Research Article

Evaluation of Posted Speed Limits Reductions on Urban Roads with a High Percentage of Cyclists

Jaclyn S. Schaefer[1] ⬤**, Miguel A. Figliozzi[1]** ⬤**, and Avinash Unnikrishnan[1]** ⬤

Abstract
This paper presents a before and after analysis of the impact of posted speed limit (PSL) changes on passenger car (FHWA class 2 vehicle) speeds in Portland, Oregon. The study focuses on urban roads, comparing sites that underwent a PSL 5-mph reduction (treatment sites) and sites where the PSL did not change (control sites). Sites with a high percentage of and priority for cyclists (neighborhood greenways) and sites with a more standard traffic composition were compared. Differences in speed characteristics such as mean and 85th percentile speeds, the speed variance, and the proportion of vehicles exceeding a speed threshold (relative to the PSL) were evaluated on aggregate and individual scales. A series of statistical hypothesis tests were employed to assess changes in the speed characteristics among individual data set pairs. The results suggest distinct differences between the treatment and control groups and neighborhood greenway and non-greenway sites. Although there is a high degree of variability, the treatment group experienced more decreases in the speed characteristics, and by a greater amount than the control group, on average. Within the treatment group, sites with a priority for cyclists were even more likely to experience a larger reduction in operating speeds. These results could be interpreted as link-level data providing indirect yet supporting evidence for the safety in numbers hypothesis and changes in motorists' behavior on neighborhood greenways.

Speed limits throughout the U.S. are typically set by state legislation and determined based on the roadway functional class and geographic area. Traditionally, in zones where these statutory limits are deemed inappropriate because of specific traffic, roadway, or safety factors, speed limits are established by conducting an engineering study.

In the U.S., traditional guidance from the *Manual on Uniform Traffic Control Devices* (MUTCD) (*1*) states that when an engineering study is conducted, the speed limit should be set within 5 mph of the 85th percentile speed of free-flowing traffic (note that new versions of the MUTCD are likely to incorporate a different type of guidance or language). The belief supporting the utilization of the 85th percentile speed is that the majority of drivers naturally choose safe and reasonable speeds according to the given conditions and setting the limit near the speed at or below which 85% of drivers travel improves compliance and reduces the burden of enforcement.

The 85th percentile speed used to have wide acceptance and support as the basis for setting speed limits, particularly within the U.S.; however, alternative methods such as the Safe System approach have been the practice in parts of Europe and Asia since the late 1990s (*2*). In more recent years, the assumption that drivers are aware of and select the safest speed for all users of the road has received a great level of scrutiny. It has also

[1]Transportation Technology and People (TTP) Lab, Department of Civil and Environmental Engineering, Portland State University, Portland, OR

Corresponding Author:
Miguel A. Figliozzi, figliozzi@pdx.edu

been argued that setting the posted speed limit (PSL) based on 85th percentile speeds is likely to generate an upward drift in operating speeds over time (*3*). Additionally, the 85th percentile speed methodology is heavily weighted toward motor vehicles and does not balance multimodal needs. As such, alternative speed zoning guidelines that are drastically different from the traditional method are being proposed within the U.S. For example, the proliferation of Vision Zero campaigns (a Safe System approach) has led many U.S. cities to act toward lowering speed limits, especially in urban and residential areas where there are high numbers of active travelers. On roadways with a high percentage of active users, a more balanced approach may result in fewer crashes and fatalities, as well as better driving, bicycling, and walking environments. However, excessively reducing speed limits on roadways without the appropriate roadway and traffic characteristics may negatively affect mobility and the overall level of safety.

Many previous studies have attempted to determine which contextual, geometric, or environmental factors may influence operating speeds (*4–7*), but few of them have included variables related to active travel or analyzed sites where active travel is prevalent. In addition, only a low number of these studies were concentrated on urban environments or those with a high percentage of active travelers.

The focus of this research is to examine the effects of a 5-mph PSL reduction on urban roads with a high percentage of cyclists, that is, when cyclists represent more than 15% of the roadway traffic, usually on shared-use roadways that are also designated as neighborhood greenways. Speed studies conducted at the same locations before and after a PSL reduction (treatment sites) were compared with repeat studies performed at locations where the PSL did not change (control sites). Performance measures evaluated included the mean and 85th percentile speeds, the speed variance, and the proportion of vehicles exceeding a speed threshold (relative to the PSL). The findings from this study may help guide speed zoning decisions in urban areas with a high percentage of cyclists.

Literature Review

Previous research has suggested several factors that may influence operating speeds. For example, factors such as the lane or road width, the number of lanes, and segment length have been positively associated with operating speeds (*4, 5*).

Negative associations have been observed between operating speed and access density or the density of roadside objects, such as trees and poles (*4, 6, 7*). Few studies have considered variables pertaining to active

travel. Positive associations have been observed between operating speed and the presence of bicycle lanes or routes (*5, 7*), and a negative association between operating speed and the presence of pedestrian crossings has been observed (*7*).

One of the most important factors to influence operating speeds is the PSL. From a study of suburban arterial roads, Fitzpatrick et al. (*6*) indicated that the PSL was the only statistically significant variable out of several geometric and roadway variables examined which affect operating speeds on straight segments. Himes et al. (*8*) also discovered the influence of the PSL, suggesting that it explains 82% of the variation in operating speed on urban and rural highways. In both studies, positive relationships between operating speed and the PSL were observed.

