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FACTORS FOR ENHANCING INHERENT RESILIENCE IN TRAFFIC NETWORK

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Abstract: The study of the inherent resilience of traffic networks has not received due research attention. The ability of a link or a corridor can be enhanced with design factors. Traffic control means such as adaptive systems can be applied as well and these have been studied in the past and are in use in many cities around the world. However, there has been a general lack of attention to improving inherent resilience with geometric design factors. The paper will consist of five parts. The first part serves as a background. The second part defines a model of traffic service capability and its inputs. The intent is to investigate link and corridor-level means to enhance the inherent resilience in terms of sustained service flow. Specifically, the developed predictive model incorporates geometric factors, volume-delay functions, and operating speed. This model can be used to study service volume changes in relation to selected variables. The third part defines a microsimulation methodology, which enables testing of factors for enhancing inherent resilience. The simulation-based methodology will be described, and the process followed to prepare inputs will be explained. The U.S. Bureau of Public Roads (BPR) equation was used in simulation studies. The fourth part will cover an analysis of simulation outputs. Finally, conclusions are presented. The findings of this research are intended for use by traffic engineers so that traffic networks can be designed and operated with the improved ability of links and corridors to withstand traffic shocks better as compared to the conventional approaches.

1 INTRODUCTION

The subject of inherent (also called static) and dynamic resilience of adaptive capacity in urban traffic networks is “new and developing.” Inherent resilience is the ability to resist the loss of traffic-serving capability owing to geometric and control system design (Khan et al. 2016). The study of inherent resilience intends to look at different levels of traffic flow through a corridor and analyze the ability of the corridor to sustain the traffic serving capability. Numerous ways have been adopted by transportation engineers to mitigate the problem of congestion. This paper goes beyond current knowledge and practices by developing methods and technologies that enhance the inherent resilience of a transportation system. More than a decade ago, an initial step was taken in the form of adaptive traffic control of intersections and ITS installations. The majority of all network delays are experienced at signalized intersections. Implementation of Traffic Adaptive Control (TAC) demonstrated the effectiveness and wide range of benefits related to auto speed and delays, transit speed and delays, left-turn delays, intersection delays, pedestrian delays, fuel consumption, emission levels, and traffic conflicts. (Jagannathan and Khan 2001)

Depending upon the inherent resilience of a link or a corridor, the rate of decline of service flow can vary from one facility to another. From a planning and design perspective, it is highly desirable to enhance the inherent resilience of a facility to reduce the rapid decline of its traffic serving ability. See Figure 1 for profiles of inherent resilience impacted by disruptive events. How to reduce rapid drop in the ability of a facility to serve traffic is the same question as how to improve the inherent resilience.

