial platform (Vallet and Mallet 2016). A terrestrial 3D laser scanner captures a 360-degree view of a scene giving accurate position of every pixel, thus obtaining a 3D point cloud. The principle behind the 3D laser scanner is that it emits a continuous laser beam and the scanner automatically rotates around its vertical axis; a rapidly spinning mirror moves the beam up and down; when the beam hits an object, some of its energy bounces back to the scanner, and the sensor detects it (Zhang et al. 2008). For each distance measurement, a laser scanner also records the horizontal angle of the rotating laser and the corresponding vertical angle of the moving mirror. The scanner automatically combines this to calculate the three dimensions (3D), X, Y, and Z coordinate positions for each point. The optimal scan positions should

Table 1 Pavement rutting severity levels (Shahin 2005)

Severity level	Mean rut depth (in or mm)
Low	0.25 to 0.5 in (6 to 13 mm)
Medium	> 0.5 to 1 in (> 13 to 25 mm)
High	> 1 in (> 25 mm)

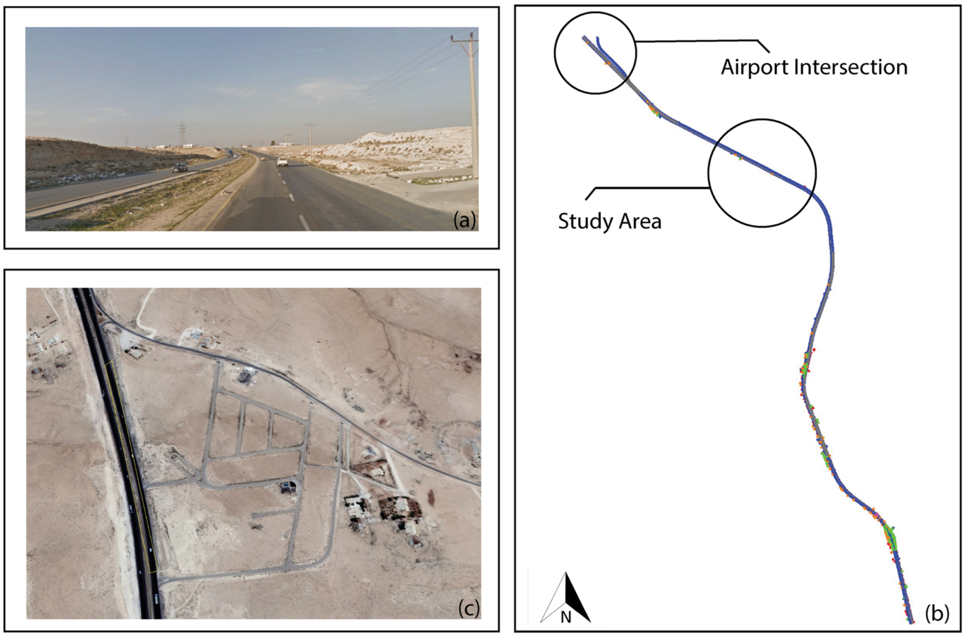


Fig. 3 Location map of the study area: **a** an image for the studied road, **b** horizontal alignment for the road, **c** road neighborhood (courtesy of Google Earth)

be selected with regard to the complete coverage and the minimum amount of scan positions, as well as a sufficient overlap (Telling et al. 2017). The resulting scan is a detailed 3D representation of the area, a point cloud (Rakitina et al. 2008). In this study, Trimble TX8 laser scanner has been used. This instrument provides a 360°×317° field of view and captures full high density scans. The Trimble TX8 maintains its high precision over the entire range of 340 m with angular accuracy of 80 μrad and range systematic error of less than 2 mm, while the used IMU/sensor in the mobile mapping system is LIDAR USA INS and Velodyne HDL 32 laser with a range accuracy of 1.5–2 cm. The used Mobile Mapping system has two returns with horizontal field of view (FOV) of 41 and vertical FOV of 360 degrees. Figure 4 shows the used laser scanner and mobile mapping system.

Terrestrial laser scanners offer solutions for point cloud acquisition at different ranges and with different accuracies (Fröhlich and Mettenleiter 2004). Mobile laser scanners provide corridor mapping of terrestrial platforms such as cars or trains (Barber et al. 2008). All laser scanning systems, airborne, mobile, and terrestrial, are used to acquire point clouds. In most cases, point clouds are used to extract georeferenced information. Common steps in information extraction procedures include detection of flat or smooth surfaces and classification of points or clusters of points based on local point patterns, echo intensity, and echo count information (Vosselman et al. 2004; Darmawati 2008). Point

Fig. 4 Data collection systems used in the study (left, static laser scanner; right, mobile laser scanner)

clouds can be used in a variety of ways, especially in relation to survey needs. They can be oriented and projected to perform orthogonal projections; they can be intersected with operator-selected planes to perform traditional slices or to highlight specific aspects such as deformations (Vacca et al. 2012).