Despite the associations between speed and the PSL, a decrease in the PSL is not likely to produce an equivalent decrease in operating speeds. A meta-analysis on the relationship between changes in the PSL and changes in the mean traffic speed revealed a high degree of variability in outcomes. The research suggested that a 10 km/h (6.2 mph) reduction in the PSL would likely produce a reduction in the mean traffic speed of 2.5 km/h (1.6 mph) (*9*). Guidance on speed management policies has also advised that the average change in mean operating speed will be approximately one-quarter of the change in the speed limit when no other interventions have been performed (*2*).

The variability in speed outcomes relating to PSL reductions can be demonstrated with two studies. Islam et al. (*10*) found that mean speeds on urban residential roads were reduced by nearly 4–5 km/h (2.5–3 mph) 3 and 6 months after the PSL was decreased from 50 km/h (31 mph) to 40 km/h (25 mph), while speeds at control sites showed an increasing trend. Conversely, Hu and Cicchino (*11*) did not observe a significant difference in the mean or 85th percentile speeds after the default PSL in Boston was lowered from 30 mph to 25 mph. The proportions of vehicles exceeding speed thresholds of 25 mph, 30 mph, and 35 mph did decrease, however. The results of Islam et al. (*10*) and Hu and Cicchino (*11*) indicate that speed reductions are contingent on other factors in addition to the PSL. Enforcement expectations, marketing campaigns, and social norms may also influence a driver's choice of speed (*12, 13*) and it is necessary to control for such effects in studies such as those discussed previously to better isolate the roles of the studied factors.

Although the current MUTCD guidance is to set the PSL within 5 mph of the 85th percentile operating speed, adjustments are permitted for risk factors related to road geometry, the pace speed, roadside development, parking practices, pedestrian activity, and crash experience (*1*).

There are no specific considerations for bicyclists or other active travelers (e.g., electric scooters), however.

Expert systems approaches to setting speed limits attempt to simplify the process by relying on data-driven approaches and decision rules to produce consistent recommendations. Research by Fitzpatrick et al. (*14*) has recently created a speed limit setting spreadsheet tool that helps users make informed decisions related to establishing speed limits. However, the tool does not offer specific guidance for roads with a high percentage of active travelers.

The MUTCD and expert systems approaches are heavily weighted toward motorized vehicles, basing PSL recommendations on the observed speed of motorized traffic. While these approaches may be appropriate for higher functionally classed roadways or in rural environments, urban environments are much more complex because of increased opportunities for conflict and multimodal travel. New guidance from the Oregon Department of Transportation (ODOT) suggests that basing the PSL on the 50th percentile speed is more appropriate in urban environments. Vulnerable users and the type of facilities available to them should be considered when making changes (*15*). Alternatively, under the Safe Systems approach, PSLs are determined by what is safest for all people using the road, and infrastructure is built to support that speed. The National Association of City Transportation Officials (NACTO) offers guidance for setting PSLs through the Safe Systems approach (*16*). However, the outcomes of these updated or alternative guidelines for setting PSLs have not been thoroughly studied or evaluated.

The literature also indicates that the percentage and number of cyclists on roadways have an impact on safety outcomes. This is commonly known as the "safety in numbers" effect which indicates that the likelihood of an individual cyclist being injured decreases as the number of cyclists increases (*17*). Traffic calming and reducing speed limits improves safety and increases walking and cycling volumes (*18*). In addition, lower motorized vehicle speeds increase cyclists' comfort (*19*). Therefore, there is likely a positive feedback loop among increased cycling safety, higher cycling volumes, and lower motorized traffic speeds. A meta-analysis of cycling safety studies indicates there is clear evidence supporting the safety in numbers hypothesis for active travelers but also indicates that no study has controlled properly for all potential confounding factors (*20*).

The general lack of previous research on setting PSLs on urban roads with a high percentage of active travelers emphasizes the need for the current study. The current study assesses the outcomes of a 5-mph reduction in the PSL on operating speeds, with a focus on urban roads with high bicycle volumes.

Data

Speed data were collected by the Portland Bureau of Transportation (PBOT) from 2011 to 2019 using pneumatic tubes configured to classify vehicles according to the FHWA Scheme F (*21*) and to record speed in 1-mph increments. Data sets were collected from 39 directional sites for a minimum of two survey periods. More than two surveys were performed at 11 of the sites. The data collection produced 95 unidirectional data sets. Using all possible combinations of the repeat survey data sets, 80 before–after pairs were produced for comparison. Changes to the PSL occurred between subsequent surveys in 43 of the pairs. These pairs are henceforth referred to as treatment pairs. No changes were made to the PSL between repeat surveys in the remaining 37 pairs, which are referred to as control pairs.

Treatment locations were selected so that they were not adjacent to each other and sharing the exact same roadway characteristics to avoid spatial correlations. Control locations were selected based on the proximity to treatment locations and similarity of roadway characteristics. Roadway characteristics considered included geometry and traffic control as well as proximity to stop signs or traffic signals, transit and pedestrian activity, parking and sidewalk presence and geometry, pedestrian crossings, topography, and land use. No specific traffic enforcement operations were noted for any location during the survey periods, but PBOT did begin a citywide speed safety education campaign in the spring of 2018 which included advertisements via billboards, buses, movie theaters, and social media channels.

Table 1 summarizes the basic characteristics of the 43 treatment and 37 control data set pairs. The PSL shown for the treatment pairs is the PSL during data collection of the subsequent, "after" survey. For treatment pairs, the initial, "before" PSL was posted 5-mph higher than during the "after" survey at all sites.

