Field Evaluation of Traffic Performance Measures for Two-Lane Highways in Spain

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ABSTRACT

Two-lane highways operation has been extensively studied. Many of these studies state that the current Highway Capacity Manual (HCM) procedure is difficult to measure in the field. Several promising alternative measures have been proposed which are easy to measure in field, such as the follower density, percent impeded or freedom of flow. Nevertheless, some of these measures are based on hypotheses that may only be applicable to local driver behavior. Moreover, the previous field studies that compared performance measures had very limited traffic flow range and did not compare all these performance measures. The present field study calibrates and evaluates ten performance measures in Spanish two-lane highways.

The data was collected using video recordings in 10 sites on two-lane rural highways in Spain. Observed two-way traffic volumes ranged from 120 to 1,000 veh/h and traffic flows were mainly balanced. From this data, time headways, average travel speed and platooning variables were calculated. The studied performance measures included: average travel speed; average travel speed of passenger cars; percent free-flow speed; percent free-flow speed of passenger cars; percent followers; follower density; percent impeded; average platoon length; traffic intensity; and, freedom of flow.

The results indicated that the follower density had the strongest correlation with traffic variables, with a coefficient of determination of 94%, and it is recommended as major performance measure. The estimations were compared with previous models and they were alike within their observation range. The second best performance measure was the percent followers and the estimates were very similar to the models in Finland. The 2010 HCM overestimated the percent followers at low traffic flows, which could indicate that the extrapolation of medium-high traffic volume driver behavior was not too accurate at our observation range. The other platooning-related variables had lower correlations, while the speed-related measures presented the weakest correlation with traffic variables.
INTRODUCTION

Two-lane highways constitute about 70% of all roads in Spain. Their unique characteristics, derived from the level of interaction between vehicles traveling in the same and in opposing direction, make the evaluation of their traffic operations a complex process. Currently, the Highway Capacity Manual (2010 HCM) of the Transportation Research Board (1) is used for the analysis of the operation on these roads, not only in the US but also in Spain (2).

The 2010 HCM provides an analysis procedure for directional segments of two-lane highways based on the Average Travel Speed (ATS) and Percent-Time-Spent-Following (PTSF). The level of service (LOS) for Class I two-lane highways depends on both values, while the LOS for Class II two-lane highways depends only on PTSF. The percentage of followers (PF), defined as the percentage of vehicles with time headways smaller than 3 seconds, may be used as a surrogate measure for the PTSF (1). The Percent of Free-Flow Speed (PFFS) is introduced as a performance measure for the new Class III two-lane highways, following recommendations from Washburn et al. (3).

Romana and Perez. (4) proposed a threshold speed to determine whether it is more appropriate to define the level of service based on the ATS or on the PTSF. However, the threshold speed was subjective. On the other hand, Luttinen et al. (5) stated that the performance measures should ideally be easy to measure and estimate and should correlate with the traffic conditions in a meaningful way. However, the HCM performance measures are difficult to measure in the field (5-10) and some authors have developed alternative performance measures to overcome this problem and they are discussed below.

LITERATURE REVIEW

Speed-related performance measures

The speed-related performance measures include the average travel speed (ATS), the average travel speed of passenger cars (ATS\(_{pc}\)), the percent of free-flow speed (PFFS) and the percent of free-flow speed of passenger cars (PFFS\(_{pc}\)).

The ATS is the output mean speed and is one of two performance indicators used by the current HCM and in Brazil (11). However, several researchers indicated that it fails to provide an accurate indication of traffic performance (8-10). The ATS\(_{pc}\) is used in Germany as a major performance measure (12) and it replaces the average travel speed in Finland (3, 13), however this speed-related measure was hardly sensitive to traffic flow in some field studies (8-10). Moreover, they also reported weak relationships between ATS, ATS\(_{pc}\), and the flow rate (r\(^2\) between 10 and 13%), and the PFFS and PFFS\(_{pc}\) and flow rate (r\(^2\) lower than 1%). 8-second headway criterion was used to determine free-flow conditions.

Platooning-related performance measures

In addition to the percent-time-spent-following (PTSF) and the percent followers (PF) that are defined at the 2010 HCM, more performance measures have been defined and calibrated with field data. These measures are: follower density (FD), percent impeded (PI), average platoon length (APL), traffic intensity (\(\rho\)), and freedom of flow (\(\eta\)).

The PTSF is the performance measure defined by the HCM, but it is difficult to measure in the field and the percent followers is used as its surrogate measure. Theoretically, low traffic levels could still have high percent followers if speed dispersion is relatively high and passing opportunities are limited; therefore it can be misleading (14). Previous field studies showed good relationship between the percent followers and the flow rate, with coefficient of determination of 73% (7), 79% (8), 30% (10), 93% (16) and 61% (18). The high difference on the study in Egypt (10) may be caused...
by the low traffic volumes or more specific driving behavior. However, the previous field studies only observed low traffic flows (7, 8, 10, 16).