Research methodology

The used methodology of this work consists of five main steps:

a) Data acquisition of high accuracy from the study area using mobile laser scanning and static terrestrial laser scanner. Three subsequent images were captured for the study area using static terrestrial laser scanner because of its field of view limitations. However, an image was taken using the mobile system as it has a higher coverage area.
b) Image enhancement, filtering, and preprocessing. These activities are normally done for most of the captured images under the sunlight. ImageJ software was used for this task and other relevant image processing activities (Rasband, 1997–2018).
c) Creation of digital surface model (DSM) from the laser scanning could give clear interpretation for the deformation happening due to rut depth.
d) Detection of edge of rutting and feature extraction. This step would work as baseline for rut depth measurements as it will use the original surface plane of the road as a datum of difference elevation of measurements.
e) Statistical analysis for differences in measured rut depths for the used methods. This will give clear vision about potential accuracy of the new technique used and comparison between their accuracies and precisions.

The followed methodology in this study is based on two main approaches: the first approach dealing with the extraction of digital surface model (DSM) from the two systems including filtering of point clouds generated from both scanning systems and classification of points into main classes such as buildings, ground, light poles, trees, and high voltage poles. The second approach is building GPS network that is used as ground truth for accuracy assessment of the two extracted DSMs. The flow chart in Figure 5 shows the used methodology in this research work.

Used equipment

The used static terrestrial laser scanner can measure one million points per second while capturing precise data over its full measurement range. It has an integrated camera to colorize scans which can quickly take full field of view HDR images in just 2 min. It provides a 360° × 317° field of view and captures full high density scans in only 3 min. Plus, it maintains its high precision over the entire range of 120 m with no need to reduce speed. With such system, it is possible to reach an angular accuracy of 80 μrad and point spacing of 11.3 mm at 30 m.

However, mobile mapping system typically mounts on the roof of a vehicle and rapidly captures laser scans and images both panoramic and multi-angle as you drive. Rich, immersive data can be captured at highways speeds, avoiding the need for expensive road closures and eliminating the risk associated with employees working along busy highways in dense traffic. This system has an accuracy of 5 mm with a field of view of 360°. It captures 500 scans per second with a maximum range of 420 m in all directions.

Data acquirement and mechanism of rut depth measurements

The automated methods that have been used in this study in order to measure rut depth have high accuracy measurements and high measurements rate, do not need traffic control tools, operate safely, and can collect more compressive data than manual methods. In this study, real-time kinematic (RTK) using GPS system is used as ground truth to measure rut depth. The purpose of this process was to compare the actual values of rut depth with those extracted from automated methods, in the hope to obtain a high level of accuracy with a new technique of rut measurement. Several stations were used for each road section to minimize any error by registering the scenes of each station.

Images extracted from point clouds of the two laser scanning methods were used to measure rut depth in the study area. Setting off an imaginary grid with numbering system was located on the surface of the road to compute rut distress in each grid.