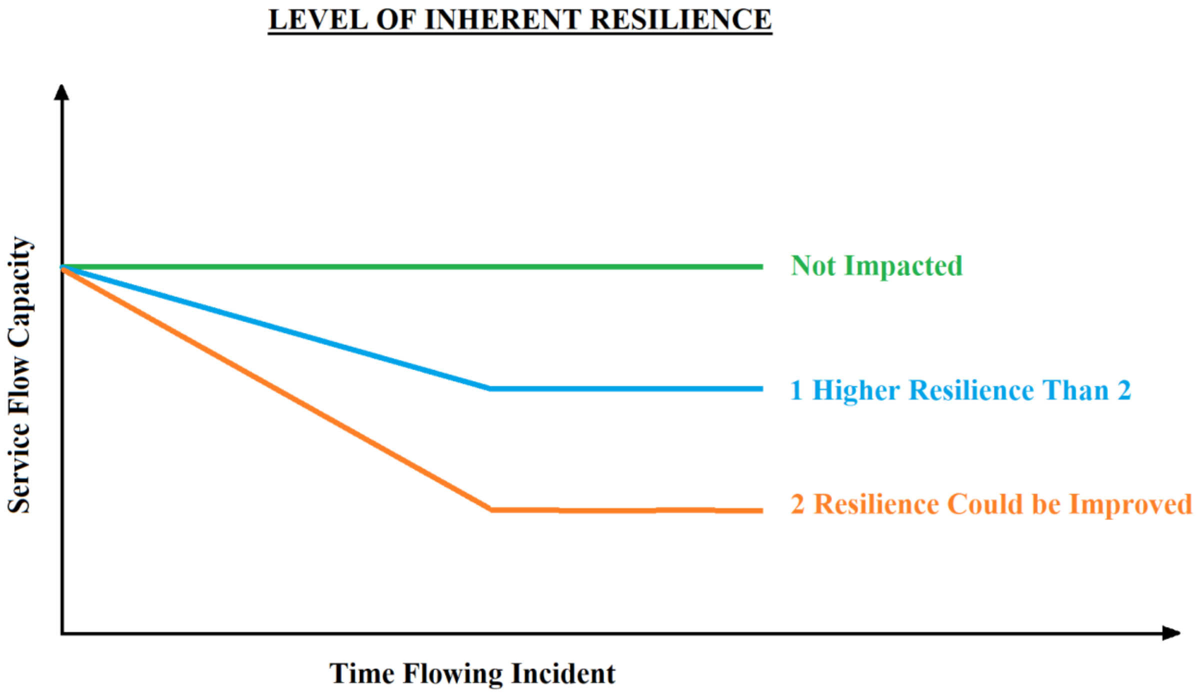

Figure 1:Level of inherent resilience

2 LITERATURE REVIEW

Recent advancement in traffic modelling and simulation software is expected to produce realistic speed and travel time estimation. For most research, VDFs are generalized for a particular class of links in the transportation network, e.g. highway speed estimation given FFS, the number of lanes, and flow. There has been a little exploration of the effect of different road parameters on the flow speed, i.e., segment length, number of lanes, road class. Difficulty measures vary for different speed estimation approaches. Adjusting VDFs type functions can be easily implemented with the most current available travel demand forecasting software and require little or no adjustment to the coded network (Kurth, van den Hout, and Ives 1996). Implementation of calculation-based approaches is difficult to use for network-based estimation, as it requires a high amount of data, extensive specific to link details, high computation overhead, and significant changes to network coding and specialized software. Uncertainty in inherent transportation traffic serving capabilities (inherent resilience) limit the use of the deterministic approach when modelling traffic demand in a transportation network. While browsing through literature, there has been more focus on determining the inherent flow speed and travel times of freeways more than that of networks, which consist of arterials, collectors, and local links connected by intersections. The U.S. Bureau of Public Roads (BPR) equation was found to be the most extensively applied Volume-Delay Function used in practice. "The Bureau of Public Roads (BPR) equation and its variations are used by transportation demand modellers to predict speed as a simple function of volume/capacity ratio" (TRB 1999) The standard BPR equation is:

[1] $s = s_f / 〖1+a(v/c)〗\hat{}b$

Where:

s = predicted mean speed

s_f = free flow speed

v = volume

c = practical capacity

a = 0.15 Standard

b = 4 Standard

On a study of “Analysis of Vehicle Running Speed and Its Influencing Factors on Urban Major Streets,” (Zi-lei, Chang-qiao, and Jian 2010) analyzed the running speed on major urban streets based on field data collected in Beijing city, China. The base running speed was defined under base conditions and calibrated based on BPR Volume delay functions. The correlation between running speed, segment length and number of lanes is as segment length and number of lanes increases, running speed increases. In 1997 Skabardonis, and Dowling proposed and tested improved speed-estimation techniques comparing field data and simulation results to provide better accuracy of long-range transportation planning models for predicting the relationship between the average speed and flow on links (Skabardonis and Dowling 1997). The model compared average speed of standard BPR, updated BPR, Akcelik Model equation; Highway Capacity Manual HCM- based model, and simulation data. The model compared the results for both freeway link speed estimation with Free flow speed of 96 km/ hour and a capacity of 2300 vehicle per hour per lane; and arterials links with a free-flow speed of 64 km/ hour and green/cycle=0.45 with various Arrival Types ranging from 1 – 6, 1 corresponding to poor progression and 6 correspond to perfect progression. The study concluded that the standard BPR curve predicts lower speed for volume/capacity (v/c) < 1 and higher speeds for v/c > 1. In addition, the study indicated, “Comparisons with real-world data sets indicate that the updated BPR curve for arterials significantly improved the accuracy of the estimated average speeds compared with the standard BPR curve.” The updated generalized BPR volume-delay function which produced the best fit to the HCM-based model and FREQ model had the parameters value for a = 0.2 and b = 10. Moreover, a research paper “Calibration and Evaluation of Link Congestion Functions: Applying Intrinsic Sensitivity of Link Speed as a Practical Consideration to Heterogeneous Facility Types within Urban Network” by (Mtoi and Moses 2014) used public data to calibrate volume delay functions namely: Bureau of Public Roads (BPR) curve, Davidson’s delay model, Akcelik function and conical delay model – and updated their input parameters.

