Comparation of Impedance Functions for Modelling Student Trip Distribution at Surabaya Senior High Schools

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Abstract

Student travel from home to school is an important component of urban mobility because it generates concentrated travel demand during school arrival and dismissal periods. This study compared the Negative Power, Negative Exponential, and Tanner impedance functions in representing student trip-length distributions at four public senior high schools in Surabaya, Indonesia. Primary data were collected through questionnaire-based surveys involving 262 students. Home-to-school travel distances were grouped into 3-km intervals, and the proportion of trips within each interval was calculated for each school. The three functions were calibrated using the observed distributions and evaluated using the Sum of Squared Error (SSE) and Mean Absolute Percentage Error (MAPE). The Tanner function produced the lowest SSE values at all study sites, indicating the smallest aggregate deviation between observed and estimated distributions. In contrast, the Negative Exponential function produced the lowest MAPE values at each school, indicating the lowest relative prediction error. Practically, the findings provide an initial empirical basis for identifying dominant student travel-distance ranges and selecting an impedance function according to the analytical objective. This information can support school accessibility planning, traffic management around school areas, the determination of school service zones, and student transportation planning in Surabaya. The Tanner function is more suitable for representing the aggregate distribution shape, whereas the Negative Exponential function is more appropriate when relative accuracy is prioritised. Detailed planning applications still require additional data on travel modes, travel times, traffic volumes, and road-network conditions.

Keywords: *Gravity Model, Impedance Functions, Negative Exponential, Tanner, Trip Distribution*

1. Introduction

Student travel from home to school constitutes an important component of urban mobility because it occurs repeatedly on school days and generates concentrated travel demand during morning arrival and afternoon dismissal periods. These travel patterns are influenced not only by educational activities but also by school location, home-to-school distance, travel time, mode availability, built-environment conditions, and household decisions regarding school selection. Previous school-travel studies have consistently identified home-to-school distance as a major determinant of travel behaviour and mode choice, although the degree of sensitivity may vary according to spatial context, socioeconomic characteristics, and transport-service availability [1]–[4]. Student travel should therefore be understood as a source of transport demand with distinct spatial characteristics that may affect school accessibility, motorised travel, and traffic conditions in educational areas.

Trip distribution is a principal component of transport-demand modelling because it describes the spatial relationship between trip origins and destinations. Within the gravity-model framework, the magnitude of travel interaction is influenced by trip production at the origin, trip attraction at the destination, and the impedance separating the two locations. Impedance may be represented by distance, travel time, travel cost, or generalised travel cost, depending on the analytical objective and the availability of observed data [5], [6], [8]. This study does not construct a complete origin–destination matrix; instead, it applies the impedance-function component to analyse the relationship between home-to-school distance and the proportion of student trips within each distance interval. Three functions are evaluated: Negative Power, Negative Exponential, and Tanner. The first two represent declining interaction as distance increases, whereas the Tanner function combines power and exponential components and can represent a distribution that rises over an initial distance range, reaches a peak, and subsequently declines at longer distances [5]–[8]. These different mathematical properties indicate that an impedance function should be selected through empirical calibration rather than a uniform assumption.

Previous school-travel research has predominantly examined mode choice, active travel, road safety, accessibility, and the influence of the built environment on student mobility [1]–[4], while Indonesian trip-distribution studies have generally applied gravity models and impedance functions at broader urban or regional scales [7]–[9]. Within the literature reviewed for this study, limited attention has been given to a direct comparison of the Negative Power, Negative Exponential, and Tanner functions for representing student trip-length distributions across several senior high schools in Indonesia. The novelty of this study lies in the empirical comparison of three functions with different mathematical characteristics using observed home-to-school travel data from four public schools in Surabaya, with separate calibration for each school and a common performance assessment based on the Sum of Squared Error (SSE) and Mean Absolute Percentage Error (MAPE). This design makes it possible to distinguish the function that best represents the aggregate distributional shape from the function that produces the lowest relative prediction error. From a sustainability perspective, locally calibrated models can provide an initial analytical basis for identifying concentrations of student origins by distance, evaluating school service coverage, and supporting more targeted school-transport and accessibility planning. In future applications, this information may contribute to reducing unnecessary motorised trips, congestion around schools, energy consumption, and vehicle emissions, although a direct assessment of these outcomes requires additional data on travel modes, travel times, traffic volumes, and road-network conditions.