The follower density (FD) is the major performance measure in South Africa (14) and in Japanese expressways (15). It is defined as the number of followers per kilometer per lane and is calculated as the percent followers multiplied by the traffic flow and divided by the travel speed. It showed the best correlation with traffic variables in all the field evaluations (8-10) compared to the speed-related measures and the percent followers (r² between 75% and 98%). Besides, this measure had some degree of correspondence with the analysis of freeways and multilane highways (5, 14).

The percent impeded (PI) estimates the PTSF using a probabilistic approach (7). It is calculated by multiplying the probability of being part of a platoon and the probability of being impeded. The 3-second headway platoon definition is used to calculate the probability of being part of a platoon. The probability of being impeded is calculated at the percentile of the desired speed distribution for all the vehicles that is equal to the average speed of slow-moving vehicles. Platoon leaders are used as the slow-moving vehicles while the distribution of desired speed is calculated using vehicles outside of platoons (6-second headway). This measure presented stronger correlation to traffic flow than the percent followers but it was not compared to other platooning measures. In Egypt (10), the relationship between percent impeded and flow rate was disperse (r² = 22%).

The final three performance measures are based on queuing theory (16) and depend on the average number of headways inside platoons and between platoons (Equations 1, 2). Platoons are identified using 3-second headway. The average platoon length (APL) is the number of vehicles including the leading vehicle, while the traffic intensity (ρ) is the ratio between the average time spent in the first position when waiting for an appropriate gap and the average inter-arrival times at the back of the queue and it represents how busy the system is. The freedom of flow (η) is the ratio between the average travel time between platoons and the expected value of the time interval between the arrival of a fast vehicle into a position behind the slow vehicle and the time when the passing maneuver starts; and it reflects an individual driver’s undisturbed travel time versus the delay in first position resulting from inability to pass. The measures were calibrated to Israel field data (17, 18) and the correlation to traffic flow of the freedom of flow was strong (r² = 93%) while the traffic intensity presented a fair correlation (r² = 62%). The theoretical model assumes that (1) all drivers are rational and are always willing to pass a slower vehicle and that (2) only the first impeded is performing a passing maneuver at one time. This disagrees with actual passing maneuvers field data of other countries that reported considerable number of multiple passing maneuvers (19-22) or faster vehicles’ speed accommodation to the slower vehicle’s speed (22, 23).

\[
\begin{align*}
\rho &= 1 - 1/Q_0 \\
\eta &= N_0/\rho
\end{align*}
\]

Where \( \rho \) = traffic intensity; \( Q_0 \) = average number of headways inside platoons; \( \eta \) = freedom of flow; \( N_0 \) = average number of headways between platoons.

**Passing-related performance measures**

The 2010 HCM provides a qualitative definition of the level of service depending on driver expectations and perceptions of service, which are influenced by the passing capacity and passing demand balance. The passing ratio (or overtaking ratio) was defined by Morral and Werner as the number of passes achieved by the number of passes desired (24) and was considered as a possible performance measure to be included in the 2000 HCM. However, passing ratio would be complicated to measure directly in the field and it was not rated high by HCM users(25).
Research Motivation

Two-lane highways operation has been extensively studied. Many studies state that the current HCM procedure is difficult to measure in field and they propose alternative promising measures which are easy to measure in field, such as the follower density, percent impeded or freedom of flow. However, some of the measures are based on hypotheses that may only be applicable to local driver behavior. Moreover, the previous field studies that compared performance measures had very limited traffic flow range and did not include all the performance measures. The present field study calibrates and evaluates all the defined performance measures using data from Spanish two-lane highways.

OBJECTIVES AND INITIAL HYPOTHESES

The objective of the paper was to calibrate and evaluate performance measures for two-lane rural highways in the same data set. The relationships between the performance measures and the traffic variables were estimated for 10 sites from three Spanish two-lane rural highways.

The performance measures include: average travel speed ($ATS$); average travel speed of passenger cars ($ATSp$); average travel speed as percentage of free-flow speed ($PFFS$); average travel speed of passenger cars as percentage of free-flow speed of passenger cars ($PFFSp$); percent followers ($PF$); follower density ($FD$); percentage of vehicle impeded ($PI$); average platoon length ($APL$); traffic intensity ($\rho$); and freedom of flow ($\eta$). Besides, average travel speed deviation ($ATSdev$) would also be evaluated to confirm the hypothesis of high speed dispersion at low traffic flow.

Based on the literature, the following hypotheses were established:

- Speed-related measures will present weaker relationships with traffic variables compared to platooning-related measures.
- Follower density will present the best correlation with traffic variables.
- Speed dispersion will be higher at low traffic flow.
- Spanish drivers may behave more aggressively than US drivers. Therefore, the percent of followers, follower density or percent impeded may be lower.
- Average platoon length will fail to represent traffic performance because it misinterprets the actual platoon distribution.
- Freedom of flow and traffic intensity will not represent accurately traffic performance as the theoretical hypotheses differ with Spanish driver behavior.