Table 1 shows that most of the data set pairs analyzed were from locations along lower-classed roadways (local and urban collector) with lower speed limits in the range of 20–25 mph. Two-thirds of the data set pairs were from shared road facilities. All the shared road facilities studied within this research correspond to streets that are designated as neighborhood greenways. Neighborhood greenways are residential streets with low motorized traffic volumes and speeds where priority is given to active travelers such as cyclists. Accordingly, cyclists tend to comprise a higher share of the total traffic on these streets. These streets are posted at 20–25 mph and are classified as local or urban collectors, correlating to the abundance of data set pairs in Table 1 sharing those basic characteristics. Neighborhood greenways have several other characteristics that differentiate them from non-greenway roads. Neighborhood greenways are

Table 1. Summary of the Basic Characteristics of the Data Set Pairs

	Treatment	Control
Functional class		
Local	20	10
Urban collector	16	24
Minor arterial	1	0
Principal arterial	6	3
Bike facilities		
Shared	30	24
No facility	4	10
Bike lane*	9	3
Posted speed limit (PSL)**		
35	0	1
30	7	2
25	2	20
20	34	14

* Includes bike lanes with increased spatial separation from traffic (buffered).
**For treatment pairs, the PSL of the "after" data set is given.

identified by signage and the presence of sharrows (shared lane pavement markings), while continuous centerline markings are absent. Neighborhood greenways also feature a varying mix of traffic calming measures such as speed humps, circles, and diverters which are used to manage motorized traffic speed and volume (*22*).

Traffic calming measures are generally implemented based on need, but all neighborhood greenways studied in this research featured at least one of these traffic calming measures. Examples of a neighborhood greenway and a non-greenway from this study are displayed in Figure 1.

Class 2 observations (passenger cars) were retained for analysis as they are the predominant motorized vehicle type. Histograms were constructed to inspect for normally distributed speeds. Differences between the mean and median speeds were also calculated to check for deviations from normal distributions. In all data sets, the differences between the mean and median speeds were less than 1 mph.

For each data set, a preliminary exploration was conducted, whereby class 2 observations were aggregated into 15-min intervals. The mean speed, mean gap time between vehicles, and the vehicle count were calculated for each 15-min interval. Scatterplots of the mean gap time or vehicle count versus the mean speed were created to investigate relationships between these metrics. A distinct pattern difference was revealed between data sets from neighborhood greenways and those from non-greenways. Non-greenway data sets exhibited evidence of a positive relationship between mean speed and mean gap time or a negative relationship between mean speed and vehicle count. Conversely, these relationships were

Figure 1. Example of (*a*) a neighborhood greenway and (*b*) a non-greenway.
Source: Google Street View.

absent in almost all (97%) of the neighborhood greenway data sets. More details on the relationship between mean speed and mean gap time can be found in Figliozzi et al. (*23*).

Analysis Methods

Differences in performance measures from before to after were evaluated between aggregated data sets and between individual data set pairs. Multiple performance measures were selected and investigated to provide a broad overview of the operating speed behaviors in the data sets. The performance measures varied slightly between the aggregate and individual analyses and are discussed in the subsequent sections.

Aggregate Analysis

To calculate differences on the aggregate level, data sets were aggregated according to whether they were part of a treatment or control pair, the PSL at the time of the survey, and the neighborhood greenway designation. The decision to separate data sets by neighborhood greenway designation was guided by the results of the preliminary data exploration, suggesting there may be distinct differences in speed behavior between the two categories. Additionally, the neighborhood greenway designation was used as a proxy to distinguish sites with a high percentage of cyclists from sites with more typical percentages. Performance measures were computed for each aggregation, and differences were calculated as the after value minus the before value. Therefore, a negative difference represents a decrease in the performance measure statistic, and a positive difference represents an increase in the performance measure statistic.

Performance measures examined included the mean and 85th percentile speeds, the pace (i.e., the 10-mph range containing the most observations), the percentage of vehicles within the pace, and the percentage of vehicles exceeding three speed thresholds. The speed thresholds were defined as (i) the PSL of the after period, (ii) the PSL of the after period plus 5 mph, and (iii) the PSL of the after period plus 10 mph.

Individual Analysis

Differences in the mean and 85th percentile speeds, the speed variance, and the proportion of vehicles exceeding the PSL of the after data set were compared among individual data set pairs using a series of hypothesis tests, described in the following sections. A 95% confidence level was used for all hypothesis tests. For $p < 0.05$, the null hypothesis is rejected, suggesting the alternative hypothesis is true. If $p \geqslant 0.05$, the sample data fail to reject the null. Note that for control pairs, the PSL of the after data set is equal to the PSL of the before data set. For all hypothesis tests henceforward, the subscripts B and A symbolize the before and after conditions, respectively.

Mean Speed Hypothesis Tests. The statistical significance of differences in mean speeds from the before condition to the after condition was assessed using Welch two-sample *t*-tests. Two hypotheses were tested for all data set pairs in the treatment and control groups.

The first null hypothesis and its alternative were selected to indicate whether the mean speeds of the before and after conditions were equal (H_0: $\mu_B - \mu_A = 0$) or if the mean speed of the after condition was greater than the before condition (H_A: $\mu_B - \mu_A < 0$).The second null hypothesis and its alternative were chosen to test if the mean speed in the after condition decreased by 1.25 mph compared with the before condition (H_0: $\mu_B - \mu_A = 1.25$), or if the mean speed decreased by more than 1.25 mph from before to after (H_A: $\mu_B - \mu_A > 1.25$). The value of 1.25 mph was chosen as the threshold for the second null hypothesis based on research by Elvik (*9*), which concluded that a 1:4 ratio of the change in mean operating speed to the change in the PSL could be expected for a 5-mph reduction in the PSL.