Based on this research gap, the study compares the performance of the Negative Power, Negative Exponential, and Tanner impedance functions in representing student trip-length distributions at SMAN 1, SMAN 2, SMAN 5, and SMAN 9 in Surabaya. The analysis uses primary data from 262 student respondents, with home-to-school travel distances grouped into 3-km intervals. The objectives are to describe the observed student trip-length distributions, calibrate the three impedance functions separately for each school, and compare their performance using SSE and MAPE. The findings are expected to provide an empirical basis for selecting an impedance function according to the analytical objective and the local travel characteristics of senior high school areas.

2. Research Methodology

This study was conducted at four public senior high schools in Surabaya, namely SMAN 1, SMAN 2, SMAN 5, and SMAN 9. The sites were selected because they are located within the urban area and generate recurrent student travel, particularly during morning arrival and afternoon dismissal periods. Primary data were collected through questionnaire-based surveys involving 262 students, comprising 60 respondents from SMAN 1, 84 from SMAN 2, 64 from SMAN 5, and 54 from SMAN 9. The information used in the analysis included students' residential locations and home-to-school travel distances. Origins within Surabaya were represented at the kelurahan level, whereas origins outside the city were represented at the kecamatan level. Home-to-school distance was used as the operational representation of travel impedance because the study focused on trip-length distributions. Observed distances were grouped into 3-km intervals, and the midpoint of each interval was used as the representative distance in calibration. The number of trips within each interval was converted into a percentage of the total respondents at the respective school, enabling consistent comparison among schools despite differences in sample size.

The research process began with a literature review to establish the conceptual basis of trip distribution, gravity models, impedance functions, and performance indicators. The subsequent stages comprised data collection and processing, calibration of the Negative Power, Negative Exponential, and Tanner functions, evaluation using SSE and MAPE, and formulation of conclusions according to the analytical objective. Calibration and evaluation were conducted separately for each school so that the resulting parameters could reflect local travel characteristics. The research flow is presented in Figure 1.

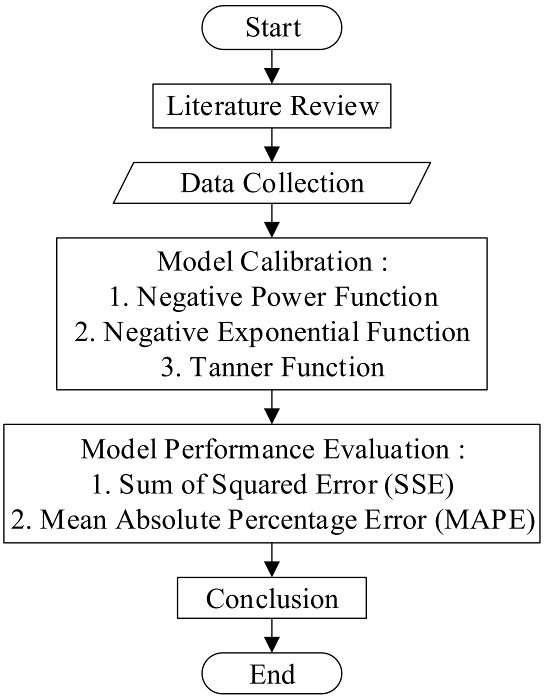

Figure 1. Research Methodology Flowchart

The survey data were processed into observed trip-percentage distributions by distance interval. These distributions were used to calibrate the three impedance functions, after which the estimated values were compared with the observations using SSE and MAPE. The evaluation was not intended to identify a single universally superior function, but to determine which function was most appropriate for the performance indicator and analytical purpose being prioritised.