“The process of refining the outputs of regional travel demand models depends on data that reflects regional travel activities. Travel demand models comprise complex computation steps nested together to accomplish multifaceted travel behavior in the network. Each step is represented by mathematical model, which needs to be calibrated, validated, and updated regularly to cope with the changes in trends of travel demand and behavior. The common practice is to calibrate and validate each step individually and not the entire model at once. This is done in order to control and minimize propagation of errors from one step to other subsequent steps.” (Mto i and Moses 2014) The free flow speeds estimates for freeways (uninterrupted flow facilities) was based on average speeds under low flow conditions of less than 10 passenger cars per hour per mile per lane. For arterials and interrupted flow facilities, the vehicle was considered to be free-flowing when it has a headway of 8 seconds or more to the vehicle ahead and 5 seconds or more for the vehicle behind in the same lane. Table 1 below shows the field estimate of free flow-speed for different facilities.

Curve fitting was then conducted for four most commonly used VDFs. Parameters were estimated for four facility types namely freeways or expressways, toll roads, managed lanes (HOV or HOT lanes), and signalized facilities. Each category of facility type comprises of three area types distinguished by land uses: urban (1), residential (2) and rural (3). Findings are shown in Table 2 below.

Table 1: Field estimated free-flow speeds and capacities (Mto i and Moses 2014)

Facility Type	Area Type	Number of Sites	Sample size	Speed Limit (mph)	Mean FFS (mph)	q_{max}(pc/h/ln)	Capacity (pc/h/ln)
Freeway	Urban	3	6810	55	64.671	1891	1686
Freeway	Urban	6	13081	65	66.79	2384	2027
Freeway	Residential	3	12083	55	60.537	1632	1418
Freeway	Residential	4	14115	65	67.783	2108	1887
Freeway	Residential	17	71033	70	71.131	2435	1722
Freeway	Rural	4	14115	65	67.783	2108	1878
Freeway	Rural	17	71033	70	71.131	2435	1742
Toll road	Urban	2	24104	60	64.324	1916	1748
Toll road	Urban	3	35586	65	68.503	2315	1938
Toll road	Residential	2	33872	55	63.324	2235	2074
Toll road	Residential	2	52570	65	71.441	1877	1741
Toll road	Residential	2	36288	70	74.031	2183	2025
Toll road	Rural	2	54210	65	73.72	1802	1772
Toll road	Rural	4	68446	70	75.627	2377	2205
HOV/HOT	Urban	1	18445	65	71.116	1917	1857
HOV/HOT	Residential	2	15367	65	70.451	1823	1702
Arterial	Urban	4	16015	30	34.609	984	846
Arterial	Urban	3	10046	45	52.046	969	825
Arterial	Residential	4	12125	35	41.92	936	884

Table 2: Parameter estimates for fitted models *(Mto i and Moses 2014)*

		Facility and Area Type									
		Freeways/Expressways			Toll Roads			HOV/HOT Lanes		Signalized Arterials	
Function		1	2	3	1	2	3	1	2	1	2
Fitted BPR	α	0.263	0.286	0.15	0.162	0.25	0.32	0.32	0.33	0.24	0.26
	β	6.869	5.091	5.61	6.34	7.9	6.71	8.4	8.6	7.5	8.2
Conical	β	18.39	18.39	15.06	18.39	15.064	15.064	18.55	18.7	18.8	18.8
	α	1.029	1.029	1.04	1.029	1.036	1.036	1.028	1.028	1.03	1.03
Modified Davidson	J	0.009	0.0092	0.0099	0.008	0.0099	0.0099	0.009	0.0089	0.01	0.01
	μ	0.95	0.949	0.951	0.94	0.952	0.94	0.95	0.947	0.95	0.95
Akcelik	τ	0.1	0.101	0.099	0.11	0.098	0.097	0.09	0.08	0.1	0.1

