# Predicting Operating Speeds at Urban Multilane Roundabouts in Abu Dhabi, United Arab Emirates 

Mohammad Almoarawi and Essam Dabbour (D)<br>Department of Civil Engineering, Abu Dhabi University, P.O. Box 59911, Abu Dhabi, UAE<br>Correspondence should be addressed to Essam Dabbour; edabbour@hotmail.com

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#### Abstract

There are more than 460 multilane roundabouts located in Abu Dhabi, the capital city of the United Arab Emirates, and its surrounding areas. Most of those roundabouts have three entry/circulatory/exit lanes with large radii, which resulted in the majority of drivers exceeding the speed limits for those roundabouts. Those excessive operating speeds, along with lack of drivers' awareness of the proper rules of driving at roundabouts, have resulted in increased collision frequencies at Abu Dhabi roundabouts. In this paper, operating speeds were measured at 12 roundabouts in Abu Dhabi and those collected speed observations were used to calibrate regression models to predict the 85th percentile operating speeds at roundabouts in Abu Dhabi. Predicting operating speed at a roundabout, during its design stage, is necessary to ensure that the expected operating speed and capacity will meet the design expectations. Three models were calibrated to predict the entry, circulating, and exit speeds, respectively. The calibrated models were validated with data not used in calibration and they were found to be stable and robust. The findings of this research study will help engineers when designing new roundabouts in Abu Dhabi or other cities with similar characteristics. This research study also provides a methodological framework for other researchers when conducting similar speed studies for roundabouts in other cities or metropolitan areas around the world.


## 1. Introduction

Roundabouts are very common in the United Arab Emirates with more than 460 roundabouts located in its capital city Abu Dhabi and its surrounding suburban areas. Most of those roundabouts have three entry/circulatory/exit lanes with large radii and large operating speeds.

Previous research studies found a correlation between operating speeds at roundabouts and the frequency and severity of collisions at those roundabouts [1-4]. Therefore, predicting the potential operating speed at a roundabout, during its design stage, is vital to ensure that the expected operating speed will meet the design expectations and the safety target for that roundabout. Furthermore, the capacity of a roundabout is highly correlated with critical time headways and follow-up times selected by drivers [5-9], which are related to the operating speed at the roundabout [ $2,10-14]$. Therefore, predicting the operating speed will also help in estimating the potential capacity of the roundabout
being designed and ensure that the capacity meets the design requirements and the expected traffic volume. Predicting the operating speed will also help in estimating emissions [1517]. Finally, precise prediction of the operating speed is also needed for different software applications related to traffic simulation.

A speed prediction model for US roundabouts [2, 18] is based on the assumption that the operating speed at any segment of the roundabout is correlated with the radius of the vehicle path at that segment. This approach is similar to an earlier prediction model for operating speeds at Australian roundabouts [19]. Džambas et al. [20] found similar correlation between vehicle speeds at turbo roundabouts and the radius of vehicle path. Another approach for speed prediction models was developed for Italian roundabouts [21] where the predicted operating speed was found to be correlated with the diameter of the inscribed angle, the width of the circulatory roadway, and the width of the entry lane. Pilko et al. [22] measured operating speeds at four single-lane roundabouts
in the City of Zagreb, the capital city of Croatia, where they found correlation between entry speed and entry radius. Similar correlations were also observed between circulating speed and circulating radius and between exit speed and exit radius.

This paper presents regression models that predict the operating speeds at three-lane roundabouts in the city of Abu Dhabi, the capital city of the United Arab Emirates, based on the traffic hourly volumes and the geometric characteristics of the roundabouts. Radar guns were used to measure speeds of all vehicles, with different paths, at 12 three-lane roundabouts in the city Abu Dhabi and its surrounding suburban areas. Hourly traffic volumes and the geometric characteristics related to those roundabouts were all obtained from Abu Dhabi Department of Municipal Affairs and Transport. The following section provides details on data collection, followed by another section that provides details on how the developed models were calibrated and validated. Conclusions and recommendations for future research are also provided.

## 2. Data Collection

Operating speeds of individual vehicles were measured at 12 three-lane roundabouts in Abu Dhabi and its surrounding suburban areas. The speeds were measured using Bushnell Velocity speed guns [23], which are capable of measuring vehicle speeds from $16 \mathrm{~km} / \mathrm{h}$ to $322 \mathrm{~km} / \mathrm{h}$ at a range up to 457 m . All the roundabouts in the sample had three entry/circulatory/exit lanes, which represent the majority of roundabouts in Abu Dhabi and its surrounding suburban areas. Figure 1 shows satellite images of the roundabouts included in the sample. It must be noted that all the roundabouts in the sample were designed according to the UAE geometric design guide, which is mainly derived from the US design guide [18]. There is currently a newer design guide for Abu Dhabi urban streets, which is Abu Dhabi Urban Street Design Manual [24]. That manual started to be implemented in 2011. However, all the roundabouts included in the sample were designed according to the older design guide that was derived from US design guide [18].