<u>Analysis Method</u>

The trip-distribution analysis was based on the impedance-function component of the gravity-model framework, which represents travel interaction as a function of trip production at the origin, trip attraction at the destination, and travel impedance between the two zones [6], [8]. The general form of the model is expressed as :

$$T_{ij} = O_i \,.\, D_j \,.\, f\left(C_{ij}\right) \qquad (1)$$

Where T_{ij} is the number of trips from origin zone i to destination zone j; O_i is trips production at origin zone i; D_j is trip attraction at destination zone j; $f(C_{ij})$ is the impedance function; and C_{ij} is the travel impedance between the two zones. This study did not construct a complete origin-destination matrix or estimate balancing factors. Equation (1) was used only as a conceptual basis, while the operational analysis examined the relationship between distance-interval midpoints and observed student-trip percentages. Therefore, the model output represents estimated trip proportions by distance interval rather than trip volumes between specific origin-destination pairs.

<u>Impedance Function and Model Calibration</u>

Three impedance functions were evaluated. The Negative Power function is expressed as:

$$f(C_{ij}) = C_{ij}{}^{-\alpha} \quad (2)$$

where α is the distance-sensitivity parameter. This impedance function represents a non-linear decline in travel interaction as travel distance increases. A larger value of α indicates a more pronounced reduction in travel interaction as travel distance increases.

The Negative Exponential impedance function is expressed as :

$$f(C_{ij}) = e^{-\beta C_{ij}} \quad (3)$$

where β is the distance-decay parameter and e is the base of the natural logarithm. This impedance function represents an exponential decline in travel interaction as travel distance increases. A larger value of β indicates a more rapid reduction in trip distribution as travel distance increases.

The Tanner impedance function combines power and exponential components and is expressed in this study as :

$$f(C_{ij}) = C_{ij}{}^{-\alpha} e^{-\beta C_{ij}} \quad (4)$$

where α controls the power component and β controls the exponential-decay component. The positive power–negative exponential form was adopted because it is consistent with the Tanner equations obtained from the calibration procedure in this study. Unlike the Negative Power and Negative Exponential impedance functions, the Tanner impedance function allows the function value to increase over an initial distance range, reach a maximum value at a particular distance, and subsequently decline as travel distance increases. Consequently, the Tanner impedance function can represent a non-monotonic and unimodal trip-length distribution [6].

During calibration, a scaling coefficient was introduced to transform each impedance function into an estimated trip-distribution equation. Accordingly, the general form of the calibrated model is expressed as :

$$\hat{Y}_i = af(C_i) \quad (5)$$

where a is a scaling coefficient, $\hat{Y}_i$ is the estimated percentage of student trips in distance interval i, and $f(C_i)$ is the selected impedance function evaluated at the distance midpoint C_i. The notation C_i is used by grouped distance intervals, whereas C_{ij} is retained in the conceptual formulation of the impedance function within the gravity-model framework.

Calibration was conducted separately for each school using C_i as the independent variable and the observed trip percentage Y_i as the dependent variable. Original unrounded percentages were used throughout the calculations. The Negative Power and Negative Exponential functions were calibrated through regression-based curve fitting using the Microsoft Excel trendline facility, producing the scaling coefficient and the corresponding α or β parameter. The coefficient of determination R^2 was reported only for these two functions. The Tanner function was calibrated iteratively by adjusting a, α, and β, with the parameter combination producing the minimum SSE retained as the calibrated equation.

Because the Tanner function was calibrated directly by minimising SSE, whereas the Negative Power and Negative Exponential functions were fitted using regression-based trendlines, the SSE comparison was influenced by the adopted calibration procedures. A lower Tanner SSE should therefore be interpreted as better aggregate fit under the present calibration approach rather than as evidence that the Tanner function is universally superior. Future studies should calibrate all functions using a common nonlinear optimisation criterion.