85th Percentile Speed Hypothesis Tests. The 85th percentile operating speed has traditionally been used as an important input when setting speed limits in the U.S. Thus, the magnitude or direction of change in the 85th percentile speed is of interest to this study. A modified *t*-test was used to determine the significance of differences in the 85th percentile speeds from the before condition to the after condition. Details of the test can be found in Hou et al. (*24*).

Two null hypotheses were tested, constructed similarly to those for mean speeds. The first null hypothesis tested whether the 85th percentile speeds were equal from before to after (H_0: $\zeta_{85,B} - \zeta_{85,A} = 0$), with the alternative (H_A: $\zeta_{85,B} - \zeta_{85,A} < 0$) suggesting the 85th percentile speed was higher in the after period.

The second test was selected to indicate whether the 85th percentile speed of the after condition was 1.25 mph lower than the before condition (H_0: $\zeta_{85,B} - \zeta_{85,A} = 1.25$), or if the 85th percentile speed was reduced by more than 1.25 mph from before to after (H_A: $\zeta_{85,B} - \zeta_{85,A} > 1.25$).

Speed Variance Hypothesis Test. The equivalence of speed variance between the before and after periods for all data sets was analyzed using an F-test, H_0: $\sigma_B^2 = \sigma_A^2$. Here, a rejection of the null would suggest the speed variance

Table 2. Performance Measure Averages for All Data Sets Included in a Treatment Pair, Grouped by PSL and Greenway Status

	PSL	Mean	85th	% exc. 30 mph	% exc. 35 mph	% exc. 40 mph	Pace*	% in pace
Non-greenways								
Before (*N* = 4)	35	34.37	39.25	80.39	44.30	10.76	30.25	71.34
After (*N* = 5)	30	33.15	37.40	75.01	29.15	5.51	28.80	75.99
Difference	0.00	−1.22	−1.85	−5.38	−15.15	−5.25	−1.45	4.65
Before (*N* = 2)	30	27.28	31.50	66.41	22.96	3.62	23.00	74.68
After (*N* = 2)	25	25.34	29.50	48.02	10.76	1.43	20.50	77.68
Difference	0.00	−1.94	−2.00	−18.39	−12.20	−2.20	−2.50	3.00
Before (*N* = 4)	25	20.26	25.25	47.78	14.25	2.05	15.50	70.35
After (*N* = 2)	20	20.26	24.50	48.06	11.98	1.91	15.50	73.60
Difference	0.00	0.00	−0.75	0.29	−2.28	−0.14	0.00	3.25
Neighborhood greenways								
Before (*N* = 22)	25	21.30	25.00	59.84	13.34	1.17	17.07	82.70
After (*N* = 22)	20	19.51	23.06	39.74	7.02	0.63	15.00	82.85
Difference	0.00	−1.78	−1.94	−20.10	−6.32	−0.53	−2.07	0.15

Note: PSL = posted speed limit; 85th = 85th percentile; exc. = exceeding; *N* = the number of data sets averaged; na = not applicable.
*Lower limit of the 10-mph range.

either increased or decreased in the after period compared with before (H_A: $\sigma_B^2 \neq \sigma_A^2$).

Proportion Exceeding Speed Threshold Hypothesis Test. The proportions of vehicles exceeding a defined speed threshold were compared for all treatment and control pairs using a chi-square test. In the chi-square test, the null hypothesis states that the proportion of class 2 vehicles exceeding the speed threshold in the before data set is equal to the proportion of class 2 vehicles exceeding the speed threshold in the after data set, H_0: $P_B - P_A = 0$. Rejection of the null would indicate that the percentage of vehicles traveling at speeds higher than the threshold either decreased or increased in the after period (H_A: $P_B - P_A \neq 0$). For this hypothesis test, the PSL of the data set from the after period was chosen as the speed threshold. Thus, for control pairs, the speed threshold is also equal to the PSL of the before data set.

Results

Aggregated Data Sets

The results for the treatment data sets are provided in Table 2. Note that the number of before data sets may not necessarily be equal to the number of after data sets because of performing more than two surveys at some locations. Within the treatment data sets, the percentage of vehicles within the pace increased for each speed group. Neighborhood greenway sites showed consistent decreases in all other performance measure categories. In other words, on average, operating speeds and the percentage of vehicles exceeding the speed thresholds were

reduced in the after period. Similar trends of decreased speeds and percentage of vehicles exceeding the speed thresholds were observed for most of the remaining, non-greenway treatment groups, although the low numbers of data sets within these groups do not allow for any broad conclusions to be drawn.

Table 3 shows the results of the aggregated data set analysis for the control groups. Small to negligible changes within the performance measures were observed for the control groups. There does not appear to be a trend in either direction for the changes observed. In general, the magnitude of differences from before to after was larger in the treatment groups than the control groups, particularly when considering the percentages exceeding the speed thresholds.

Individual Data Sets

A summary of the hypothesis testing results is displayed in Table 4. The table shows the percentage of data sets that rejected the null hypothesis for each test. The results are categorized according to the treatment or control groups, as well as by the neighborhood greenway designations to facilitate comparisons.