“ It is obvious that, the effect of change in congestion, near or at capacity, will have different impact on travel speed for a freeway link compared to a signalized arterial link. Speed tends to deteriorate faster in shorter links (urban signalized arterials) than in longer links (uninterrupted flow facilities such as freeways and expressways) when demand is close to capacity…. Conical, Akcelik and modified Davidson reach their steepest slopes at capacity (x = 1.0) different from fitted BPR which reaches its steepest slope at a demand 20% higher than capacity (x = 1.2)…. a link is robust to change in demand if either the demand or travel speed is low—that is, changes in demand have lesser effect to travel speed if there are a few travelers in the link (free-flow condition), or if the link is already highly congested, and therefore the speed will not deteriorate much further."(Mtoi and Moses 2014)

This paper will analyse microsimulation results of roads with different properties to investigate the means to enhance inherent resilience. The existing interpretation of the capability of our transportation infrastructure is dated.

3 TRAFFIC SERVING CAPABILITY AND ITS INPUTS

Traffic congestion in the business-as-usual context occurs in two forms. Recurring traffic congestion is the first form, which is owed to the increasing demand over time while the capacity supply does not improve at the same rate. The second form of congestion is the non-recurring type, which is owed to the surges in traffic due to frequent type incidents (e.g. traffic accidents) and roadwork zones. There is a third type of congestion that is caused by less frequent but very disruptive type of events such as severe traffic incident, nature-induced disruption (e.g. flooding of major arterials, bridge collapse), or human-related disruption (terrorist attack).

Technology advancements have introduced the analytical capability to manage existing infrastructure and shift away from new construction, which might not be an option in fully developed areas such as downtown.

The stochastic traffic assignment (Vissim) enables the study of traffic flow. The input variables for the traffic simulation model includes fixed infrastructure, vehicles, traffic control or traffic lights, and driver's behaviour. "The Bureau of Public Roads (BPR) equation and its variations are used by transportation demand modellers to predict speed as a simple function of volume/capacity ratio" (TRB 1999). However, more factors can affect the operating speed on a road segment than volume to capacity ratio. Analytical approach of several models to test the effect of changes in variables on the inherent resilience of a road will be used. Data will be collected from micro-simulated street segments with varying road characteristics. The models consist of different road classes with varying speed limit, segment length, geometry, number of lanes, and right and left turns lane availability.

3.1 Segment Length

Road segment length ranges from 100 m to 1000 m in length. The distance between intersections has an impact on the free flow speed observed on the road. The increased travel speed directly affects the capacity of the road segment.

3.2 Cycle Length

Green time duration will be chosen from a pool of random designs. Cycle length is assumed to be 60s, 90s, 120s, and 150s with 1 s all red / phase (maximum two phases), and amber = 3 s/ phase.

3.3 Number of Lanes

The study area consists of roads with up to 4 lanes; and includes left turn bay and right turn bay.

3.4 Posted Speed Limit

the focus of this part of the research is on a central business district. The posted speed limit analyzed will consist of 40 km/h, 50 km/h, and 60 km/hour.

3.5 Vehicle Composition

The composition of traffic is an important input to the findings. The light-duty vehicles will make up to 97 percent of the vehicle composition, and the remaining 3 percent will be heavy-duty vehicles (HDV). Volumes of turning vehicles is randomly selected between 5 percent and 10 percent of flow per corridor per hour.

3.6 Vehicle Volume

The volume/hour of vehicle inputs will be increased at a random rate of for each model to account for the variation of flow speed, and capacity of each model.