<u>Model Performance Evaluation</u>

The performance of the three impedance functions was evaluated using the Sum of Squared Error (SSE) and Mean Absolute Percentage Error (MAPE).these indicators were applied jointly because they provide different perspectives for assessing the agreement between the estimated and observed student trip-length distributions. SSE measures the sum of squared differences between observed and estimated values across all distance intervals. Because the differences are squared, larger discrepancies contribute more strongly to the SSE value. Therefore, SSE was used to identify the impedance function that produced the smallest overall discrepancy between the estimated and observed trip distributions. The SSE calculation was conducted separately for each school using the distance intervals included in the calibration procedure, while the original unrounded trip-percentage values were retained throughout the calculation. The SSE equation is expressed as :

$$SSE = \sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \quad (6)$$

where Y_i is the observed percentage of student trips in distance interval i, $\hat{Y}_i$ is the estimated percentage of student trips in the corresponding interval, and n is the number of distance intervals included in the evaluation procedure for the respective school. A lower SSE value indicates that the estimated trip-length distribution more closely represents the observed distribution in aggregate terms. However, because the differences are squared, SSE is more sensitive to relatively large discrepancies within particular distance intervals.

MAPE was used to measure the average relative prediction error between observed and estimated trip percentages. Unlike SSE, which emphasises the magnitude of the overall absolute difference, MAPE evaluates the difference relative to the corresponding observed value. This indicator was used to compare the relative prediction performance of the impedance functions for each school. The MAPE calculation was conducted separately for each school and included only distance intervals with observed trip percentages greater than zero. Distance intervals displayed as 0,00% in the combined trip-distribution table were retained to maintain a consistent presentation across the schools; however, these intervals were excluded from the MAPE calculation for the respective school because MAPE is undefined when the observed value equals zero [10], [11]. The MAPE equation is expressed as :

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Y_i - \hat{Y}_i}{Y_i}\right| \times 100\% \quad (7)$$

where Y_i is the observed percentage of student trips in distance interval i, $\hat{Y}_i$ is the estimated percentage of student trips in the corresponding interval, and n is the number of distance intervals with non-zero observed values for the respective school. A lower MAPE value indicates a lower average relative prediction error. Nevertheless, MAPE should be interpreted carefully because its value may increase when the observed trip percentage within a distance interval is very small, even when the absolute difference between the observed and estimated values is limited [10], [11]. Therefore, the selection of the most appropriate impedance function in this study was not based on a single evaluation indicator.

3. Results and Discussion

Observed Student Trip-Length Distribution

The observed student trip-length distributions at SMAN 1, SMAN 2, SMAN 5, and SMAN 9 are presented in Table 1. In general, student trips were concentrated within the first three distance intervals, with midpoints of 1,5 km, 4,5 km, and 7,5 km. the cumulative trip proportions within these intervals reached 78,34% at SMAN 1, 64,28% at SMAN 2, 67,20% at SMAN 5, and 66,67% at SMAN 9. This indicates that most students travelled up to approximately 9 km from home to school.

Table 1. Student Trip-Length Distribution by Distance Interval

Distance Interval (km)	Distance Midpoint, x (km)	SMAN 1 (%)	SMAN 2 (%)	SMAN 5 (%)	SMAN 9 (%)
0-3	1,5	11,67	11,90	15,63	5,56
3-6	4,5	31,67	26,19	21,88	22,22
6-9	7,5	35,00	26,19	29,69	38,89
9-12	10,5	11,67	14,29	18,75	9,26
12-15	13,5	6,67	15,48	6,25	9,26
15-18	16,5	3,33	3,57	4,69	12,96
18-21	19,5	0,00	1,19	3,13	1,85
21-24	22,5	0,00	1,19	0,00	0,00