Mean Speeds. The first null hypothesis tested, stating that the means of the before and after periods are equal, produced significant results ($p < 0.05$) for four out of the 43 treatment pairs tested (9.3%). The results indicate that mean speeds increased in the after period, despite a decrease in the PSL. Increases in mean speeds ranged from 0.3 mph to 1.4 mph. All four results rejecting the

Table 3. Performance Measure Averages for All Data Sets Included in a Control Pair, Grouped by PSL and Greenway Status

	PSL	Mean	85th	% exc. 35 mph	% exc. 40 mph	% exc. 45 mph	Pace*	% in pace
Non-greenways								
Before (*N* = 1)	35	35.29	41.00	49.36	15.05	2.94	31.00	69.21
After (*N* = 1)	35	35.18	40.00	48.47	14.10	2.49	31.00	69.07
Difference	0.00	−0.11	−1.00	−0.89	−0.95	−0.45	0.00	−0.14
Before (*N* = 2)	30	32.76	37.50	71.60	26.94	5.65	28.50	73.18
After (*N* = 2)	30	32.88	37.00	72.59	25.95	5.00	28.50	76.05
Difference	0.00	0.12	−0.50	0.99	−0.98	−0.66	0.00	2.87
Before (*N* = 4)	25	19.69	25.00	11.90	1.71	0.14	15.25	68.66
After (*N* = 4)	25	19.28	24.25	10.45	1.44	0.16	14.50	70.08
Difference	0.00	−0.41	−0.75	−1.45	−0.27	0.02	−0.75	1.42
Before (*N* = 5)	20	21.40	25.80	58.74	18.34	3.26	16.80	72.63
After (*N* = 5)	20	20.95	25.40	55.20	15.41	2.22	16.60	74.13
Difference	0.00	−0.45	−0.40	−3.54	−2.93	−1.04	−0.20	1.50
Neighborhood greenways								
Before (*N* = 14)	25	20.23	23.93	7.74	0.47	0.04	15.93	83.41
After (*N* = 14)	25	20.28	23.71	7.25	0.43	0.02	16.00	83.45
Difference	0.00	0.05	−0.21	−0.48	−0.04	−0.02	0.07	0.04
Before (*N* = 7)	20	19.69	23.49	40.86	7.77	0.74	15.07	81.67
After (*N* = 7)	20	19.38	22.91	38.17	6.80	0.73	15.07	81.05
Difference	0.00	−0.31	−0.57	−2.69	−0.97	−0.01	0.00	−0.62

Note: PSL = posted speed limit; 85th = 85th percentile; exc. = exceeding; *N* = the number of data sets averaged; na = not applicable.
*Lower limit of the 10-mph range.

Table 4. Percentage of Treatment and Control Data set Pairs Producing Statistically Significant Results for All Hypothesis Tests

Hypothesis test	Neighborhood greenway		Non-greenway		Combined	
	Cont.	Treat.	Cont.	Treat.	Cont.	Treat.
H_0: $\mu_B - \mu_A = 0$ H_A: $\mu_B - \mu_A < 0$	37.5	0.0	15.4	30.8	29.7	9.3
H_0: $\mu_B - \mu_A = 1.25$ H_A: $\mu_B - \mu_A > 1.25$	8.3	73.3	7.7	38.5	8.1	62.8
H_0: $\zeta_{85,B} - \zeta_{85,A} = 0$ H_A: $\zeta_{85,B} - \zeta_{85,A} < 0$	12.5	0.0	7.7	7.7	10.8	2.3
H_0: $\zeta_{85,B} - \zeta_{85,A} = 1.25$ H_A: $\zeta_{85,B} - \zeta_{85,A} > 1.25$	12.5	73.3	15.4	38.5	13.5	62.8
H_0: $\sigma_B^2 = \sigma_A^2$ H_A: $\sigma_B^2 > \sigma_A^2$	25.0	36.7	46.2	69.2	32.4	46.5
H_0: $\sigma_B^2 = \sigma_A^2$ H_A: $\sigma_B^2 < \sigma_A^2$	33.3	20.0	7.7	7.7	24.3	16.3
H_0: $P_B - P_A = 0$ H_A: $P_B - P_A > 0$	29.2	100.0	38.5	61.5	32.4	88.4
H_0: $P_B - P_A = 0$ H_A: $P_B - P_A < 0$	20.8	0.0	15.4	15.4	18.9	4.7

Note: Cont. = control; Treat. = treatment.

null occurred at sites that are not designated as neighborhood greenways. Bike lanes were present in two of the data sets. No bicycle facilities were present in the other two data sets.

In the control group, there were 11 pairs out of 37 tested (29.7%) that rejected the null hypothesis. Increases ranged from 0.2 mph to 2.3 mph. Nine of the 11 significant results were from locations carrying a neighborhood greenway designation.

Testing of the second null hypothesis, stating the mean speed of the before condition is 1.25 mph greater than the mean speed of the after condition, yielded significant
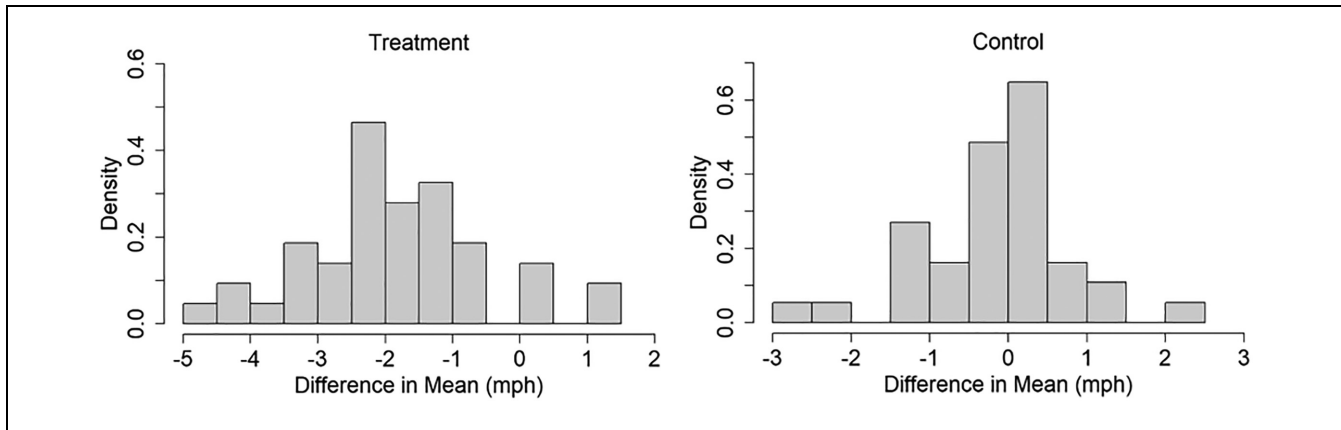
Figure 2. Histograms depicting the change in mean speeds from before to after for all treatment pairs (left) and all control pairs (right).