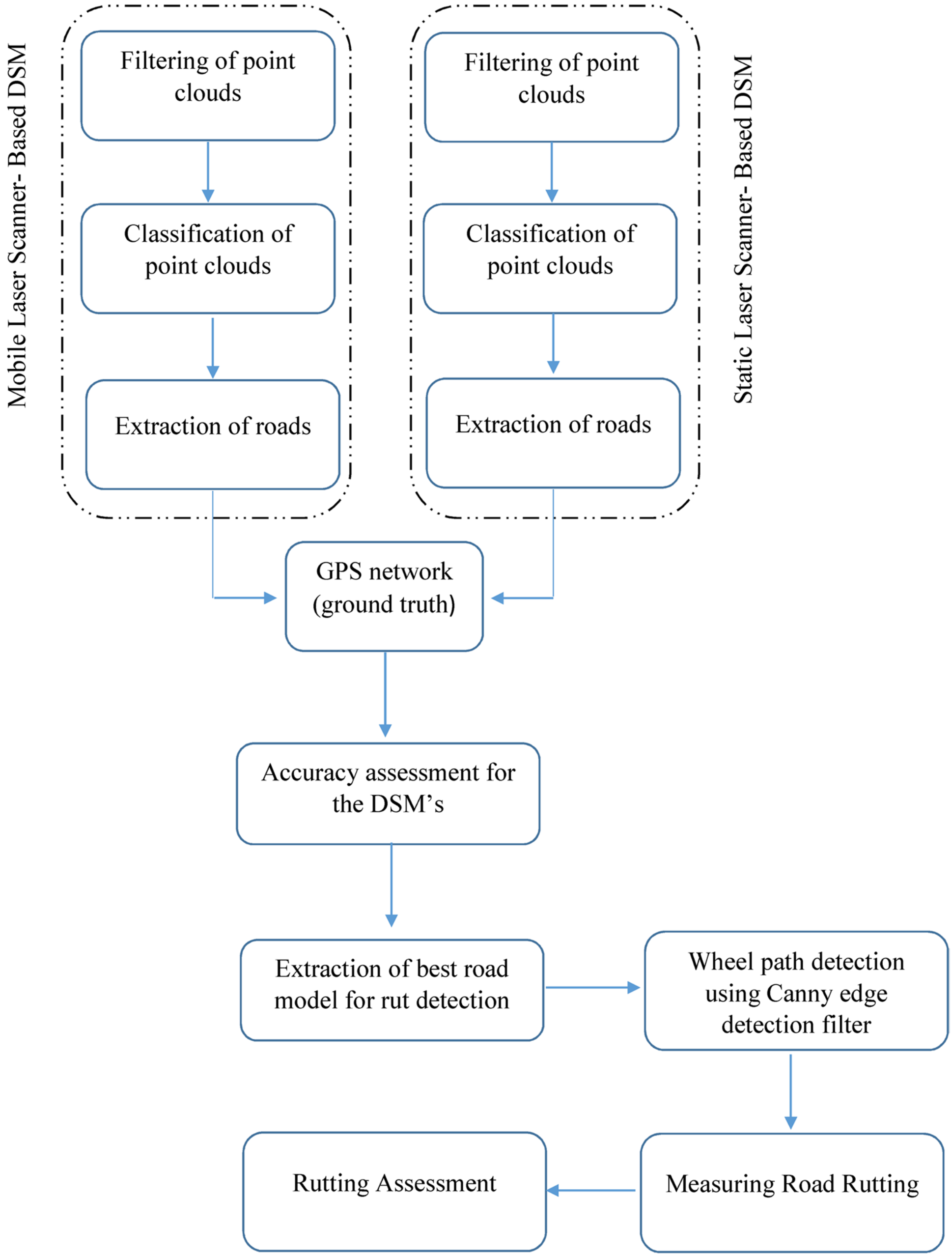
Results and discussion

Validation of the DSMs

In order to select the most accurate extracted DSM's, which are shown in Fig. 6, commission and omission error assessment was carried out.

The area was divided into grids of 1 m × 1 m. Every grid (cell) in the sample data set which has an elevation measured by the GPS system was compared with the corresponding extracted elevation by mobile and static laser scanners.

Fig. 5 Flow chart showing the followed methodology in this research work



For all cells in the used two methods, the percentage of commission and omission errors are measured as shown in Table 2.

Type I error (omission error) represents a case in which the type on the ground is not that type on the classified image; the real type is omitted from the image (Pierce 2015). Equation (1) shows how to compute type I error (Pierce 2015):

$$Type\ I = \frac{\mathrm{a}}{a+b} \tag{1}$$

where a is the number of ground points well classified (filtered) as ground and b is the number of ground points filtered out as objects.

Type II Error (Commission Error) represents a case in which the classification algorithm assigns pixels to a class that they do not belong to. This error indicates that the type on the image does not relate to the type on the ground (Pierce 2015). Equation (2) shows the type II error:

$$Type\ II = \frac{\mathrm{c}}{c+d} \tag{2}$$

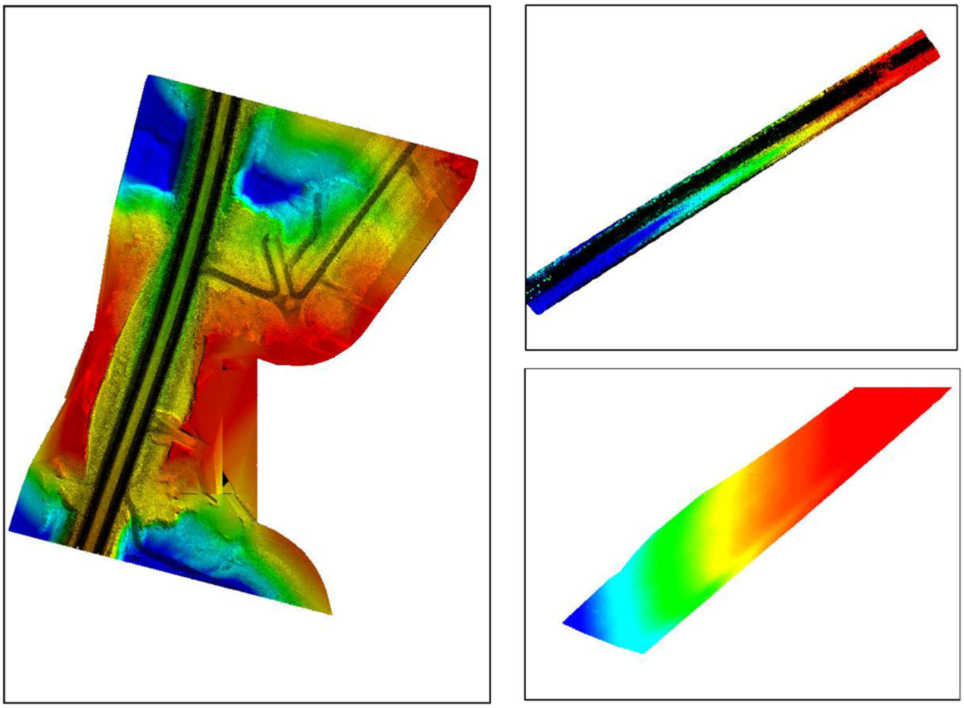


Fig. 6 Extracted sample of DSM of the study area. Left: DSM of the study area. Top right: sample of mobile laser scanning system. Bottom right: sample of static laser scanning system

where *c* is the number of object points misclassified as ground and *d* is the number of object points well classified.

From the initial assessment, it is concluded that the extracted DSM from static laser scanner exhibited the least commission error, while the results of mobile scanner showed lowest omission error. The commission errors can be interpreted due to the presence of objects such as high traffic flow during the scanning process. Omission errors may appear due to shadows of the moving traffic that might omit parts of the road. Since there is no specific model that has the lowest commission and omission error values together, statistical analysis has been used to detect the best model that could describe the actual situation of rutting compared with GPS readings. Discrepancies of numbers of rutting points among the used techniques were due to the following: (1) existence of shadow in some of the images; (2) coverage and computational concepts of the used techniques; (3) variations of levelling between the measured rutting points and the instrument exposure settings; and (4) resolutions, spacing, and locations of rutting points.

Table 2 Commission and omission error percentages compared with actual GPS readings

Technique	Commission percentage (%)	Omission percentage (%)
Static system	21.17	17.36
Mobile system	24.31	13.18

Regression and correlation assessment

The used two systems showed that the DSM derived by each method fitted closely to the ground truth data measured by GPS system as shown in Table 3.

The statistical analysis results shown in Table 3 also indicates that the mobile system shows slight preference than the static laser system regarding accuracy potential, even though the differences are not that high. However, the mobile laser scanning data were more precise in terms of standard error of the mean measurements; also, it was more precise for single measurements. Using GPS as base ground true value measurements, the mobile system mean measurements were more accurate compared to static measurements. Table 4 shows that the mean difference

Table 3 Statistical analysis of the selected GCPS' compared with mobile and static laser scanner DSMs

	Mobile system	Static system
N	151	151
Mean (mm)	37.73	41.29
Std. error of mean (mm)	0.39	0.41
Median (mm)	25.00	30.00
Mode (mm)	10.00	15.00
Std. Deviation (mm)	2.84	2.95
Variance (mm)	8.11	8.74
Skewness (mm)	1.00	0.84
Std. error of skewness (mm)	0.33	0.33

Table 4 Statistical differences of measured rut depths using the three methods

	GPS	Static system	Mobile system
Mean (mm)	35.29	80.30	59.70
Std. deviation (mm)	2.89	2.96	2.85
C.O.V	0.82	0.37	0.48
Difference from GPS (mm)		- 45.00	-240.00

of measured rut depths between mobile scanner and GPS was 24 mm, while it was 45 mm respectively for the static laser scanner. Table 4 also shows the statistical differences between the measured rut values for the three methods. Table 4 shows that the standard deviations for the various measurement methods are all the same, indicating that there are some systematic errors. These errors could be caused by device misalignment as a result of long-term operation. Factory calibration might help reduce these errors from time to time. Additionally, using comparable orientations on each scan may support in the reduction of these errors.

This highway has extensive heavy traffic of high equivalent single axle loads (ESALs) because it is the major road in Jordan to transport phosphate to Aqaba port for the purpose of export the material outside of Jordan. This reason clarifies the high values of rutting depth measurements as well.

Because some rutting spots, particularly in the wheel path, are not always detected, image processing is utilized to improve the visualization of these spots. In fact, visual inspection revealed that the rut is darker than the neighboring pavement pixels, making it easy to identify. However, because the gray-level distribution of rut areas is difficult to distinguish from that of the road pavement, image processing techniques are employed in this study.

Canny edge detection filter was used to detect the wheel paths on the road based on the intensity of the area as shown in Fig. 7 as high pixel intensities associated with edges.