Hourly traffic volumes, proportions of heavy vehicles (including buses and heavy trucks), and the geometric characteristics of the roundabouts were all obtained from Abu Dhabi Department of Municipal Affairs and Transport. The hourly traffic volumes and proportions of heavy vehicles obtained from Abu Dhabi Department of Municipal Affairs and Transport were all based on real-time sensor data that were collected within a month before the experiments; and therefore, they were believed to be up-to-date data at the time of the experiments. There were four roundabouts in the sample where traffic volumes and the proportions of heavy vehicles were not available from the Department of Municipal Affairs and Transport. For those four roundabouts, manual counting was used to obtain hourly traffic volumes and the proportions of heavy vehicles. The hourly traffic volumes used for this study included the morning traffic volume, $V_{m}$, the afternoon traffic volume, $V_{a}$, and the evening traffic volume, $V_{e}$. The proportions of heavy vehicles were observed during the morning, $\mathrm{PHV}_{m}$, the afternoon, $\mathrm{PHV}_{a}$, and the
evening, $\mathrm{PHV}_{e}$. Table 1 shows the traffic and geometric characteristics of the roundabouts included in this study. Figure 2 shows the typical locations of the entry radius, $R_{1}$, the radius of the central island, $R_{2}$, the exit radius, $R_{3}$, and the diameter of the inscribed circle, $D_{I}$.

For every possible vehicle path within a roundabout (turning right, turning left, going through, or making a U turn), speeds were typically measured at the following three areas shown in Figure 2:
(a) The entry speed along the entry path arc, with the radius of the vehicle path, is mainly determined by the entry radius $R_{1}$.
(b) The circulating speed around the inscribed circle, with the radius of the vehicle path, is mainly determined by the radius of the central island, $R_{2}$.
(c) The exit speed along the exit path arc, with the radius of the vehicle path, is mainly determined by the exit radius $R_{3}$.

To ensure the highest level of precision in measuring the speeds, the speed guns were placed as close as possible at collision course with the target vehicles to minimize the angle of incidence and therefore eliminate the cosine effect [25]. This is illustrated in Figure 2, which shows that the speed guns were placed at point " $A$ " to measure entry speeds, point " $B$ " to measure circulating speeds, and point " $C$ " to measure exit speeds. To avoid sampling bias, the speed of only the first vehicle was measured in cases when vehicles were traveling in platoons.

For every roundabout, vehicle speeds were measured during four different weekdays. Since weekend in Abu Dhabi is typically Friday and Saturday, speeds were typically measured on Mondays, Tuesdays, and Wednesdays. For each day, vehicle speeds were measured during one hour in the morning (between 7:30 AM and 9:30 AM), one hour in the afternoon (between 2:30 PM and 4:30 PM), and one hour in the evening (between 6:30 PM and 8:30 PM). Due to the weather and travel habits in Abu Dhabi, the hours during which speeds were measured are within the morning, afternoon, and evening peak-hour periods as per the data provided by Abu Dhabi Department of Municipal Affairs and Transport.

There were a total of 38,764 speed observations obtained for all the sites. For every site, the 85th percentile entry/circulating/exit speeds were calculated from those speed observations during every observation hour. The 85th percentile speed is the speed at which $85 \%$ of drivers drive at or below that speed [26]. The 85th percentile speed is the most frequently used descriptive statistics for the operating speed associated with a particular location or geometric feature [27]. Since vehicle speeds were measured in each site for three hours on four different weekdays, there were 12 different values observed for the 85th percentile entry/circulating/exit speeds for each site. Those values are shown in Table 2, which shows the 85th percentile speed during the morning hour, $V_{85 m}$, during the afternoon hour, $V_{85 a}$, and during the evening hour, $V_{85 e}$. Based on this, for each of the entry, circulating, and exit speeds, there


Figure 1: Satellite images of the sites selected for the study (map data ©2018 Google).
Table 1: Traffic and geometric characteristics.

| Site | Area | Latitude | Longitude | $R_{1}$ <br> $(\mathrm{~m})$ | $R_{2}$ <br> $(\mathrm{~m})$ | $R_{3}$ <br> $(\mathrm{~m})$ | $D_{I}$ <br> $(\mathrm{~m})$ | $V_{m}$ <br> $(\mathrm{vph})$ | $V_{a}$ <br> $(\mathrm{vph})$ | $V_{e}$ <br> $(\mathrm{vph})$ | $\mathrm{PHV}_{m}$ | $\mathrm{PHV}_{a}$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | | $\mathrm{PHV}_{e}$ |
| :---: |