The highest trip proportions at SMAN 1, SMAN 5, and SMAN 9 occurred at the 7,5 km distance midpoint, reaching 35,00%, 29,69%, and 38,89%, respectively. At SMAN 2, the highest proportion of 26,19% was recorded at both the 4,5 km and 7,5 km midpoints. These patterns indicate that student trip-length distributions did not decline directly from the shortest distance interval; instead, trip proportions generally increased towards intermediate distance before declining at longer distances. The observed distributions were subsequently used as the basis for calibrating and evaluating the Negative Power, Negative Exponential, and Tanner impedance functions.

Calibration Outcomes of the Travel Distribution Model

The calibration procedure produced Negative Power, Negative Exponential, and Tanner impedance-function equations for each school, as presented in Table 2. In all equations, $\hat{Y}$ denotes the estimated percentage of student trips, whereas C_i denotes the midpoint of the distance interval in kilometres. The Negative Power and Negative Exponential equations were obtained through regression-based curve fitting; therefore, the coefficient of determination (R^2) is reported to describe the agreement between the fitted curves and the observed data. In contrast, the Tanner equations were obtained through an iterative procedure based on the minimisation of the SSE. Accordingly, the overall comparison of the three impedance functions is presented in the subsequent subsection using SSE and MAPE.

Table 2. Calibrated Impedance-Function Equations

School	Negative Power	Negative Exponential	Tanner
SMAN 1	$Y = 30{,}132x^{-0{,}463}$ $R^2 = 0{,}205$	$Y = 34{,}327e^{-0{,}115x}$ $R^2 = 0{,}508$	$Y = 21{,}94x^{0{,}707}\ e^{-0{,}184x}$
SMAN 2	$Y = 53{,}565x^{-0{,}89}$ $R^2 = 0{,}390$	$Y = 44{,}159e^{-0{,}149x}$ $R^2 = 0{,}720$	$Y = 15{,}90x^{0{,}874}\ e^{-0{,}193x}$
SMAN 5	$Y = 38{,}914x^{-0{,}611}$ $R^2 = 0{,}399$	$Y = 35{,}349e^{-0{,}113x}$ $R^2 = 0{,}712$	$Y = 19{,}47x^{0{,}627}\ e^{-0{,}160x}$
SMAN 9	$Y = 15{,}031x^{-0{,}196}$ $R^2 = 0{,}032$	$Y = 20{,}635\ e^{-0{,}069x}$ $R^2 = 0{,}210$	$Y = 15{,}16x^{0{,}740}\ e^{-0{,}152x}$

Note : The R^2 values are reported only for the Negative Power and Negative Exponential functions, which were calibrated through regression-based curve fitting. The Tanner function was calibrated through an iterative SSE-minimisation procedure.

As shown in Table 2, the Negative Exponential function produced higher R^2 values than the Negative Power function at all study sites. The R^2 values of the Negative Exponential function were 0.508 at SMAN 1, 0.720 at SMAN 2, 0.712 at SMAN 5, and 0.210 at SMAN 9, whereas the corresponding Negative Power values were 0.205, 0.390, 0.399, and 0.032. These differences indicate that an exponential-decay pattern generally provided a closer curve fit to the observed trip distributions than a negative-power pattern. The strongest Negative Exponential fits were obtained at SMAN 2 and SMAN 5, suggesting that the changes in trip proportions at these schools could be relatively well represented by an exponential-decay relationship.

The parameters of the Negative Power function also indicate differences in trip-distribution characteristics across the schools. The highest α value was obtained at SMAN 2, at 0.890, followed by SMAN 5 at 0.611 and SMAN 1 at 0.463. Within the negative-power functional form, these values indicate that SMAN 2 exhibited a sharper decline in the estimated trip proportion as distance increased. In contrast, SMAN 9 had the lowest α value, at 0.196, together with a very low R^2 value. This result indicates that the trip-length distribution at SMAN 9 could not be adequately represented by a simple monotonic decline. In the Negative Exponential function, the highest β value was also obtained at SMAN 2, at 0.149, whereas the lowest value was obtained at SMAN 9, at 0.069. These parameter differences reflect variations in the rate at which the estimated trip proportion declined as travel distance increased across the schools.