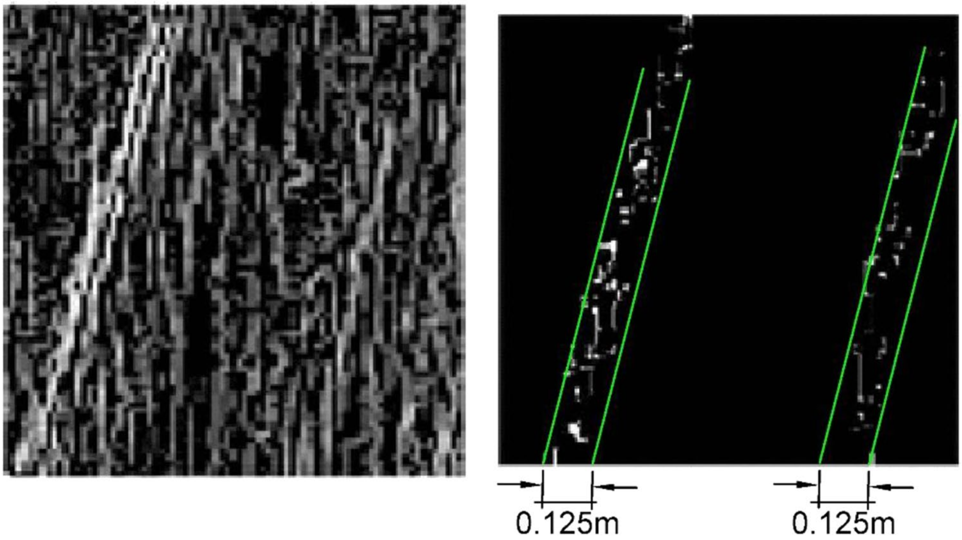


Fig. 7 Wheel paths as results of applying Canny edge detection filter (left, smoothed image by median filter; right, detected wheel paths after Canny edge detection filter)

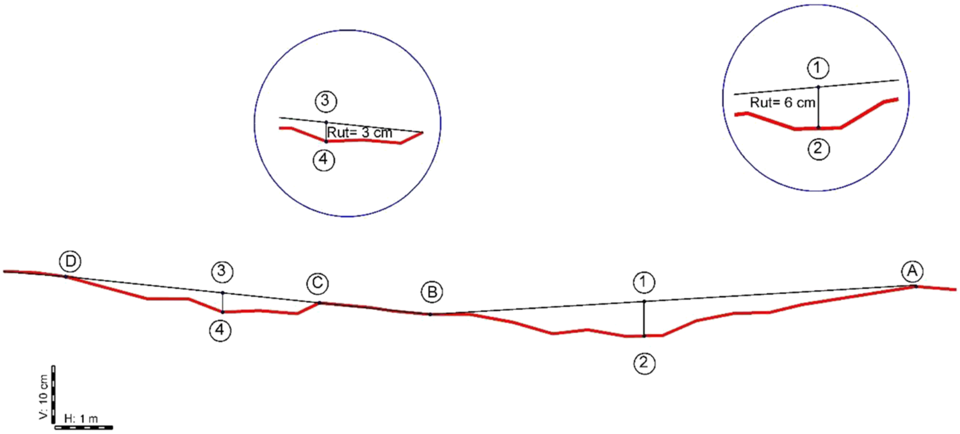
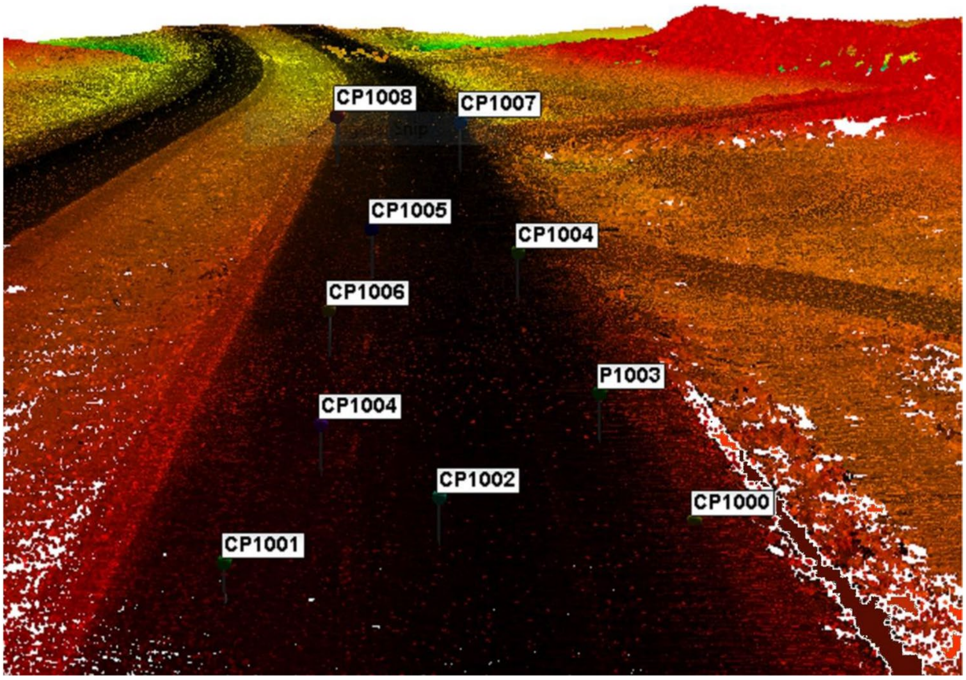