results for 27 of the 43 treatment pairs (62.8%), of which 22 were collected from designated neighborhood greenways. Decreases in mean speed up to approximately 4 and 5 mph were observed at a few locations.

In comparison with the large number of significant results in the treatment group, only three out of 37 pairs from the control group (8.1%) were observed to reject the second null hypothesis, suggesting that mean speeds did not decrease by more than 1.25 mph at most sites.

The differences in mean speeds for all data sets, regardless of hypothesis test outcomes, can be visualized by the histograms in Figure 2, showing the treatment data sets on the left, and the control data sets on the right. From these histograms, it is clear that mean speeds in the treatment group were more likely to decrease and by a greater magnitude than those of the control group.

85th Percentile Speeds. Only one of the 43 treatment pairs (2.3%) showed a statistically significant increase in the 85th percentile speed, rejecting the null hypothesis that the before and after 85th percentile speeds were equal. This data set pair also showed a statistically significant increase in mean speed. The 85th percentile speeds for this data set pair were 37 mph and 38 mph for the before and after periods, respectively.

Four of the 37 control pairs (10.8%) yielded significant results for the first null hypothesis for the 85th percentile speeds (H_0: $\zeta_{85,B}$–$\zeta_{85,A} = 0$); three of these are designated neighborhood greenways. All four of these control pairs also showed statistically significant increases in the mean speed. Increases in 85th percentile speeds of 1–3 mph were observed.

In the second hypothesis test for 85th percentile speeds, 27 of the 43 treatment pairs (62.8%) generated statistically significant results. These results indicate that the 85th percentile speeds in the after condition were reduced by more than 1.25 mph. Most (22 out of 27) of

the treatment pairs that rejected the null were collected from designated neighborhood greenways. Nearly all significant treatment pairs (25 of 27) also had statistically significant decreases in mean speed. Statistically significant decreases in 85th percentile speeds for treatment pairs ranged from 2 to 5 mph.

Only five of the 37 control pairs (13.5%) rejected the second null hypothesis for 85th percentile speeds. These decreases in 85th percentile speeds were observed to range from 2 to 3 mph.

Speed Variance. Of the 43 treatment pairs, 20 (46.5%), were found to have a speed variance in the after period that was significantly lower than in the before period. Nine of these 20 treatment pairs were collected from non-greenways. Statistically significant increases in the speed variance between the before and after periods were observed in seven of the 43 treatment pairs (16.3%).

Twelve of the 37 control pairs (32.4%) rejected the null hypothesis in favor of a decrease in the variance during the after period. Conversely, the variance significantly increased from the before to after periods in nine of 37 control data set pairs (24.3%).

Proportions Exceeding Speed Thresholds. For treatment pairs, the proportion of vehicles exceeding the speed threshold decreased significantly ($p < 0.05$) in 38 of the 43 (88.4%) pairs. Decreases ranged from 4% to 58%, with an average decrease of 23%. In comparison, only 12 of the 37 control data sets (32.4%) rejected the null, with decreases in the proportions exceeding the speed threshold of 2% to 12%.

Significant increases in the proportion of vehicles exceeding the speed threshold were found in two of the 43 treatment pairs (4.7%), both of which were collected from sites with higher PSLs. Increases ranged from 7%

to 9%. For control pairs, significant increases of 1% to 8% were found in seven of the 37 data set pairs (18.9%).

Discussion

Overall, the results of the data analyses suggest there are distinct differences in the outcomes of a 5-mph PSL reduction between treatment pairs and control pairs, and between neighborhood greenway sites and non-greenway sites. When comparing congested and all-day periods the overall results did not change (*23*).

The results of the before and after analysis indicate that treatment sites experience larger decreases in mean speeds than control sites—in the order of 1.5 mph to 2 mph on average for all 43 treatment pairs, compared with small or negligible changes in the 37 control pairs. Treatment sites also appear to have larger decreases in the 10-mph pace and larger increases in the percentage of vehicles within the pace than control sites. This finding suggests that the operating speed reductions seen with the treatment data sets are more likely to be a result of the reduced PSLs rather than of chance or other global factors, such as the evolution of driver attitudes toward speed or compliance with the PSL.

The results of the hypothesis tests for mean speed are generally in agreement with those for the 85th percentile speed across the treatment and control pairs. Nearly 63% of the 43 treatment pairs showed statistically significant reductions of more than 1.25 mph in mean and 85th percentile speeds, compared with only 8.1% and 13.5% of the 37 pairs in the control group for mean and 85th percentile speeds, respectively. Furthermore, the percentage of data set pairs exhibiting any increase in mean or 85th percentile speeds was lower for the treatment group than for the control group.