METHODOLOGY

Field study

Data were collected in 10 sites of three highways in the province of Valencia, Spain. The sites were located at the beginning of passing zones. The highways were classified as Class II two-lane highway, according to the 2010 HCM, and were selected to cover as much range of passing zone length, traffic volume and percentage of heavy vehicles as possible. Passing zones’ characteristics were included as selection criteria for another study (23).

Data was collected using two coordinated high definition (HD) video cameras located at the beginning and ending of the passing zones. They were at the roadside and were not perceived by drivers. At some sites, the whole passing zone was covered with the camera and accepted and rejected gaps, passing times and time-to-collision could be calculated (26). The sites characteristics are summarized in Table 1 and the directional splits were mainly balanced: directional splits higher than 40/60 were observed in a 15 % of the sample and higher than 30/70, in 1.7 %.
Table 1 Sites characteristics

<table>
<thead>
<tr>
<th>ID</th>
<th>Highway</th>
<th>Speed limit (km/h)</th>
<th>Annual average daily traffic (veh/day)</th>
<th>Station (km)</th>
<th>Bound</th>
<th>Passing zone length (m)</th>
<th>Two-way traffic volume (veh/h)</th>
<th>Duration (h)</th>
<th>Total directional traffic flow (veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N-225</td>
<td>100</td>
<td>5,925</td>
<td>5.5</td>
<td>Vall</td>
<td>265</td>
<td>120 – 900</td>
<td>9:30</td>
<td>1,614</td>
</tr>
<tr>
<td>2</td>
<td>N-225</td>
<td>100</td>
<td>5,925</td>
<td>5.5</td>
<td>Teruel</td>
<td>510</td>
<td>1,614</td>
<td>1,614</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>N-225</td>
<td>100</td>
<td>5,925</td>
<td>6.1</td>
<td>Vall</td>
<td>1,270</td>
<td>1,614</td>
<td>1,614</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>N-225</td>
<td>100</td>
<td>5,925</td>
<td>6.1</td>
<td>Teruel</td>
<td>1,050</td>
<td>1,614</td>
<td>1,614</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>CV-405</td>
<td>80</td>
<td>15,342</td>
<td>12.0</td>
<td>Monserrat</td>
<td>895</td>
<td>520 - 1,000</td>
<td>2:30</td>
<td>791</td>
</tr>
<tr>
<td>6</td>
<td>CV-405</td>
<td>80</td>
<td>15,342</td>
<td>12.0</td>
<td>Torrent</td>
<td>895</td>
<td>520 - 1,000</td>
<td>2:30</td>
<td>1,073</td>
</tr>
<tr>
<td>7</td>
<td>CV-35</td>
<td>100</td>
<td>5,797</td>
<td>46.5</td>
<td>Casinos</td>
<td>1,690</td>
<td>200 – 450</td>
<td>2:50</td>
<td>445</td>
</tr>
<tr>
<td>8</td>
<td>CV-35</td>
<td>100</td>
<td>5,797</td>
<td>46.5</td>
<td>Losa</td>
<td>1,860</td>
<td>200 – 450</td>
<td>2:50</td>
<td>497</td>
</tr>
<tr>
<td>9</td>
<td>CV-35</td>
<td>100</td>
<td>5,797</td>
<td>42.8</td>
<td>Casinos</td>
<td>780</td>
<td>200 – 450</td>
<td>2:50</td>
<td>445</td>
</tr>
<tr>
<td>10</td>
<td>CV-35</td>
<td>100</td>
<td>5,797</td>
<td>42.8</td>
<td>Losa</td>
<td>1,135</td>
<td>200 – 450</td>
<td>2:50</td>
<td>497</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td>TOTAL</td>
<td>10,224</td>
</tr>
</tbody>
</table>

Data reduction

Traffic volumes, vehicles type, headways and average travel speeds were obtained from the videos. The counting period was 5 minutes and the results were aggregated in 15 minutes as the sum of three overlapping consecutive 5-minute period in order to skip the error of peak 15-minute period overlapped on two 15-minute counting periods (27). Then, equivalent hourly data were calculated based on the 15-minute data. The 15-minute period was chosen over hourly period times in order to better represent passing maneuvers, as peak traffic volumes and traffic proportion are smoothed on hourly periods.

To calculate the average travel speed of each vehicle, the travel time between the beginning and the end of the passing zone was divided by the passing zone length. Platooning measures considered the headways criteria indicated before. To calculate the percent impeded, the average speed of slow-moving vehicles and the speed distribution of isolated vehicles were obtained. The percentile that corresponds to the average was then multiplied by the percent followers.

Statistical analysis

Preliminary analysis of each variable was carried out in order to obtain the probabilistic distribution that best fitted the data. The normal distribution is preferred, as many non-normally distributed dependent variables can distort relationships and significance parametric tests (28). If the variable failed to be normally distributed, they were transformed to the lognormal or inverse to check their normality. The analysis should be carried out by site and across-sites.