Table 2: Observed 85th percentile operating speeds.

| Site | Day 1 |  |  | Day 2 |  |  | Day 3 |  |  |  |  |  | Mean | Std. Dev. | Speed Limit |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $V_{85 m}$ | $V_{85 a}$ | $V_{85}$ | $V_{85 m}$ | $V_{85 a}$ | $V_{85 e}$ | $V_{85 m}$ | $V_{85 a}$ | $V_{85 e}$ | $V_{85 m}$ |  | $V_{85}$ |  |  |  |
| 1 (Entry) | 26.7 | 32.4 | 29.7 | 25.4 | 33.1 | 30.6 | 28.8 | 34.5 | 31.2 | 27.4 | 33.7 | 32.9 | 30.5 | 2.8 | 40 |
| 1 (Circ.) | 30.4 | 36.1 | 32.8 | 32.5 | 38.9 | 34.7 | 35.1 | 40.2 | 38.6 | 34.4 | 41.5 | 37.6 | 36.1 | 3.2 | 40 |
| 1 (Exit) | 32.4 | 37.1 | 33.6 | 33.5 | 41.2 | 36.5 | 38.2 | 44.2 | 41.0 | 36.9 | 40.1 | 34.5 | 37.4 | 3.5 | 40 |
| 2 (Entry) | 28.7 | 33.1 | 30.4 | 29.6 | 34.8 | 33.2 | 32.2 | 35.8 | 33.6 | 36.2 | 39.5 | 37.4 | 33.7 | 3.1 | 40 |
| 2 (Circ.) | 33.2 | 36.8 | 35.2 | 35.1 | 38.6 | 37.4 | 34.7 | 39.2 | 37.4 | 30.2 | 33.2 | 31.8 | 35.2 | 2.7 | 40 |
| 2 (Exit) | 37.9 | 41.2 | 40.5 | 38.9 | 36.1 | 35.7 | 36.8 | 42.5 | 39.7 | 34.7 | 36.5 | 33.9 | 37.9 | 2.6 | 40 |
| 3 (Entry) | 40.6 | 43.2 | 44.8 | 41.5 | 45.6 | 46.7 | 41.2 | 44.7 | 48.3 | 40.1 | 42.5 | 46.7 | 43.8 | 2.6 | 50 |
| 3 (Circ.) | 42.3 | 44.1 | 45.2 | 40.8 | 44.3 | 43.8 | 40.1 | 42.7 | 46.0 | 39.7 | 41.4 | 44.8 | 42.9 | 2.0 | 50 |
| 3 (Exit) | 45.2 | 47.5 | 48.1 | 46.8 | 48.5 | 44.3 | 43.2 | 44.4 | 48.9 | 41.1 | 40.1 | 42.8 | 45.1 | 2.8 | 50 |
| 4 (Entry) | 44.7 | 48.3 | 50.1 | 43.9 | 46.2 | 44.5 | 47.2 | 46.1 | 50.3 | 48.3 | 50.7 | 51.6 | 47.7 | 2.5 | 50 |
| 4 (Circ.) | 46.0 | 49.3 | 51.2 | 44.5 | 45.6 | 48.7 | 49.1 | 45.5 | 51.1 | 48.3 | 52.5 | 54.6 | 48.9 | 3.0 | 50 |
| 4 (Exit) | 48.3 | 52.1 | 53.4 | 48.7 | 46.3 | 50.7 | 53.4 | 48.9 | 52.7 | 49.3 | 54.6 | 55.8 | 51.2 | 2.8 | 50 |
| 5 (Entry) | 28.4 | 33.4 | 31.8 | 29.6 | 34.8 | 33.5 | 33.0 | 34.7 | 32.6 | 37.1 | 30.4 | 31.9 | 32.6 | 2.3 | 40 |
| 5 (Circ.) | 32.4 | 34.5 | 33.6 | 30.1 | 36.7 | 39.5 | 34.8 | 35.0 | 34.6 | 38.7 | 31.2 | 33.6 | 34.6 | 2.6 | 40 |
| 5 (Exit) | 34.5 | 36.8 | 38.7 | 31.5 | 36.9 | 41.2 | 37.0 | 36.4 | 35.9 | 40.1 | 33.5 | 39.7 | 36.9 | 2.7 | 40 |
| 6 (Entry) | 39.8 | 44.5 | 43.6 | 41.8 | 48.6 | 45.7 | 42.3 | 44.5 | 48.7 | 45.0 | 47.8 | 43.2 | 44.6 | 2.6 | 50 |
| 6 (Circ.) | 42.6 | 48.7 | 44.6 | 47.6 | 47.6 | 46.9 | 44.3 | 47.8 | 50.2 | 47.8 | 49.6 | 51.3 | 47.4 | 2.4 | 50 |