The Tanner equations for all schools contained a positive power component and a negative exponential component. This form allows the estimated trip percentage to increase over the initial distance range, reach a maximum value at a particular distance, and subsequently decline across longer distance intervals. This characteristic corresponds with the observed trip-length distributions, which were generally concentrated within intermediate distance intervals, particularly at the 4.5 km and 7.5 km midpoints. Therefore, the Tanner function is conceptually more flexible for representing trip-length distributions that do not decline directly from the shortest distance interval. However, because the Tanner function was calibrated using a different procedure from the two regression-based functions, its performance cannot be compared using R^2 alone. Further evaluation using SSE and MAPE is required to determine the impedance function that provides the closest representation of the observed student trip distributions at each school.

Comparison of Model Performance Based on SSE and MAPE

The performance of the Negative Power, Negative Exponential, and Tanner impedance functions was compared using the Sum of Squared Error (SSE) and Mean Absolute Percentage Error (MAPE). SSE was used to assess the total squared difference between the observed and estimated student trip percentages across all distance intervals, whereas MAPE represents the average relative percentage deviation from the observed values. Both indicators should be interpreted jointly because SSE places greater emphasis on the overall agreement of the trip-length distribution, whereas MAPE emphasises relative agreement within each distance interval. Table 3 presents the SSE comparison for the three impedance functions at each school.

Table 3. Comparison of SSE Values for the Impedance Functions

School	Negative Power	Negative Exponential	Tanner	Model with Lowest SSE
SMAN 1	1.021,90	848,49	339,23	Tanner
SMAN 2	1.267,98	817,70	102,25	Tanner
SMAN 5	702,56	480,46	156,01	Tanner
SMAN 9	1079,55	982,29	539,30	Tanner

As shown in Table 3, the Tanner function consistently produced the lowest SSE values at all study sites. At SMAN 1, the SSE value of the Tanner function was 339.23, lower than the values of 1,021.90 for the Negative Power function and 848.49 for the Negative Exponential function. The same pattern was observed at SMAN 2, SMAN 5, and SMAN 9, where the Tanner SSE values were 102.25, 156.01, and 539.30, respectively. These results indicate that the Tanner function produced estimated trip-length distributions that most closely represented the observed distributions in aggregate terms. This advantage is associated with the Tanner functional form, which allows the estimated trip proportion to increase over the initial distance intervals, reach a peak at intermediate distances, and subsequently decline at longer distances. This characteristic corresponds with the observed distributions in Table 1, which generally did not decrease directly from the shortest distance interval.

Although the Tanner function produced the lowest SSE values, the MAPE results showed a different pattern. As presented in Table 4, the Negative Exponential function produced the lowest MAPE value at all four schools.

Table 4. Comparison of MAPE Values for the Impedance Functions

School	Negative Power (%)	Negative Exponential (%)	Tanner (%)	Model with Lowest MAPE
SMAN 1	71,36	52,85	63,79	Negative Exponential
SMAN 2	108,86	61,38	87,32	Negative Exponential
SMAN 5	59,33	35,71	45,14	Negative Exponential
SMAN 9	94,99	84,94	97,27	Negative Exponential

At SMAN 1, the MAPE value of the Negative Exponential function was 52.85%, lower than the values of 71.36% for the Negative Power function and 63.79% for the Tanner function. Similar results were found at SMAN 2 and SMAN 5, where the Negative Exponential MAPE values were 61.38% and 35.71%, respectively. At SMAN 9, the Negative Exponential function also retained the lowest MAPE value, at 84.94%. These results indicate that the Negative Exponential function produced the smallest average relative difference from the observed data across all schools. However, the MAPE values remained relatively high at some sites, particularly SMAN 2 and SMAN 9. This result should be interpreted by considering the sensitivity of MAPE to distance intervals with small observed trip proportions.