A total of 240 preliminary analyses were carried out. Two-way traffic flow, directional traffic flow, opposing traffic flow and follower density were adjusted as lognormal distributions, while the average platoon length and the freedom of flow were inverse distributions and the number of following vehicles followed a negative binomial distribution. The remaining variables were normally distributed. Based on the results of the preliminary analysis, the variables were adjusted to the most suitable probability distribution, that was normal, lognormal or inverse (Table 2).
Table 2. Adjusted distribution of each variable, across-site examination

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>Better Adjustment</th>
<th>Normal Average</th>
<th>Standard deviation</th>
<th>Transformed scale Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-way traffic flow</td>
<td>Log(V)</td>
<td>220</td>
<td>47.92</td>
<td>4.624</td>
<td>0.414</td>
</tr>
<tr>
<td>Traffic proportion</td>
<td>Prop</td>
<td>49.94</td>
<td>7.31</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Direct traffic flow</td>
<td>Log(Vd)</td>
<td>55.38</td>
<td>25.46</td>
<td>3.918</td>
<td>0.438</td>
</tr>
<tr>
<td>Opposing traffic flow</td>
<td>Log(Vo)</td>
<td>55.53</td>
<td>25.55</td>
<td>3.921</td>
<td>0.438</td>
</tr>
<tr>
<td>Percentage trucks</td>
<td>%HGV</td>
<td>14.58</td>
<td>9.47</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average travel speed 100</td>
<td>ATS100</td>
<td>101.19</td>
<td>5.49</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average travel speed 80</td>
<td>ATS80</td>
<td>75.94</td>
<td>2.30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average travel speed PC 100</td>
<td>ATSpc100</td>
<td>102.77</td>
<td>6.20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average travel speed PC 80</td>
<td>ATSpc80</td>
<td>76.22</td>
<td>2.42</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Percent free flow speed</td>
<td>PFFS</td>
<td>0.98</td>
<td>0.04</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Percent free flow speed PC</td>
<td>PFFSpc</td>
<td>1.00</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Following vehicles</td>
<td>NB(FV)</td>
<td>22.09</td>
<td>17.19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Percent followers</td>
<td>PF</td>
<td>35.03</td>
<td>13.52</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Follower density</td>
<td>Log(FD)</td>
<td>0.24</td>
<td>0.27</td>
<td>-1.807</td>
<td>0.895</td>
</tr>
<tr>
<td>Percent impeded</td>
<td>PI</td>
<td>23.64</td>
<td>13.08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average platoon length</td>
<td>1/APL</td>
<td>2.72</td>
<td>0.54</td>
<td>0.381</td>
<td>0.068</td>
</tr>
<tr>
<td>Traffic intensity</td>
<td>ρ</td>
<td>0.36</td>
<td>0.18</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Freedom of flow</td>
<td>1/μ</td>
<td>18.74</td>
<td>25.43</td>
<td>0.130</td>
<td>0.092</td>
</tr>
</tbody>
</table>

Statistical differences

Once the variables were adequately described and the outliers were identified and removed from the sample, we tested whether the dependent variable was statistically different considering each independent variable. As all the variables (or transformed variables) were normal or almost normal, the parametric test (ANOVA) could be applied grouping the variables in levels with approximately equal sample. The percentage of no passing zones failed to provide statistical differences on most of the platooning variables and the percent of free flow speed, while the average travel speed deviation was uniform for all the traffic flows, which disagrees with the theoretical misleading of PTSF estimation of level of service at low traffic flows (14).

Simple linear relationships

Simple linear relationships were tested between the dependent variables and the independent variables, one-to-one. Only the statistically significant variables were tested. The analysis of the residuals plot allowed verifying the normality of the residuals and the homocedasticity. Consequently, the assumptions of the linear regression were fulfilled in all the cases.

The platooning measures were more correlated to the traffic variables than the speed-related measures as their $r^2$ varied between 31% and 76% and between 3 and 9%, respectively. On the other hand, using the directional traffic flow provided higher correlations than the two way traffic flow ($r^2$ increased between 2% and 8%).

Multiple regression analysis

The last phase of the statistical analysis was the multiple regression. The regression models would be trustworthy if the p-value of the F-statistic is lower than 0.05, at a level of confidence of 95%. Moreover, the p-value of the F-statistic of each one of the independent variables must be lower than 0.05. Considering the previous analysis, all the assumptions would be fulfilled and the regression...
models would be valid. The multiple regression analysis was carried out considering two approaches: directional traffic flows and two-way traffic flows; so the results can be compared and discussed with previous research.

**Directional analysis**

The directional analysis considers as independent variables the directional traffic flow, opposing traffic flow, percentage of trucks and percentage of no-passing zones in the analysis segment travel direction. The multiple regression models were fitted using forward stepwise selection. Table 3 shows the equations obtained from the multiple regression analyses.