| 6 (Exit) | 44.7 | 51.8 | 46.3 | 52.7 | 53.2 | 51.4 | 45.3 | 48.2 | 51.4 | 48.9 | 52.3 | 53.7 | 50.0 | 3.1 | 50 |
| 7 (Entry) | 42.1 | 48.9 | 44.6 | 50.2 | 51.3 | 50.8 | 44.6 | 47.9 | 50.7 | 49.3 | 50.7 | 51.2 | 48.5 | 3.0 | 40 |
| 7 (Circ.) | 44.6 | 51.2 | 47.9 | 53.0 | 53.4 | 51.7 | 48.9 | 49.0 | 53.6 | 51.4 | 53.2 | 54.8 | 51.1 | 2.8 | 40 |
| 7 (Exit) | 46.9 | 53.8 | 49.1 | 55.3 | 56.8 | 53.7 | 51.2 | 49.8 | 55.6 | 52.3 | 55.4 | 57.8 | 53.1 | 3.2 | 40 |
| 8 (Entry) | 39.7 | 37.4 | 38.1 | 36.5 | 34.1 | 33.8 | 32.8 | 33.9 | 34.7 | 30.8 | 32.5 | 33.6 | 34.8 | 2.5 | 40 |
| 8 (Circ.) | 37.1 | 34.2 | 33.3 | 36.1 | 30.2 | 29.8 | 28.7 | 26.9 | 27.8 | 28.6 | 30.7 | 27.4 | 30.9 | 3.3 | 40 |
| 8 (Exit) | 38.3 | 35.4 | 31.9 | 37.5 | 31.6 | 32.1 | 29.4 | 27.8 | 28.6 | 29.0 | 33.1 | 28.5 | 31.9 | 3.4 | 40 |
| 9 (Entry) | 36.1 | 31.5 | 33.8 | 35.6 | 34.7 | 30.8 | 29.7 | 28.4 | 27.3 | 26.8 | 27.0 | 28.6 | 30.9 | 3.3 | 40 |
| 9 (Circ.) | 35.1 | 34.6 | 33.7 | 33.6 | 32.7 | 30.1 | 31.4 | 28.4 | 27.6 | 26.8 | 27.8 | 26.3 | 30.7 | 3.1 | 40 |
| 9 (Exit) | 34.8 | 35.6 | 34.1 | 33.2 | 33.1 | 28.9 | 29.7 | 28.7 | 29.0 | 31.0 | 30.8 | 27.4 | 31.4 | 2.6 | 40 |
| 10 (Entry) | 36.1 | 37.4 | 38.0 | 35.3 | 33.8 | 34.7 | 33.1 | 34.8 | 36.0 | 30.1 | 31.2 | 33.2 | 34.5 | 2.2 | 40 |
| 10 (Circ.) | 37.0 | 39.1 | 40.1 | 37.4 | 35.0 | 36.7 | 34.1 | 33.8 | 39.8 | 30.8 | 32.4 | 33.9 | 35.8 | 2.9 | 40 |
| 10 (Exit) | 40.1 | 41.2 | 43.6 | 39.8 | 38.6 | 37.8 | 39.0 | 34.7 | 42.5 | 33.6 | 37.4 | 36.9 | 38.8 | 2.8 | 40 |
| 11 (Entry) | 32.1 | 29.7 | 28.6 | 28.4 | 27.0 | 26.9 | 30.4 | 31.2 | 28.6 | 30.7 | 33.1 | 31.8 | 29.9 | 1.9 | 40 |
| 11 (Circ.) | 34.8 | 35.6 | 38.1 | 40.2 | 39.8 | 41.5 | 38.6 | 42.3 | 41.8 | 36.9 | 42.7 | 41.6 | 39.5 | 2.6 | 40 |
| 11 (Exit) | 39.6 | 42.3 | 44.7 | 46.9 | 47.2 | 44.3 | 40.8 | 45.6 | 43.6 | 39.6 | 45.7 | 44.0 | 43.7 | 2.5 | 40 |
| 12 (Entry) | 38.4 | 37.6 | 41.0 | 45.6 | 44.2 | 40.8 | 41.2 | 44.3 | 42.1 | 38.6 | 37.6 | 39.0 | 40.9 | 2.6 | 40 |
| 12 (Circ.) | 39.1 | 40.2 | 43.6 | 44.2 | 43.8 | 41.3 | 42.9 | 41.7 | 43.0 | 39.6 | 38.5 | 41.0 | 41.6 | 1.9 | 40 |
| 12 (Exit) | 44.2 | 45.3 | 46.8 | 47.2 | 45.0 | 43.6 | 47.2 | 44.3 | 45.6 | 47.6 | 41.2 | 43.1 | 45.1 | 1.9 | 40 |