Fig. 8 Road transverse cross section showing rut depth under wheel paths of the vehicle

Fig. 9 Sample of selected check points (CP) from the study area



Transverse road cross sections were plotted over the mobile laser-extracted DSM every 5 m in order to measure road rutting as shown in Fig. 8.

The accuracy assessment was carried out by comparing the elevation values extracted from the mobile laser-derived DSM and static laser scanner-derived DSM with the field-collected elevation data measured with total station and GPS. Figure 9 shows sample ground control points (GCPs) collected from the study area.

The comparison was based on the value of root mean square error (RMSE) and mean absolute error (MAE) presented in Eqs. (3) and (4) respectively, as shown in Table 5:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Z_{Model_i} - Z_{GCP_i})^2}{n}} \tag{3}$$

$$MAE = \frac{\sum_{i=1}^{n}\left|Z_{Model_i} - Z_{GCP_i}\right|}{n} \tag{4}$$

where n is the number of samples, Z_{Model} is the terrain elevation obtained from the mobile-derived DSM or static laser scanner-derived DSM, and Z_{GCP} is terrain elevation value obtained from the field GCP.

Potential accuracy of mobile system is better ($RMSE = 74$ mm), compared to 93 mm of static system. However, the consistency of accuracy of measurements was better for the static laser system ($MAE = 66$ mm), while it was 97 mm for the mobile laser system. These discrepancies between RMSE and MAE for both systems were due to the wider coverage of the mobile system that did not require any matching between adjacent photos like the ones took by static laser system. Moreover, the mobile system has the capability of real-time correction unlike the static laser system.

Table 5 Statistical analysis of rutting values measured from the two extracted DSMs

	RMSE (mm)	MAE (m)
Static system DSM	93	66
Mobile system DSM	74	97

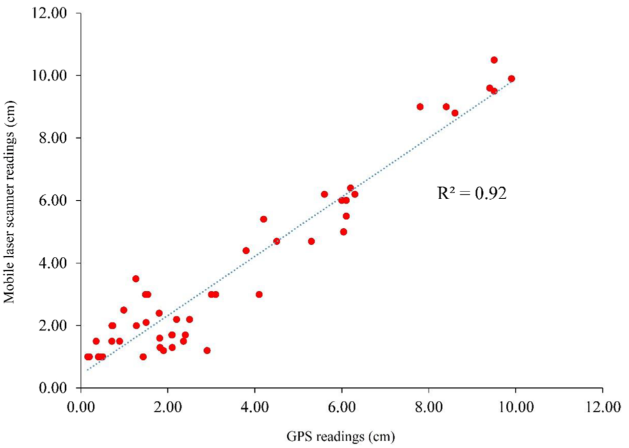


Fig. 10 Correlation between GPS readings (ground truth) and mobile laser scanner reading

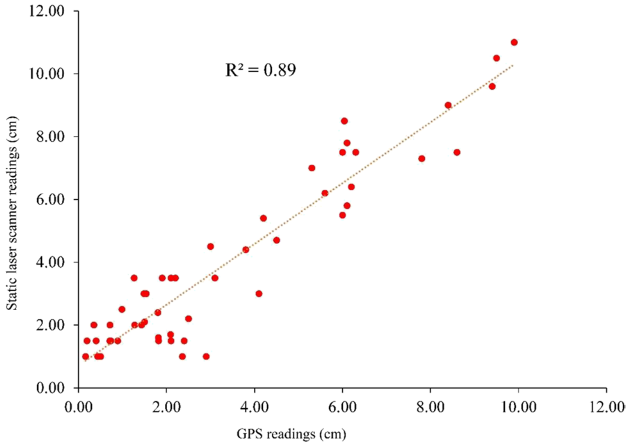


Fig. 11 Correlation between GPS readings (ground truth) and static laser scanner readings

The relationships between mobile and static laser systems with GPS extracted data are shown in Figs. 10 and 11, respectively.

High correlations do exist between mobile system and GPS measurements with R^2 of 0.92, while it was 0.89 between the static laser and GPS. This result supports the previous mentioned statistical findings in both Tables 3 and 4. The two figures also show the normalization of the measured rut depth around the 45° line.