**Table 3. Directional analysis multiple regression models**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>$R^2$ (%)</th>
<th>$R^2_{adj}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ATS_{100}$</td>
<td>$ATS_{100} = 129.265 - 6.03 \cdot \ln(Vo) - 0.314 \cdot %HGV$</td>
<td>16.54</td>
<td>16.14</td>
</tr>
<tr>
<td>$ATS_{80}$</td>
<td>$ATS_{80} = 87.644 - 2.606 \cdot \ln(Vo)$</td>
<td>9.19</td>
<td>7.48</td>
</tr>
<tr>
<td>$ATSp_{100}$</td>
<td>$ATSp_{100} = 140.12 - 0.555 \cdot \ln(Vo) - 0.288 \cdot %HGV$</td>
<td>16.62</td>
<td>16.22</td>
</tr>
<tr>
<td>$ATSp_{80}$</td>
<td>$ATSp_{80} = 89.295 - 2.912 \cdot \ln(Vo)$</td>
<td>10.22</td>
<td>8.56</td>
</tr>
<tr>
<td>$PFFS$</td>
<td>$PFFS = 1.233 - 0.056 \cdot \ln(Vo) - 0.002 \cdot %HGV$</td>
<td>18.36</td>
<td>18.01</td>
</tr>
<tr>
<td>$PFFSp_{pc}$</td>
<td>$PFFSp_{pc} = 1.113 - 0.030 \cdot \ln(Vo) + 0.001 \cdot %HGV$</td>
<td>34.12</td>
<td>34.84</td>
</tr>
<tr>
<td>$FV$</td>
<td>$FV = \exp(-3.034 + 1.5308 \cdot \ln(Vo) - 0.0051 \cdot %HGV)$</td>
<td>96.61</td>
<td>96.30</td>
</tr>
<tr>
<td>$PF$</td>
<td>$PF = -69.693 + 24.4293 \cdot \ln(Vo)$</td>
<td>62.65</td>
<td>62.57</td>
</tr>
<tr>
<td>$FD$</td>
<td>$\ln(FD) = -9.5670 + 1.9160 \cdot \ln(Vo) + 0.0051 \cdot %HGV$</td>
<td>85.72</td>
<td>85.65</td>
</tr>
<tr>
<td>$FD$</td>
<td>$FD = -0.2083 + 0.0003 \cdot Vd - 0.0003 \cdot Vo + 0.0012 \cdot %HGV$</td>
<td>94.84</td>
<td>94.81</td>
</tr>
<tr>
<td>$PI$</td>
<td>$PI = -36.730 + 15.7006 \cdot \ln(Vo) - 0.1123 \cdot %HGV$</td>
<td>58.69</td>
<td>58.73</td>
</tr>
<tr>
<td>$APL$</td>
<td>$\frac{1}{APL} = 0.663 - 0.0039 \ln(Vo) + 0.001 \cdot %NPZ$</td>
<td>36.00</td>
<td>35.73</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$\rho = 0.117 + 0.174 \cdot \ln(Vo) - 0.002 \cdot %HGV - 0.003 \cdot %NPZ$</td>
<td>33.80</td>
<td>33.34</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$\frac{1}{\mu} = -0.325 + 0.145 \cdot \ln(Vo) - 0.002 \cdot %NPZ$</td>
<td>49.90</td>
<td>49.67</td>
</tr>
</tbody>
</table>

Where: - $ATS_{100}$ = average travel speed at highways with 100 km/h speed limit (km/h); - $ATS_{80}$ = average travel speed at highways with 80 km/h speed limit (km/h); - $ATSp_{100}$ = average travel speed of passenger cars at highways with 100 km/h speed limit (km/h); - $ATSp_{80}$ = average travel speed of passenger cars at highways with 80 km/h speed limit (km/h); - $PFFS$ = percent of free-flow speed; - $PFFSp_{pc}$ = percent of free-flow speed of passenger cars; - $FV$ = followers per period (followers/15-min); - $PF$ = percent followers per period (followers/veh/15-min); - $FD$ = follower density per period (veh/km/15-min); - $PI$ = percent impeded (%/15-min); - $\rho$ = traffic intensity; - $\mu$ = freedom of flow; - $Vd$ = traffic volume on the direction of analysis (veh/15-min); - $Vo$ = traffic volume on the opposing direction (veh/15-min); - $%HGV$ = percentage of trucks and recreational vehicles (%); - $%NPZ$ = percent no passing zones in the analysis segment (%).

The follower density presented the best adjustment to the field data (Figure 1) as the coefficient of determination of the models presented 85% and 94%, respectively. The first model was conducted for the transformed variable, while the second model was carried out for the original variable. The residuals of the model were normally distributed, so the main assumptions of the
multiple regression analysis were fulfilled and the model was valid. The follower density increased as
the directional traffic flow and the percentage of trucks increased and the opposing traffic flow
decreased, which is in agreement with previous models and hypothesis. Based on the simple
regression analysis, the most influential variable was the directional traffic flow, as expected. The
relatively high correlation between direct and opposing traffic flow may explain the low increase on
the coefficient of correlation of the overall model when the opposing traffic flow was added as
variable.