Figure 2: Example of speed measuring locations at a multilane roundabout.
were a total of 144 observed values of the 85 th percentile speeds for all the 12 sites. From those 144 observations, 108 observations were used to calibrate the prediction models for entry/circulating/exit speeds, and the remaining 36 observations were used to validate those calibrated models.

For each roundabout in the sample, the controlling speed limit is also shown in Table 2. The controlling speed limit is the lowest speed limit posted on the four roads intersecting at the given roundabout. As shown in Table 2, the measured mean speeds exceed the posted speed limits in 4 roundabouts, representing $33.33 \%$ of the sample size. The mean values of the entry/circulating/exit speeds in all the sites are $37.7 \mathrm{~km} / \mathrm{h}$, $39.6 \mathrm{~km} / \mathrm{h}$, and $41.9 \mathrm{~km} / \mathrm{h}$, respectively. Those values are higher than those found in literature for roundabouts in other countries [28]. In a previous research study to measure the 85th percentile speeds at 98 roundabout approaches in the United States [29], it was found that the mean 85th percentile entering speed was $34.9 \mathrm{~km} / \mathrm{h}$ (with a standard deviation of $3.9 \mathrm{~km} / \mathrm{h}$ ). In another study to measure the 85th percentile speeds at 7 roundabouts in Italy [21], the mean 85th percentile circulating speed was found to be $34.9 \mathrm{~km} / \mathrm{h}$ (with a standard
deviation of $6.3 \mathrm{~km} / \mathrm{h}$ ). Kim and Choi [1] measured the 85th percentile operating speeds at 14 roundabouts in South Korea where they found that the mean entry, circulating, and exit speeds, along with their respective standard deviations, were $(26.3 \pm 5.2) \mathrm{km} / \mathrm{h},(23.2 \pm 4.0) \mathrm{km} / \mathrm{h}$, and $(27.0 \pm 6.3) \mathrm{km} / \mathrm{h}$, respectively. Rubio-Martín et al. [30] presented a case study for a single-lane roundabout in Spain where the mean values and standard deviations of entry, circulating, and exit speeds were estimated to be $(35.1 \pm 4.3) \mathrm{km} / \mathrm{h},(33.3 \pm 4.6) \mathrm{km} / \mathrm{h}$, and ( $38.4 \pm 7.6$ ) km/h, respectively. Pilko et al. [22] measured operating speeds at four single-lane roundabouts in the City of Zagreb, the capital city of Croatia, where they found those operating speeds to be typically below $33.9 \mathrm{~km} / \mathrm{h}$. Several other studies found that vehicle speeds at turbo roundabouts are typically below $40 \mathrm{~km} / \mathrm{h}$ [20, 31, 32]. Based on these studies, the measured operating speeds at Abu Dhabi roundabouts are typically higher than those in other parts of the world. Those excessive speeds seem to be mainly attributed to the use of large radii used in Abu Dhabi roundabouts. As an example, Table 1 shows that the mean value of the inscribed circle diameter in Abu Dhabi is $(78.59 \pm 11.96)$ m. By

Table 3: Developed speed prediction models.

| Parameter | Coefficient | $t$-stat |
| :--- | :---: | :---: |
| Predicting entry speed: |  |  |
| Intercept | 35.622 | 9.806 |
| Entry radius ${ }^{(\mathrm{a})}:\left(R_{1}\right)^{0.8}$ | 1.754 | 8.510 |
| Hourly traffic volume: $(V)^{0.5}$ | -0.595 | -9.506 |
| Proportion of heavy vehicles: $(\mathrm{PHV})^{0.2}$ | -14.728 | -3.156 |
| Coefficient of determination $\left(R^{2}\right)$ | 0.675 | - |
| Significance of $f$ statistic | 0.000 | - |
| Standard error | 3.245 | - |
| Predicting circulating speed: |  |  |
| Intercept | 36.971 | 17.514 |
| Radius of the central island ${ }^{(\mathrm{a})}:\left(R_{2}\right)^{0.8}$ | 1.885 | 14.521 |
| Hourly traffic volume: $(V)^{0.5}$ | -0.456 | -8.446 |
| Proportion of heavy vehicles: $(\mathrm{PHV})^{0.2}$ | -19.531 | -6.124 |
| Coefficient of determination $\left(R^{2}\right)$ | 0.787 | - |
| Significance of $f$ statistic | 0.000 | - |
| Standard error | 2.734 | - |
| Predicting exit speed: |  |  |
| Intercept | 35.729 | 8.314 |
| Exit radius ${ }^{(\mathrm{a})}:\left(R_{3}\right)^{0.8}$ | 1.914 | 7.443 |
| Hourly traffic volume: $(V)^{0.5}$ | -0.378 | -5.218 |
| Proportion of heavy vehicles: $(\mathrm{PHV})^{0.2}$ | -36.616 | -5.847 |
| Coefficient of determination $\left(R^{2}\right)$ | 0.646 | - |
| Significance of $f$ statistic | 0.000 | - |
| Standard error | 3.611 | - |
| See |  |  |