4 METHODOLOGY

Developing a new volume-delay function is complicated and implementing it require changes to network coding and processing procedures. On the other hand, improving adjustments on the BPR volume-delay function is more comfortable and implementing it require little or no changes to the currently available travel demand forecasting software. Assessment of transportation network sustainability and resilience needs a good estimate of vehicle flow speed and travel times under varying congestion densities. Flow speed estimation for area-wide models have been developed in the literature for general road classifications and posted speed limit. Flow speed estimation can still be improved. More details about road characteristics can help produce a better estimate of flow, flow-speed, and travel times prediction. Calibration of Volume Delay Function (VDF) parameter for each link with different properties (speed limit, segment length, number of lanes, geometric design features for turning movements, etc.) can be simulated to study the effect in terms of serving traffic. Use of advanced simulators to study road segments and networks is an asset to find traffic volume and flow speed and would help in planning and quantifying effects of network improvements.

Resilience studies had been conducted in an idealized network or to evaluate system performance given a predefined condition. Inherent resilience estimation approach aims to calculate traffic flow on roads with different characteristics; such as characteristics of links crossing, and flow-speed. The methodology is to estimate the capability of links to serve traffic using microsimulation techniques. The results should then be compared to the values of traffic flowing in the link from standard volume-delay function (VDF). Moreover, microsimulation will provide a means to measure the effect of link properties on traffic flow. Should actual traffic volumes flowing on links that are simulated, a comparison of data with simulated traffic would be useful.

The objectives of this paper are to investigate link and corridor-level means to enhance the inherent resilience in terms of sustained ability to serve traffic while resisting deterioration of quality of flow. Specifically, identify static (inherent) resilience measures for increasing traffic serving ability of urban roads/corridors and develop a predictive model for testing such measures. The predictive model is intended to estimate improvements in service flow and operating speed as a result of changes in geometric design under given traffic control factors (i.e. segment length, turning lanes, posted speed limit).

The output of the traffic model is a microscopic scale flow speed, and vehicles count. The results are analyzed and fitted to BPR formula in the intention to find a correlation between segment length, capacity, flow speed, cycle length, and number of lanes.

5 ANALYSIS OF SIMULATION OUTPUTS

This section of the paper identifies inputs variables and results of the simulated models. The flow speed trajectory is averaged for the number of vehicles that passes a particular road segment per hour, and the hourly flow is recorded. Each test consists of five runs at least to minimize errors, see Table 3.

Table 3: Models runs inputs and outputs

Input Variables									Outputs			
Model	Seg. Length	Green Time	# of lanes	Posted speed Limit	Left Turn	Left Turn Lane	Right Turn	Right Turn Lane	a	b	c	R^2
1	600	18	1	60	1	0	1	0	0.777	24.96	863	0.94
2	200	18	2	60	0	0	1	1	0.428	16.23	2146	0.957
3	300	18	2	60	1	1	1	1	0.144	25.48	1903	0.275
4	200	18	2	50	0	0	1	1	0.057	39.09	2081	0.967
5	300	18	1	60	1	0	1	0	0.443	11.90	756	0.966
6	700	18	2	60	0	0	1	1	0.108	37.89	2127	0.952
7	700	18	2	60	1	1	1	1	0.028	31.82	1708	0.979
8	900	25	1	50	1	0	1	1	0.25	23.17	808	0.879
9	500	26	4	50	1	0	1	0	0.199	568.0	3305	0.957
10	300	25	1	60	1	0	1	1	0.651	9.755	747	0.937
11	400	26	4	60	1	1	1	0	0.125	14.67	3398	0.829
12	700	41	1	40	1	0	1	1	0.139	14.03	726	0.731
13	400	40	4	40	1	0	1	0	0.289	103.7	2980	0.58
14	300	41	2	40	1	0	1	1	0.143	17.36	1423	0.97
15	400	41	1	50	1	0	1	1	1.095	9.479	842	0.788
16	600	40	4	50	1	0	1	0	0.079	82.31	3144	0.441
17	200	41	2	50	1	0	1	1	0.543	13.28	1651	0.807
18	700	48	1	60	1	0	1	1	0.221	24.64	725	0.815
19	400	48	4	60	1	0	1	0	0.11	25.34	3024	0.936
20	300	48	2	60	1	0	1	1	0.509	30.80	1319	0.721
21	900	48	1	50	1	0	1	1	0.345	6.55	807	0.953
22	900	48	1	60	1	0	1	1	0.251	7.537	809	0.935
23	500	48	4	60	1	0	1	0	0.951	9.84	3066	0.868
24	200	55	1	60	1	1	1	1	0.225	3.085	998	0.89
25	200	56	2	60	1	1	1	1	0.432	2.763	2175	0.94
26	900	55	2	60	1	1	1	0	0.091	11.69	1820	0.979
27	700	56	3	60	1	1	1	1	0.212	18.13	3443	0.968
28	300	18	1	40	1	0	1	0	0.485	15.03	812	0.654
29	700	18	2	40	0	0	1	1	0.221	20.92	2014	0.919
30	700	18	2	40	1	1	1	1	0.052	19.72	1750	0.548
31	800	18	3	40	1	1	1	1	0.023	135.1	2236	0.749
32	600	18	1	50	0	0	1	0	0.069	83.51	1026	0.793
33	200	18	2	50	0	0	1	1	0.03	32.89	2016	0.947
34	300	18	2	50	0	0	1	1	0.049	27.90	1987	0.953
35	400	18	3	50	0	0	1	1	0.023	30.60	3080	0.963