Mobile mapping compared to static measurements indicates that these two techniques still need to explore the major factors that affect their accuracy and potential precision; one of these factors might be calibration of equipment and scale factor. Although mobile laser scanning system is a moving one, it comprises an integrated GNSS/IMU system for determination of the platform state and one or more imaging sensors. It may include additional navigation sensors such as a wheel revolution counter. The trajectory estimates from the navigation system allow direct georeferencing of acquired image data (Al-Durgham et al. 2021), while static terrestrial laser scanning system could be affected more by moving objects in the site such as cars and land large vehicles.

This is a prototype study that has been carried at a section of a highway which has clear rutting area having extensive heavy traffic of high equivalent single axle loads (ESALs).

Conclusions and recommendations

This research work shows high potential of new technologies such as mobile and static laser scanners in order to quantify rut depth measurements of flexible pavement. The work investigated rut depth using new techniques that are practical, precise, accurate, and safe. The followings are the main conclusions of this research work:

1. Mobile and static laser techniques showed compatible and high correlation rut depth measurements with GPS method that was used as a base line for the measurements.
2. The new used techniques showed fast and reliable procedures for rut depth measurements that could be adapted by pavements engineers in order to study flexible pavement performance and factors affecting on it.
3. The new method of measuring rut depth used DEM and DSM for bulk of rut depth data based on line and area-based measurements rather than conventional techniques that use straight edges and point location.
4. Rut depth measurements using mobile and static laser scanning techniques were consistently fallen within accuracy values of 24 mm to 45 mm. This is an indication of reliability and practicality of the new used techniques.
5. The new techniques of measuring rut depths would potentially open the door for different micro and macro transportation engineering applications in traffic, materials, and geometry.

Despite the potential findings of this research work, it is recommended to proceed in the following research work domain:

1. Design portable and movable platforms in order to carry the mobile and static laser scanning systems.
2. Automate much of the routine work of the scheme developed by the mentioned methodology in this research work.
3. Study the behavior of drivers' habits tracks in terms of lateral displacements.
4. Explore the new developed methodology and techniques in different areas and domains of transportation engineering.
5. Expand the methodology used in this study to include other parameters such as scale factor, road classification, equipment configuration, and other precise equipment.

Data availability Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

References

Al-Durgham K, Lichti DD, Kwak E, Dixon R (2021) Automated accuracy assessment of a mobile mapping system with lightweight laser scanning and MEMS sensors. Applied Sciences. 11(1007). https://doi.org/10.3390/app11031007

Al-Suleiman T, Obaidat MT, Abdul-Jabbar Ghassan, Khedaywi T (2000) Field inspection and laboratory testing of highway pavement rutting. Canadian Journal of Civil Engineering 27(1):1109–1119

Barber D, Mills J, Smith-Voysey S (2008) Geometric validation of a ground-based mobile laser scanning system. ISPRS J Photogramm Remote Sens 63(1):128–141

Beraldin J-A, Blais F, Lohr U (2010) Laser scanning technology. Chapter 1 of Airborne and Terrestrial Laser Scanning (Vosselman and Maas, eds.), Whittles Publishing, UK.

Campbell DMH, White B, Arp PA (2013) Modeling and mapping soil resistance to penetration and rutting using LiDAR-derived digital elevation data. J Soil Water Conserv 68(6):460–473

Cheng H, Miyojim M (1998) Automatic pavement distress detection system. Inf Sci 108(4):219–240

Darmawati AT (2008) Utilization of multiple echo information for classification of airborne laser scanning data. Master's Thesis, International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, the Netherlands

Dickmanns E, Mysliwetz B (1992) Recursive 3D road and relative ego-state recognition. IEEE Trans Pattern Anal Mach Intell 14(2):199–213

Fröhlich C, Mettenleiter M (2004) Terrestrial laser scanning – new perspectives in 3D surveying. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 36, part 8/W2, Freiburg, Germany, pp. 7–13

Fuentes R, Pauly L, Hogg D (2017) Deeper Networks for Pavement Crack Detection. 34th International Symposium on Automation and Robotics in Construction (ISARC 2017)

Haala N, Peter M, Cefalu A, Kremer J (2008) Mobile LiDAR mapping for urban data capture, In: Loannides, M., Addison, A., Georgopoulos, A., and Kalisperis, L. (eds.), 14th International Conference on Virtual Systems and Multimedia, 95- 100.

Hoffmeister D (2020) Geological records of tsunamis and other extreme waves. Chapter 9 - Mapping of subaerial coarse clasts. Elsevier. https://doi.org/10.1016/C2017-0-03458-4

Liu Z, Wang J, Liu D (2013) A new curb detection method for unmanned ground vehicles using 2D sequential laser data. Sensors 13(1):1102–1120

McGhee KH (2004) Automated pavement distress collection techniques. Transportation Research. Board, Washington, D.C.