${ }^{(a)}$ See Figure 2 for the typical locations of the entry radius, the radius of the central island, and the exit radius.
comparison, the mean values of the inscribed circle diameter in South Korea and Serbia were $(37.88 \pm 14.08) m$ and $(36.20 \pm$ 1.47 ) m , respectively $[1,33]$. More strict design standards may be needed to be implemented for roundabouts in Abu Dhabi to force drivers to reduce their speeds.

## 3. Speed Prediction Models

Multiple linear regression was used to calibrate the prediction models [34], which takes the form:

$$
\begin{equation*}
y=\beta_{0}+\beta_{1} x_{1}+\beta_{2} x_{2}+\cdots+\beta_{k} x_{k}+\varepsilon \tag{1}
\end{equation*}
$$

For the purpose of this research, the dependent variable, $y$, in the above equation is the estimated 85 th percentile entry, circulating, or exit speed. The independent variables $\left(x_{1}, x_{2} \cdots x_{k}\right)$ are the hourly traffic volumes, the percentages of heavy vehicles, and the different geometric characteristics of the roundabouts, as shown in Table 1. The regression coefficients ( $\beta_{0}, \beta_{1}, \beta_{2} \cdots \beta_{k}$ ) are calculated using the leastsquare method. The error term, $\varepsilon$, accounts for random variation in the dependent variables, $y$, not fully explained by the independent variables.

Several combinations of independent variables were attempted to develop the regression models. The final models that best fit the data are shown in Table 3 where $V$ is the hourly traffic volume (vehicles per hour) and PHV is the proportion of heavy vehicles. Different power combinations were also attempted for the selected independent variables to maximize the coefficients of determination, $R^{2}$, and minimize
the validation errors. After several attempts, it was decided to use the power values shown in Table 3 that include a power value of 0.8 for the geometric radii, 0.5 for the hourly traffic volume, and 0.2 for the proportion of heavy vehicles. In all the three developed models, the coefficients of all independent variables are significantly different from zero at 0.05 significance level. The residual plots of the independent variables exhibited random dispersion around the horizontal axis in all models, indicating a constant variance of errors. The models shown in Table 3 have logical explanations for the effect of different independent variables on the estimated speed. The positive sign associated with the curve radius coefficient suggests that the speed increases with the increase of the horizontal curve radius, which is consistent with most vehicle dynamics models found in literature and design guides [2, 18, 19, 21, 35]. The negative sign associated with the hourly traffic volume coefficient suggests that the speed decreases with the increase of the traffic volume due to the decrease in vehicle spacing which is also consistent with most traffic flow models [11, 36, 37]. Finally, the negative sign associated with the proportion of heavy vehicles suggests that the speed decreases with the increase of the proportion of heavy vehicles since heavy vehicles usually move at lower speeds when negotiating roundabouts $[2,22,38]$. The values associated with the coefficients of determination $\left(R^{2}\right)$ shown in Table 3 are mainly comparable with those found in similar prior research studies [1, 22, 39, 40].

As was aforementioned, there were 36 speed observations reserved to validate the developed models. The validation statistics for all the models are shown in Table 4. The statistics shown include the sum of errors, the sum of squared errors, the mean squared errors, and the root-mean squared errors. As shown in Table 4, the sums of errors are small indicating that the errors are fluctuating around a zero value. Furthermore, the root-mean squared errors for all models are small with values close to the standard errors associated with model calibration as shown in Table 3. Based on these statistical measures, it could be concluded that the developed models are stable and robust when being validated with data not used in calibration.

As was discussed in the previous section, the observed operating speeds at Abu Dhabi roundabouts are mainly larger than those observed at roundabouts in several other countries including South Korea [1], Spain [30], Croatia [22], Italy [21], and the United States [2,29]. The authors of this study are not aware of any other speed prediction models where traffic volumes or the proportions of heavy vehicles are used as predictors. However, it is expected that the operating speeds predicted by the models developed in this study will be typically higher than those predicted by other models. This is due to the fact that the models developed in this study are calibrated using data where higher operating speeds are observed.