Figure 1. Platooning performance measures models adjustment to field data: (a) follower
density; (b) percent followers; (c) traffic intensity; (d) freedom of flow

The percent followers and the percent impeded were the second best group of measures,
according to the coefficient of determination, 62% and 58%, respectively. Both models did not
depend on the opposing traffic flow, which could be due to the correlation between direct and
opposing traffic flow. The deviation of average travel speed was uniform, which is in accordance with
the low percent followers at very low traffic volume. The percent impeded was supposed to improve
the correlation to traffic but it failed to provide better results than the percent followers. This measure
assumes that the slow-moving vehicles are platoon leaders, but the platoon may be headed by a fast
vehicle followed by another fast vehicle traveling close to its desired speed. Similarly, fast vehicles
are characterized as vehicles outside platoons, and one truck traveling alone can be identified as a fast
vehicle even though its speed can be very low. These two hypotheses may influence the accuracy of
the results, as desired speeds may be lowered and slow-moving average speed may be overestimated.
The probability of being impeded varied between 33.5% and 83.5%, with an average value of 67%.

The third group was composed of Polus and Cohen’s measures (r² between 34 and 50%). This
may be caused because the variables were defined based on theoretical models and the assumptions
were not met in field. For example, 22% of passes were multiple and the models assumed that all vehicles in the queue would be willing to pass. Besides, 7.5% of the sample was removed to calculate the traffic intensity and the freedom of flow because they had a division by zero. After removing those periods from the sample, the freedom of flow presented lower dispersion than the average platoon length and traffic intensity. The freedom of flow decreased as the traffic flow increased, which meant that the system was busier. The traffic intensity shows similar conclusions.

The models with lowest coefficient of determination corresponded with the speed-related measures, with $r^2$ between 8 and 16%. The results were better for the highways with speed limit of 100 km/h, mainly because only two sites with speed limit of 80 km/h were observed and the traffic volume range was narrower. Generally, only passenger cars slightly improved the correlation.

**Two-way analysis**

The two-way analysis considers as independent variables the two-way traffic flow, traffic proportion, percentage of trucks and percentage of no-passing zones. The multiple regression models were fitted using forward stepwise selection, as the directional analysis. Table 4 shows the equations obtained from the multiple regression analyses. The results were similar to the directional analysis, in fact, the coefficient of determination were within 1% lower than the directional analysis. Moreover, the opposing traffic flow was not statistically significant in many of the models which will suggest that the directional analysis may not be that relevant.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>$R^2$ (%)</th>
<th>$R^2_{adj}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATS100</td>
<td>ATS100 = 139.394 - 5.747 ln(Vt) - 0.146 P - 0.308 %HGV</td>
<td>16.68</td>
<td>16.08</td>
</tr>
<tr>
<td>ATS30</td>
<td>ATS30 = 95.160 - 3.690 ln(Vt)</td>
<td>10.95</td>
<td>9.27</td>
</tr>
<tr>
<td>ATSpc100</td>
<td>ATSpc100 = 154.295 - 8.185 ln(Vt) - 0.200 P - 0.279 %HGV</td>
<td>16.61</td>
<td>16.00</td>
</tr>
<tr>
<td>PFS</td>
<td>PFS = 1.320 - 0.555 ln(Vt) - 0.001 P - 0.002 %HGV</td>
<td>18.61</td>
<td>18.09</td>
</tr>
<tr>
<td>PFSpc</td>
<td>PFSpc = 1.164 - 0.028 ln(Vt) - 0.001 P - 0.001 %HGV</td>
<td>34.33</td>
<td>33.91</td>
</tr>
<tr>
<td>FV</td>
<td>FV = exp(-6.066 + 1.581 ln(Vt) + 0.032 P)</td>
<td>95.81</td>
<td>95.50</td>
</tr>
<tr>
<td>PF</td>
<td>PF = -102.564 + 24.313 ln(Vt) + 0.504 P</td>
<td>62.71</td>
<td>62.55</td>
</tr>
<tr>
<td>Log(FD)</td>
<td>ln(FD) = -12.922 + 1.989 ln(Vt) + 0.037 P + 0.006 %HGV</td>
<td>85.90</td>
<td>85.81</td>
</tr>
<tr>
<td>PI</td>
<td>PI = 55.572 + 15.616 ln(Vt) + 0.352 P - 0.112 %HGV - 0.167 %NPZ</td>
<td>58.99</td>
<td>58.65</td>
</tr>
<tr>
<td>1/PL</td>
<td>1/PL = 0.367 - 0.096 ln(Vt) + 0.001 P - 0.001 %HGV</td>
<td>36.33</td>
<td>35.92</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$\alpha = 0.756 + 0.252 ln(Vt) + 0.003 %HGV - 0.003 %NPZ</td>
<td>34.83</td>
<td>34.42</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$\mu = 0.607 + 0.151 ln(Vt) + 0.003 P - 0.002 %NPZ</td>
<td>51.38</td>
<td>51.07</td>
</tr>
</tbody>
</table>

Where:

- $Vt$ = two-way traffic volume (veh/15-min);
- $P$ = traffic proportion on the direction of analysis (%).