Speed variance was significantly reduced in almost 50% more treatment pairs than control pairs (47% versus 32%). Over half of these treatment pairs also experienced reduced mean speeds, but three treatment pairs indicated that mean speeds increased in the "after" period. The distribution of significant decreases in speed variance was split fairly evenly between the neighborhood greenways and non-greenways for both the treatment and control groups. Meanwhile, increases in speed variance were proportionally more prevalent in control pairs than in treatment pairs at neighborhood greenway locations.

The proportion of vehicles exceeding the speed threshold decreased in 2.7 times more treatment pairs than control pairs (88% versus 32%). Decreases in the proportion of vehicles exceeding the speed thresholds were also of smaller magnitude for control pairs than for treatment pairs. As with speed variance, increases in the proportion of vehicles exceeding the speed threshold were more commonly observed in control pairs than in treatment pairs.

Statistically significant reductions in all performance measure categories were more prevalent at the neighborhood greenway sites than at non-greenway sites for the treatment group. For hypothesis testing of performance measure increases, non-greenways showed a higher propensity to produce statistically significant results than did neighborhood greenways in the treatment group. It is clear that the speed behaviors and outcomes of a 5-mph PSL reduction on these two types of roads are quite different. Differences in traffic composition and the distinctive features of the neighborhood greenways may contribute to better outcomes of PSL reductions. In addition, traffic diversion or general changes related to mode choice or origin–destination matrices may be taking place on these neighborhood greenways after the PSLs are reduced. Despite small increases in Vehicle Miles Traveled (VMT) figures in the region during the data collection period, a trend toward a reduction in motorized volumes was observed on neighborhood greenways. In contrast, non-greenways experienced small increases in volumes on average. A high degree of variability was observed across sites, however. On some roadways, it is likely that changes in motorized volumes are also linked to reductions in speed characteristics such as the mean or 85th percentile.

There is evidence that motorists' behavior is influenced by the number of cyclists; that is, when cyclists are a minority then they may not be perceived or treated by motorists as road users with the same rights that motorists enjoy (*25*). Since neighborhood greenways are residential streets with low motorized traffic volumes and a high number of active travelers, cyclists tend to comprise a higher share of the total traffic on these streets and they are likely not perceived or treated as a minority by motorists. It is then likely that neighborhood greenway design and driver behavior contribute to higher reduction of operating speeds when PSLs are reduced. Future research could measure additional benefits of PSL reductions on cyclists' stress levels (*26*) and in particular for cyclists who tend to travel at slower speeds (*27*).

Conclusions

This research has presented a before and after analysis of passenger car speeds on urban roads that underwent a 5-mph reduction in the PSL (treatment sites) and roads where the PSL did not change (control sites). Within the treatment and control groups, sites that prioritize active travel and typically have high bicycle volumes were compared with sites with a more standard traffic function and composition. The change in the mean and 85th percentile speeds, the speed variance, and the proportion of vehicles exceeding a speed threshold were evaluated in aggregate and individually through a series of hypothesis tests.

Overall, the results of the aggregate and individual data set analyses suggest that PSL reductions of 5 mph are likely to reduce speed characteristics such as mean or 85th percentile by 1.25 mph. However, it is important to highlight that there is a high degree of variability in the outcomes and that a priori, it is not possible to ascertain whether a reduction in the PSL will reduce speed characteristics. For example, nearly 31% of the non-greenway treatment pairs experienced an increase in mean speed, even though the PSL was reduced by 5 mph. Additionally, approximately 16% of all treatment pairs experienced an increase in speed variance. Therefore, it is always recommended to monitor speed characteristics before and after PSL changes and take additional measures to address situations where speed characteristics such as mean, 85th percentile, and speed variance increase after a PSL reduction.

The statistical tests indicate that a PSL reduction is more likely to reduce speed characteristics on neighborhood greenways than on non-greenways. The presence of traffic calming features and shared roadway markings (sharrows) may contribute to the more successful outcomes of PSL reductions on these roads. It is also possible that traffic is diverting to nearby roads, and the speed reductions are linked to these changes in motorized volumes.

The results show more substantial operating speed reductions because of PSL reductions on roadways that prioritize active travel and typically have higher bicycle volumes. This has practical implications for cities fostering active transportation modes. The development of active transportation corridors that attract a higher number of cyclists is likely to see a positive change in motorists' behavior and a reduction in motorists' operating speeds when PSLs are reduced, which in turn is likely to increase safety and attract more cyclists, thus creating a positive feedback loop. These findings can also be interpreted as indirect evidence supporting the safety in numbers hypothesis in relation to operating speeds and PSL changes.

Crash data analysis was not possible because of limited data availability for the number of crashes and years of data before and after PSL changes. Future research efforts should analyze the impact of PSL changes on crashes and other safety outcomes for cyclists, pedestrians, and motorized vehicles.