## 4. Conclusions

In this paper, regression models were developed to predict the 85th percentile operating speeds at multilane roundabouts in

Table 4: Validation statistics of the speed prediction models.

| Site | Observed speed |  |  | Predicted speed |  |  | Error |  |  | Squared error |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Entry | Circ. | Exit | Entry | Circ. | Exit | Entry | Circ. | Exit | Entry | Circ. | Exit |
| 1 | 27.4 | 34.4 | 36.9 | 29.8 | 32.4 | 34.0 | -2.4 | 2.0 | 2.9 | 5.6 | 4.2 | 8.6 |
|  | 37.3 | 40.5 | 40.1 | 38.2 | 38.9 | 39.7 | -0.9 | 1.6 | 0.4 | 0.8 | 2.5 | 0.2 |
|  | 32.9 | 37.6 | 38.5 | 35.7 | 37.8 | 40.8 | -2.8 | -0.2 | -2.3 | 7.6 | 0.0 | 5.5 |
| 2 | 32.6 | 32.0 | 34.7 | 30.9 | 32.9 | 36.1 | 1.7 | -0.9 | -1.4 | 2.9 | 0.8 | 2.0 |
|  | 39.5 | 39.2 | 40.5 | 40.3 | 40.2 | 42.6 | -0.8 | -1.0 | -2.1 | 0.6 | 1.1 | 4.2 |
|  | 37.4 | 38.1 | 42.3 | 39.6 | 40.7 | 45.4 | -2.2 | -2.6 | -3.1 | 5.0 | 6.9 | 9.4 |
| 3 | 37.1 | 39.7 | 41.1 | 35.8 | 40.2 | 40.6 | 1.3 | -0.5 | 0.5 | 1.7 | 0.2 | 0.3 |
|  | 37.9 | 44.1 | 41.0 | 39.6 | 43.3 | 43.8 | -1.7 | 0.8 | -2.8 | 2.9 | 0.6 | 8.0 |
|  | 43.7 | 44.8 | 48.2 | 42.1 | 45.6 | 46.7 | 1.6 | -0.8 | 1.5 | 2.7 | 0.6 | 2.3 |
| 4 | 38.3 | 42.3 | 40.9 | 37.9 | 41.1 | 41.8 | 0.4 | 1.2 | -0.9 | 0.2 | 1.4 | 0.8 |
|  | 43.3 | 45.2 | 45.6 | 42.0 | 44.5 | 45.2 | 1.3 | 0.7 | 0.4 | 1.6 | 0.4 | 0.2 |
|  | 41.6 | 45.6 | 45.8 | 42.8 | 45.4 | 46.7 | -1.2 | 0.2 | -0.9 | 1.5 | 0.0 | 0.8 |
| 5 | 27.8 | 33.7 | 33.1 | 28.7 | 33.3 | 34.2 | -0.9 | 0.4 | -1.1 | 0.8 | 0.2 | 1.2 |
|  | 34.0 | 36.2 | 35.3 | 34.1 | 37.4 | 37.7 | -0.1 | -1.2 | -2.4 | 0.0 | 1.5 | 5.7 |
|  | 39.1 | 39.6 | 39.7 | 37.7 | 41.4 | 44.0 | 1.4 | -1.8 | -4.3 | 2.0 | 3.2 | 18.7 |
| 6 | 43.0 | 42.8 | 41.9 | 39.7 | 42.9 | 42.9 | 3.3 | -0.1 | -1.0 | 10.9 | 0.0 | 1.0 |
|  | 47.8 | 46.9 | 48.1 | 45.2 | 47.4 | 47.1 | 2.6 | -0.5 | 1.0 | 6.6 | 0.2 | 1.0 |
|  | 43.2 | 48.3 | 50.7 | 45.0 | 47.6 | 48.4 | -1.8 | 0.7 | 2.3 | 3.3 | 0.5 | 5.4 |
| 7 | 39.1 | 41.4 | 42.3 | 37.7 | 41.9 | 39.7 | 1.4 | -0.5 | 2.6 | 1.9 | 0.2 | 6.7 |
|  | 40.7 | 43.9 | 44.5 | 42.3 | 45.7 | 43.6 | -1.6 | -1.8 | 0.9 | 2.6 | 3.3 | 0.8 |
|  | 41.1 | 44.8 | 47.1 | 40.2 | 44.5 | 43.8 | 0.9 | 0.3 | 3.3 | 0.8 | 0.1 | 11.2 |
| 8 | 30.8 | 28.6 | 31.9 | 31.0 | 28.2 | 33.0 | -0.2 | 0.4 | -1.1 | 0.1 | 0.1 | 1.2 |
|  | 35.2 | 32.7 | 36.1 | 36.5 | 32.6 | 37.0 | -1.3 | 0.1 | -0.9 | 1.7 | 0.0 | 0.7 |
|  | 36.3 | 29.4 | 38.5 | 35.1 | 31.9 | 37.3 | 1.2 | -2.5 | 1.2 | 1.5 | 6.1 | 1.4 |
| 9 | 28.6 | 28.6 | 31.9 | 30.6 | 28.2 | 33.3 | -2.0 | 0.4 | -1.4 | 4.1 | 0.1 | 2.1 |
|  | 33.7 | 28.7 | 38.0 | 34.2 | 31.1 | 36.3 | -0.5 | -2.4 | 1.7 | 0.2 | 6.0 | 2.9 |
|  | 38.6 | 36.1 | 37.4 | 36.5 | 33.4 | 39.4 | 2.1 | 2.7 | -2.0 | 4.5 | 7.3 | 3.9 |
| 10 | 33.1 | 33.8 | 43.1 | 33.2 | 34.1 | 40.4 | -0.1 | -0.3 | 2.7 | 0.0 | 0.1 | 7.3 |
|  | 41.1 | 42.3 | 47.3 | 39.4 | 39.1 | 45.2 | 1.7 | 3.2 | 2.1 | 2.8 | 10.0 | 4.4 |
|  | 38.2 | 39.3 | 46.9 | 39.1 | 39.1 | 45.6 | -0.9 | 0.2 | 1.3 | 0.9 | 0.0 | 1.7 |
| 11 | 31.7 | 39.6 | 39.6 | 32.5 | 38.9 | 39.6 | -0.8 | 0.7 | 0.0 | 0.7 | 0.4 | 0.0 |
|  | 42.1 | 46.1 | 47.5 | 40.3 | 45.2 | 45.7 | 1.8 | 0.9 | 1.8 | 3.3 | 0.7 | 3.4 |
|  | 38.1 | 46.1 | 44.9 | 39.9 | 45.2 | 46.1 | -1.8 | 0.9 | -1.2 | 3.3 | 0.9 | 1.4 |
| 12 | 36.8 | 39.6 | 46.7 | 35.1 | 39.1 | 43.2 | 1.7 | 0.5 | 3.5 | 2.9 | 0.3 | 12.3 |
|  | 42.6 | 48.5 | 51.2 | 44.3 | 46.3 | 49.7 | -1.7 | 2.2 | 1.5 | 2.9 | 4.7 | 2.3 |
|  | 40.3 | 45.0 | 53.1 | 43.8 | 46.3 | 50.7 | -3.5 | -1.3 | 2.4 | 12.1 | 1.8 | 6.0 |
| Sum of errors |  |  |  |  |  |  | -4.8 | 1.4 | 5.4 |  |  |  |
| Sum of squared errors |  |  |  |  |  |  |  |  |  | 102.7 | 66.6 | 144.8 |
| Mean squared error |  |  |  |  |  |  |  |  |  | 10.1 | 8.2 | 12.0 |
| Root-mean squared error |  |  |  |  |  |  |  |  |  | 3.2 | 2.9 | 3.5 |