The other variables have been previously defined.

**DISCUSSION**

The 10 performance measures models obtained from the statistical analysis were compared to the 2010 HCM estimates and to previous field studies. The field data were used as input data of the models, and directional or two-way models were selected according to the analysis considered on the previous studies. The 15-minute period results from the models were converted to equivalent hourly data. Adequate adjustments for heavy vehicles and grade were used to convert the observed flow rates to the equivalent base conditions of the 2010 HCM. Then, the HCM estimation procedure was applied.

The average travel speed was compared to the 2010 HCM (1) estimate, as the previous field studies failed to provide a statistically significant model for the same speed limit highways (Figure 2). The ATS obtained on field was similar to the HCM estimate in highways with 100 km/h speed limit but the estimates were 9 km/h lower than the field data for 80 km/h highways. The larger differences may suggest that the adjustments for no-passing zones for ATS of 55 mi/h may not be as accurate as the adjustments for no-passing zones for ATS equal to 65 mi/h. It can also be observed that the average travel speed was hardly sensitive to traffic flow, as the reductions on the model were lower than 5 km/h, and that the deviation of average travel speed was almost uniform regardless the traffic flow.

The average travel speed of passenger cars was compared to Luttinen’s models (13) developed for 100 and 80 km/h speed limit Finnish two-lane highways. The Finnish models depended on the directional traffic flow and the opposing traffic flow, and they presented higher ATS\textsubscript{pc} than our field data in highways with 80 km/h speed limit. The values were lower at highways with 100 km/h. Their model was less sensitive to traffic flow than the current study, which may be caused by a lower interaction of platooned vehicles.

On the other hand, the percent free-flow speed was compared to the 2010 HCM estimates, and they were higher than the 2010 HCM estimates. This performance measure was slightly more sensitive to traffic flow than average travel speed. However, the follower criterion was different and the observed highways were classified as Class II highways, where the PFFS is not considered as a performance measure.
Figure 2. Speed-related measures comparison: (a) ATS, (b) ATSpC

Platooning-related performance measures

As the percent followers is the surrogate measure for PTSF, both 2010 HCM PTSF estimates and percent followers were compared. As observed in Figure 3, the estimated PTSF was similar to the percent followers obtained in the field data and the PF model developed in the current research. The average difference between the model prediction and the 2010 HCM estimation was 6%; while the extreme differences were -3.8% and 28%, respectively. The larger differences were produced mainly in the CV-405, where the posted speed limit was 80 km/h, which may suggest that the adjustments for no-passing zones for FFS of 55 mi/h may not be as accurate as the adjustments for no-passing zones for FFS equal to 65 mi/h, as for ATS. Besides, more differences were observed at traffic flows lower than 250 veh/h, which would indicate that the extrapolation of their medium-high traffic volume field data was not too accurate for our observed low traffic flows.

As observed, the PF estimation of the current study was practically equal to the Finnish guidelines (6) even though their model depended on both direct and opposing traffic flow, the percentage of no passing zones and the percentage of heavy vehicles. Some minor differences could be observed for directional traffic flows higher than 500 veh/h, however they observed a maximum one-way traffic volume of 1600 veh/h (13). The second closest guideline was the Brazilian (11), followed by the 2010 HCM (7). The Brazilian model underestimated the percent followers at traffic flows lower than 200 veh/h and overestimated the value for higher traffic flows. Even though the correlation of their model was high, many of the scenarios were generated using traffic simulation and no characteristics of the observed data were given (11).
Figure 3. Percent followers comparison: (a) guidelines; (b) field studies
The current model and previous field studies that considered the percent followers using the 3-second headway criterion were also compared. The studies in Montana (7, 8) estimated similar percent followers to the current study only at their observed traffic flows (between 100 and 200 veh/h). The better adjustment of their second model (8) is caused by the presence of the standard deviation of the free flow speed of the period on the model, which was obtained from our field data and could be slightly different than theirs. On the other hand, the models from Israel (16, 18) and Egypt (10) estimated much lower percent followers than our model, which indicates a lower impact of platooning. This could be caused by a more aggressive behavior of the Israeli and Egyptian drivers or different road characteristics, such as the low percent of heavy vehicles and speed limit of 60 km/h in Egypt. On the other hand, the percent followers was calculated using the theoretical model and one of the hypotheses was that all vehicles that were at a platoon were willing to pass and they would perform a passing maneuver, which would lead to lower percent followers.

The follower density was compared to previous field studies in Montana, Oregon and Egypt, as other studies did not provide the model equation (Figure 4). The prediction of the Oregon model (9) was similar to our model, especially for high traffic flows, while for low traffic flows it provided consistently higher follower density than our observed field data. Reversely, Al-Kaisy and Karjala’s model (8) presented good fit at their observed low traffic flow and their estimate for higher traffic flows was much higher than our observations. The results confirm that the Spanish driver platooning behavior was similar to the observed in US drivers. Similarly to the percent followers, the study from Egypt (10) estimated the lowest follower density and their prediction was negative for one-way traffic flows lower than 200 veh/h, which is a common traffic flow for two-lane rural highways in Spain.