Acknowledgments

Author Contributions

Declaration of Conflicting Interests

Funding

ORCID iDs

Jaclyn S. Schaefer https://orcid.org/0000-0003-1753-6605
Miguel A. Figliozzi https://orcid.org/0000-0003-2120-4929
Avinash Unnikrishnan https://orcid.org/0000-0001-6737-0485

References

1. US Department of Transportation. *Manual on Uniform Traffic Control Devices for Streets and Highways.* US Department of Transportation, Federal Highway Administration, Washington, DC, 2009.
2. OECD, European Conference of Ministers of Transport, and OECD/ECMT Transport Research Centre. Speed Management. OECD Publishing, France, 2006.
3. Gerald, J., G. Teresa, M. Hugh, and S. Raghavan. *Methods and Practices for Setting Speed Limits.* Report No. FHWA-SA-12-004. US Department of Transportation, Federal Highway Administration, Washington, DC, 2012.
4. Dinh, D. D., and H. Kubota. Profile-Speed Data-Based Models to Estimate Operating Speeds for Urban Residential Streets with a 30 km/h Speed Limit. *IATSS Research*, Vol. 36, No. 2, 2013, pp. 115–122.
5. Eluru, N., V. Chakour, M. Chamberlain, and L. F. Miranda-Moreno. Modeling Vehicle Operating Speed on Urban Roads in Montreal: A Panel Mixed Ordered Probit Fractional Split Model. *Accident Analysis & Prevention*, Vol. 59, 2013, pp. 125–134.
6. Fitzpatrick, K., P. Carlson, M. Brewer, and M. Wooldridge. Design Factors That Affect Driver Speed on Suburban Streets. *Transportation Research Record: Journal of the Transportation Research Board*, 2001. 1751: 18–25.
7. Thiessen, A., K. El-Basyouny, and S. Gargoum. Operating Speed Models for Tangent Segments on Urban Roads. *Transportation Research Record: Journal of the Transportation Research Board*, 2017. 2618: 91–99.
8. Himes, S. C., E. T. Donnell, and R. J. Porter. Posted Speed Limit: To Include or Not to Include in Operating

Speed Models. *Transportation Research Part A: Policy and Practice*, Vol. 52, 2013, pp. 23–33.

9. Elvik, R. Speed Limits, Enforcement, and Health Consequences. *Annual Review of Public Health*, Vol. 33, No. 1, 2012, pp. 225–238.

10. Islam, M. T., K. El-Basyouny, and S. E. Ibrahim. The Impact of Lowered Residential Speed Limits on Vehicle Speed Behavior. *Safety Science*, Vol. 62, 2014, pp. 483–494.

11. Hu, W., and J. B. Cicchino. Lowering the Speed Limit from 30 mph to 25 mph in Boston: Effects on Vehicle Speeds. *Injury Prevention*, Vol. 26, No. 2, 2020, pp. 99–102.

12. Mannering, F. An Empirical Analysis of Driver Perceptions of the Relationship between Speed Limits and Safety. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 12, No. 2, 2009, pp. 99–106.

13. Toy, S., A. Tapp, C. Musselwhite, and A. Davis. Can Social Marketing Make 20mph the New Norm? *Journal of Transport & Health*, Vol. 1, No. 3, 2014, pp. 165–173.

14. Fitzpatrick, K., S. Das, M. P. Pratt, K. Dixon, and T. Gates. *Development of a Posted Speed Limit Setting Procedure and Tool*. Transportation Research Board of the National Academies, Washington, DC, 2021.

15. ODOT. *Speed Zone Manual*. Oregon Department of Transportation, Salem, 2020. https://www.oregon.gov/odot/Engineering/Docs_TrafficEng/Speed-Zone-Manual.pdf. Accessed March 18, 2020.

16. NACTO. *City Limits*. National Association of City Transportation Officials, New York, NY, 2021. https://nacto.org/safespeeds/. Accessed November 18, 2021.

17. Jacobsen, P. L. Safety in Numbers: More Walkers and Bicyclists, Safer Walking and Bicycling. *Injury Prevention*, Vol. 9, No. 4, 2003, pp. 205–209.

18. Pucher, J., and R. Buehler. Cycling for Everyone: Lessons from Europe. *Transportation Research Record: Journal of the Transportation Research Board*, 2008. 2074: 58–65.

19. Blanc, B., and M. Figliozzi. Modeling the Impacts of Facility Type, Trip Characteristics, and Trip Stressors on Cyclists' Comfort Levels Utilizing Crowdsourced Data. *Transportation Research Record: Journal of the Transportation Research Board*, 2016. 2587: 100–108.

20. Elvik, R., and T. Bjørnskau. Safety-in-Numbers: A Systematic Review and Meta-Analysis of Evidence. *Safety Science*, Vol. 92, 2017, pp. 274–282.

21. Federal Highway Administration. *Traffic Monitoring Guide*. US Department of Transportation, Washington, DC, 2016.

22. PBOT. *What Are Neighborhood Greenways?* Portland.gov, 2021. https://www.portland.gov/transportation/what-are-neighborhood-greenways. Accessed November 18, 2021.

23. Figliozzi, M., A. Unnikrishnan, and J. Schaefer. *Update to Methodology for Setting Speed Limits in Urban Areas*. Report No.: SPR 827. Oregon Department of Transportation, Salem, 2021. https://pdxscholar.library.pdx.edu/cengin_fac/560/.

24. Hou, Y., C. Sun, and P. Edara. Statistical Test for 85th and 15th Percentile Speeds with Asymptotic Distribution of Sample Quantiles. *Transportation Research Record: Journal of the Transportation Research Board*, 2012. 2279: 47–53.

25. Prati, G., V. M. Puchades, and L. Pietrantoni. Cyclists as a Minority Group? *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 47, 2017, pp. 34–41.

26. Caviedes, A., and M. Figliozzi. Modeling the Impact of Traffic Conditions and Bicycle Facilities on Cyclists' On-Road Stress Levels. *Transportation Research Part F: Traffic Psychology and Behavior*, Vol. 58, 2018, pp. 488–499.

27. Figliozzi, M., N. Wheeler, and C. M. Monsere. Methodology for Estimating Bicyclist Acceleration and Speed Distributions at Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 2013. 2387: 66–75.