Abu Dhabi, United Arab Emirates. Three models were developed to predict the entry, circulating, and exit speeds. The speeds are predicted based on the hourly traffic volumes, the proportions of heavy vehicles, and the geometric characteristics of the roundabouts. The models were validated with data not used in calibration and they were found to be stable and robust. The developed models will help roundabout designers to adjust their designs to ensure that the expected operating speeds will meet the design requirements. The developed
models will also help in predicting the potential capacities of multilane roundabouts that are being designed to ensure that the capacities meet the design requirements and the expected traffic volumes. Finally, the developed models will also help developers of traffic simulation applications by providing realistic estimates for operating speeds that may be implemented in those applications. Based on the observations collected in this research, it was found that most roundabouts were overly designed, which resulted in operating speeds that
exceed those found in other countries around the world. It must be noted that the developed models are based on the unique characteristics and attitudes of drivers in the United Arab Emirates. Further research may be needed to develop other models for other countries where driver characteristics and attitudes are different from those found in the United Arab Emirates.

## Additional Points

Highlights. (i) Speed prediction models were developed for multilane roundabouts in Abu Dhabi. (ii) Separate models were developed for entry, circulating, and exit speeds. (iii) Predicted speeds are based on traffic and geometric characteristics. (iv) Speeds at Abu Dhabi roundabouts exceed those in many other cities in the world.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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