![Figure 4. Follower density comparison](image-url)
The percent impeded was compared to previous models and the results were very different. Firstly, the Egyptian model \((10)\) estimates were lower than the other models and our field data, which can be explained because of the different driver behavior. On the other hand, the differences between the Al-Kaisy and Durbin’s model \((7)\) could be caused by an incorrect report of the model equation due to the high variability of the results, considering that their observations had a coefficient of determination of 98% and the same data set was used to calculate the percent followers, which was more similar to our field data.

The last comparisons were on the performance measures proposed by Polus and Cohen \((16)\). The average platoon length from the current study was very similar to the Polus and Cohen’s model, but the variable presented a high dispersion in the present study. Our freedom of flow was lower than their predictions \((16)\) and our traffic intensity was higher \((16, 18)\), which supports the hypothesis that Spanish drivers were more affected by platooning than Israeli drivers.

**Directional vs. two-way analysis**

All the ten performance measures were calculated using the directional models and the two-way models and then the results were compared.

The directional distribution produced similar coefficients of determination as the two-way analysis, mainly because the observed balanced flows: directional splits higher than 40/60 were observed in a 15% of the sample and higher than 30/70, in 1.7%. The estimates from both analyses were very similar and the opposing traffic flow was only statistically significant on the follower density. For higher traffic flows, the predictions of the two-way analysis were higher than the field data and the directional analysis. The results partially support Luttinen’s hypothesis that the directional analysis include the possible dependence of the performance measures on the opposing traffic flow \((13)\).

**CONCLUSIONS**

Several authors have pointed out the shortcomings of the 2010 Highway Capacity Manual procedure to characterize traffic performance on two-lane rural highways, and they have defined alternative performance measures that are easier to measure in field, such as the follower density or the traffic intensity. This study calibrates 10 performance measures identified in the literature for the same data set. The recording time was 55 hours, with more than 10,000 vehicles identified.

The studied performance measures included: average travel speed; average travel speed of passenger cars; percent free-flow speed; percent free-flow speed of passenger cars; percent followers; follower density; percent impeded; average platoon length; traffic intensity; and, freedom of flow. Both directional and two way analysis were considered and the differences between both analyses were very low, especially at the platooning variables.

The results of the analysis indicated that the follower density had the strongest correlation with traffic variables, with a coefficient of correlation of 94%. The best fitted model depended on the directional traffic flow, the opposing traffic flow and the percent of heavy vehicles. The estimations from the present model were compared with the estimations of previous models and they were similar within their observation range; which can verify that Spanish drivers’ behavior is comparable with US drivers’ behavior.

The next performance measures were the percent followers and the percent impeded, with coefficients of correlation of 62 and 58%, respectively. The percent followers observed in this field study were very similar to Luttinens’ model \((6)\) and slightly lower than the 2010 HCM estimates. Some differences with the 2010 HCM were produced at the highway with posted speed limit of 80 km/h, which may suggest that the adjustments for no-passing zones may not be as accurate as for the
100 km/h speed limit highways. However, the larger differences were detected for directional traffic flows lower than 250 veh/h. This could indicate that the extrapolation of the 2010 HCM for low traffic flows is not too accurate and provides higher percent followers than the observed in the field. Reversely, previous US linear models had similar results at low traffic flows, where their data was observed. This could indicate that the driver behavior in Spain was similar to the US and supports that the 2010 HCM overestimates the percent followers for low traffic flows.

The platooning-related performance measures defined by Polus and Cohen (16) presented higher dispersion and correlations with traffic variables between 33 and 49%, which could indicate that the observed driver behavior was more disperse and may have more influence on the results than their theoretical model expected. Moreover, they predicted less platooning for all their variables than the observed in field, which could be caused by the incompliance of the assumptions of their theoretical model (all drivers will perform a passing maneuver when possible) or by a more aggressive behavior in Israel. Finally, the speed-related measures presented the weakest correlation with traffic variables, and in some cases they were hardly sensitive to traffic flow, which agrees with previous field studies.

The conclusions of this study support the follower density selection as major performance measure, as it presents the strongest correlation to the traffic variables for the observed conditions and it is easy to measure and estimate. This performance measure combines the percent of followers, the average travel speed and the traffic flow. Even though the favorable results may be caused by the dependence of the follower density on the traffic flow, the measure can better represent the overall traffic performance than the percent-time-spent-following or its surrogate, the percent followers. The conclusions may be limited to the observed conditions and two-way traffic flows higher than 1,000 veh/h or directional traffic flows higher than 600 veh/h could provide different results, as well as skew directional distributions or two-way highways with speed limit different than 80 or 100 km/h; however, they could be used to develop two-lane highway simulation models and analytical methodologies to establish levels of service based on the follower density or better adjustments to the 2010 HCM procedure.

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