The contrasting SSE and MAPE results indicate that no single impedance function performed best under both indicators. The Tanner function is more appropriate when the objective is to obtain an overall representation of the trip-length distribution with the smallest total discrepancy. In contrast, the Negative Exponential function is more appropriate when the analytical priority is to obtain the smallest average relative percentage deviation within distance intervals for which observed data are available.

Therefore, the selection of an impedance function should be aligned with the intended purpose of the student trip-distribution analysis.

Interpretation of R^2, SSE, and MAPE Results

The evaluation results indicate that R^2, SSE, and MAPE provide different information regarding the performance of the impedance functions. The R^2 values in Table 2 describe the agreement between the fitted regression curves and the observed trip-distribution data for the Negative Power and Negative Exponential functions. At all schools, the Negative Exponential function produced higher R^2 values than the Negative Power function. This finding indicates that an exponential-decay pattern followed the general tendency of the observed data more closely than a negative-power pattern. However, R^2 was used only to assess the two functions calibrated through regression. Therefore, it was not used as a basis for direct comparison with the Tanner function, which was obtained through an iterative SSE-minimisation procedure.

As shown in Table 3, the Tanner function produced the lowest SSE value at SMAN 1, SMAN 2, SMAN 5, and SMAN 9. This result indicates that the Tanner function generated the smallest overall discrepancy between the estimated and observed trip percentages across all distance intervals. This advantage is associated with the Tanner functional form, which combines a positive power component with a negative exponential component. The form allows the estimated trip proportion to increase at shorter distances, reach a peak within an intermediate distance interval, and subsequently decline at longer distances. This pattern corresponds with the observed trip-length distributions, which at most schools were concentrated at the 4.5 km and 7.5 km midpoints rather than within the shortest distance interval.

In contrast, the MAPE results in Table 4 indicate that the Negative Exponential function produced the lowest average relative deviation at all schools. The difference between the SSE and MAPE results does not indicate inconsistency in the evaluation procedure; instead, it reflects the different emphasis of the two indicators. SSE assigns greater weight to larger differences and evaluates the overall agreement of the trip-length distribution. In contrast, MAPE compares the difference with the observed value in each distance interval. Consequently, intervals with relatively small observed trip proportions can contribute substantially to the MAPE value even when the absolute difference is limited [10], [11]. Distance intervals with observed values of 0.00% were excluded from the MAPE calculation to avoid division by zero.

Overall, these findings indicate that the Tanner function is more suitable for representing the aggregate shape of the student trip-length distribution, particularly when the objective is to obtain a curve that follows the observed increase and subsequent decline in trip proportions across distance intervals. Conversely, the Negative Exponential function is more suitable when the primary consideration is the average relative deviation across distance intervals for which observed data are available. Considering the objective of this study, which was to compare the ability of impedance functions to represent student trip-length distributions. Under the adopted calibration approach, the Tanner function provided the closest aggregate fit based on SSE. However, this result should be interpreted cautiously because SSE was also used as the Tanner calibration objective. The Negative Exponential function provided the lowest MAPE values and therefore showed the best relative agreement across the observed distance intervals. Nevertheless, the Negative Exponential function remains relevant as a comparative model because it demonstrated the best relative performance based on MAPE.

Implications of Research Results

The findings indicate that the selection of an impedance function should be aligned with the purpose of the trip-distribution analysis. The Tanner function consistently produced the lowest SSE values at SMAN 1, SMAN 2, SMAN 5, and SMAN 9. Therefore, the Tanner function is more appropriate when the main objective of modelling is to obtain an overall representation of the student trip-length distribution. By combining a positive power component and a negative exponential component, the Tanner function can represent a pattern in which student trip proportions increase across the initial distance intervals, concentrate at intermediate distances, and subsequently decline at longer distances. This characteristic makes the Tanner function relevant as the primary model for estimating student trip proportions by distance interval in senior high school areas.