Meignen D, Bernadet M, Briand H (1997) One application of neural networks for detection of defects using video data bases: identification of road distresses', IEEE 8th International Workshop on Database and Expert Systems Applications - DEXA, 1–2 September, Toulose, France, 459–464

Oliveira H (2013) Crack detection and characterization in flexible road pavements using digital image processing. Thesis in electrical and computer engineering, Universidade Técnica De Lisboa, Instituto Superior Técnico

Obaidat MT, Al-Suleiman TI, Abdul-Jabbar GT (1997) Quantification of pavement rut depth using stereo vision technology. Journal of Surveying Engineering, American Society of Civil Engineers (ASCE) Geomatics Division 123(2):55–70

Obaidat MT, Shatnawi N, Al Sharideah A (2020) Geomatics techniques for evaluation of road pavement rutting. Applied geomatics. https://doi.org/10.1007/s12518-020-00337-0)

Pierce KB Jr (2015) Accuracy optimization for high resolution object-based change detection: an example mapping regional urbanization with 1-m aerial imagery. Remote Sens 7:12654–12679

Rakitina E, Rakitin I, Staleva V, Arnaoutoglou F, Koutsoudis A, Pavlidis G (2008) An overview of 3D laser scanning technology. In Proc. of the International Scientific Conference,(Varna, Bulgaria)

Rasband WS, Image J. U. S. National Institutes of Health, Bethesda, Maryland, USA, https://imagej.nih.gov/ij/, 1997–2018.

Shahin MY (2005) Pavement for airports, roads, and parking lots. Springer, New York, USA

Shan J, Toth CK (2018) Topographic laser ranging and scanning, Principles and Processing, Second Edition. CRC Press

Shatnawi N (2018) Automatic pavement cracks detection using image processing techniques and neural network. International Journal of Advanced Computer Science and Applications(IJACSA), 9(9), 399- 402

Subirats P, Fabre O, Dumoulin J, Legeay V, Barda D (2004) A combined wavelet-based image processing method for emergent crack detection on pavement surface images. 12th European Signal Processing Conference - EUSIPCO, 6–10 September, Vienna, Austria, 257–260

Tao V, Li J (2007) Advances in mobile mapping technology. Taylor & Francis Group, London

Telling J, Lyda A, Hartzell P, Glennie C (2017) Review of earth science research using terrestrial laser scanning. Earth Sci Rev 169(1):35–68. https://doi.org/10.1016/j.earscirev.2017.04.007

Tsai Y, Ai C, Wang Z, Pitts E (2014) Mobile cross-slope measurement method using Lidar technology. Transportation Research Record: Journal of the Transportation Research Board 2367(1):0361–1981

Tsogas M, Floudas N, Lytrivis P, Amditis A, Polychronopoulos A (2011) Combined lane and road attributes extraction by fusing data from digital map, laser scanner and camera. Information Fusion 12(1):28–36

Vacca G, Deidda M, Dessi A, Marras M (2012) Laser scanner survey to cultural heritage conservation and restoration. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XXXIX-B5: 589—594. DOI ,10.5194/isprsarchives-XXXIX-B5-589-2012

Vallet B, Mallet C (2016) Urban mapping with the mobile mapping technology. Land Surface Remote Sensing in Urban and Coastal Areas , Chapter: 2 , Elsevier. https://doi.org/10.1016/B978-1-78548-160-4.50002-9

Vosselman G, Gorte BGH, Sithole G, Rabbani T (2004) Recognising structure in laser scanner point clouds. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 46, part 8/W2, Freiburg, Germany, 4–6 October, pp. 33–38

Young-Chan S, Cgo NHC, Mun S (2011). Development of mechanistic–empirical design method for an asphalt pavement rutting model using APT. Construction and Building Materials, 25(4), 1685–1690. https://doi.org/10.1016/j.conbuildmat.2010.10.014

Wang K (2000) Design and implementation of automated system for pavement surface distress survey. Journal of Infrastructure System 6(1):24–32

Zhang A, Shaoxing B, Chen A, Liu B, Yang F, Liu J (2008) The international archives of the photogrammetry, remote sensing and spatial information sciences. Vol. XXXVII. Part B1. Beijing

Zhang L, Yang F, Zhang YD, Zhu YJ (2016) Road crack detection using deep convolutional neural network. In Proceedings of the 2016 IEEE International Conference on Image Processing (ICIP), Phoenix, AZ, USA, 25–28 September 2016, 3708–3712

Zhang W, Zhang Z, Qi D, Liu Y (2014) Automatic crack detection and classification method for subway tunnel safety monitoring. Sensors 14(10):19307–19328

Zhou J, Huang P, Chiang F (2005) Wavelet-based pavement distress classification'. Journal of the Transportation Research Board 1940(1):89–98