In contrast, the Negative Exponential function produced the lowest MAPE values at all schools. This finding indicates that the function can be used as a comparative or alternative model when the analysis prioritises the average relative difference between estimated and observed values within each distance interval. Accordingly, the results do not indicate that one impedance function completely replaces the others. The Tanner function performs better in representing the aggregate form of the trip-length distribution, whereas the Negative Exponential function provides better relative agreement across intervals according to MAPE. Model selection should therefore consider the evaluation indicator that is prioritised and the intended application of the modelling results.

The different calibrated equations obtained for SMAN 1, SMAN 2, SMAN 5, and SMAN 9 also indicate that a single impedance-function equation should not be directly applied to all schools. Differences in the function parameters reflect variations in student trip-length characteristics across the study sites. Therefore, the application of impedance functions in school-travel analysis should be based on calibration using local data. This approach can support an initial assessment of student trip origins and the concentration of travel according to distance, for example, as an input for school transport-service planning, service-area arrangement, or the identification of accessibility needs to schools.

Nevertheless, the model results in this study should be interpreted as estimated proportions of student trips by distance interval. The model was not used to construct a complete origin–destination matrix or estimate travel volumes on specific road-network links. Therefore, the use of these findings in more detailed transport planning should be complemented by information on student residential locations, travel modes, travel times, and road-network conditions. Even so, the findings provide empirical support for the need to align the selected impedance-function form with the actual trip-distribution pattern at each school.

4. Conclusion

This study compared the performance of the Negative Power, Negative Exponential, and Tanner impedance functions in representing student trip-length distributions at four senior high school in Surabaya. The observed distributions showed that student trips were generally concentrated within intermediate distance intervals, particularly at the 4.5 km and 7.5 km midpoints, before declining at longer distances. This pattern indicates that student trip-length distributions do not necessarily decrease monotonically from the shortest distance interval. Therefore, the selected impedance function should be capable of representing the observed increase, concentration, and subsequent decline in student-trip proportions.

The calibration results showed that the Negative Exponential function produced higher R^2 values than the Negative Power function at all study sites. The Tanner function produced the lowest SSE values at the four schools, indicating the smallest aggregate deviation between the observed and estimated distributions under the adopted calibration procedure. In contrast, the Negative Exponential function produced the lowest MAPE values at all schools, indicating the smallest average relative prediction error across distance intervals with non-zero observations. These contrasting results confirm that no single impedance function performed best under all evaluation indicators.

Accordingly, the Tanner function may be used when the analytical priority is aggregate fit under the adopted calibration approach, whereas the Negative Exponential function is preferable when relative agreement across distance intervals is prioritised. However, the Tanner results should be interpreted cautiously because the function was calibrated directly by minimising SSE, while the Negative Power and Negative Exponential functions were fitted using regression-based trendlines. A fully equivalent comparison therefore requires future calibration of all impedance functions using a common nonlinear optimisation criterion.

The differences in the calibrated parameters among the four schools also indicate that a single impedance-function equation should not be applied uniformly without local calibration. From a practical perspective, the resulting models can provide initial estimates of student-trip proportions by distance interval and support school accessibility assessment, school service-zone planning, traffic management around school areas, and student transportation planning in Surabaya. The findings may also assist local governments, education authorities, and transportation planners in identifying schools with wider travel catchment areas and prioritising accessibility improvements. Nevertheless, detailed planning applications require complementary information on student-origin locations, travel modes, travel times, traffic volumes, and road-network conditions. Future studies should incorporate these variables and apply a common calibration criterion to develop a more comprehensive and comparable school-trip-distribution model.

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