The results are then analyzed and fitted to the BPR formula in the intention to find a correlation between segment length, capacity increase, and flow speed. As an example, Table 3 below shows the properties of each road segment simulated and the analyzed variables (segment length, green time duration, number of lanes, posted speed limit, left and right turns). The output is Nonlinear regression analysis was carried using SPSS to estimate a, b, and capacity (c). The coefficient of determination (R^2) is used as a statistical measure.

For illustration a graphical presentation of models 11, 25, 29, and 35 is presented in graphs 2,3,4, and 5 respectively.

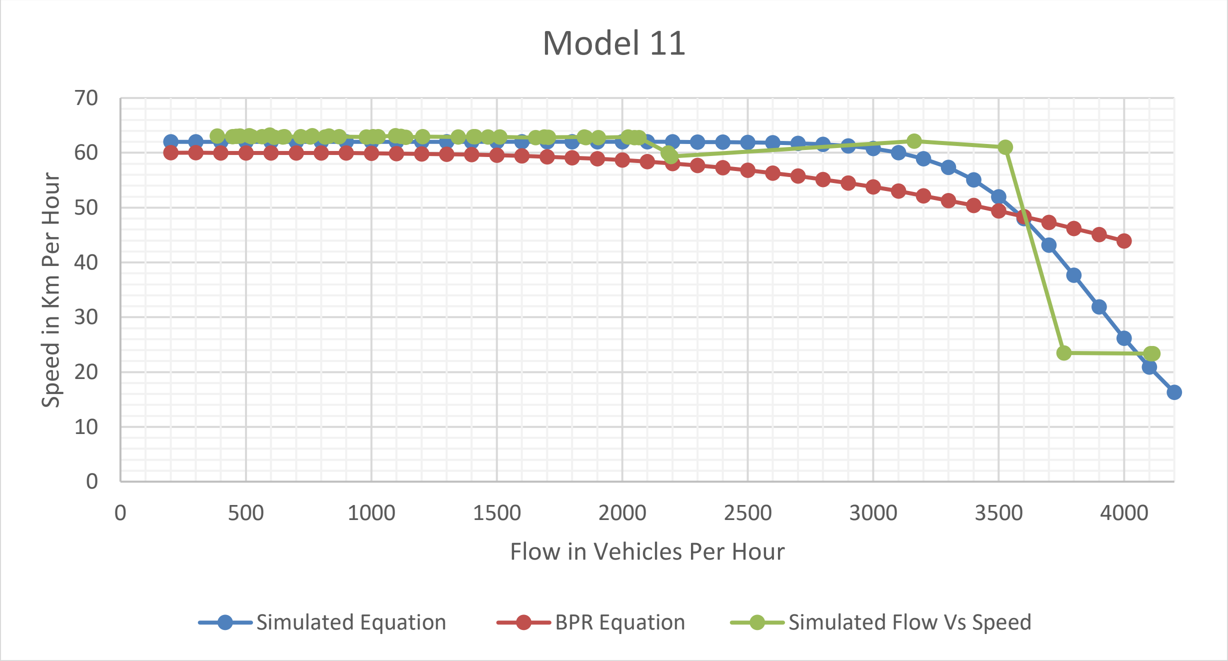

Figure 2: Model 11 fitted VS standard BPR equation parameters

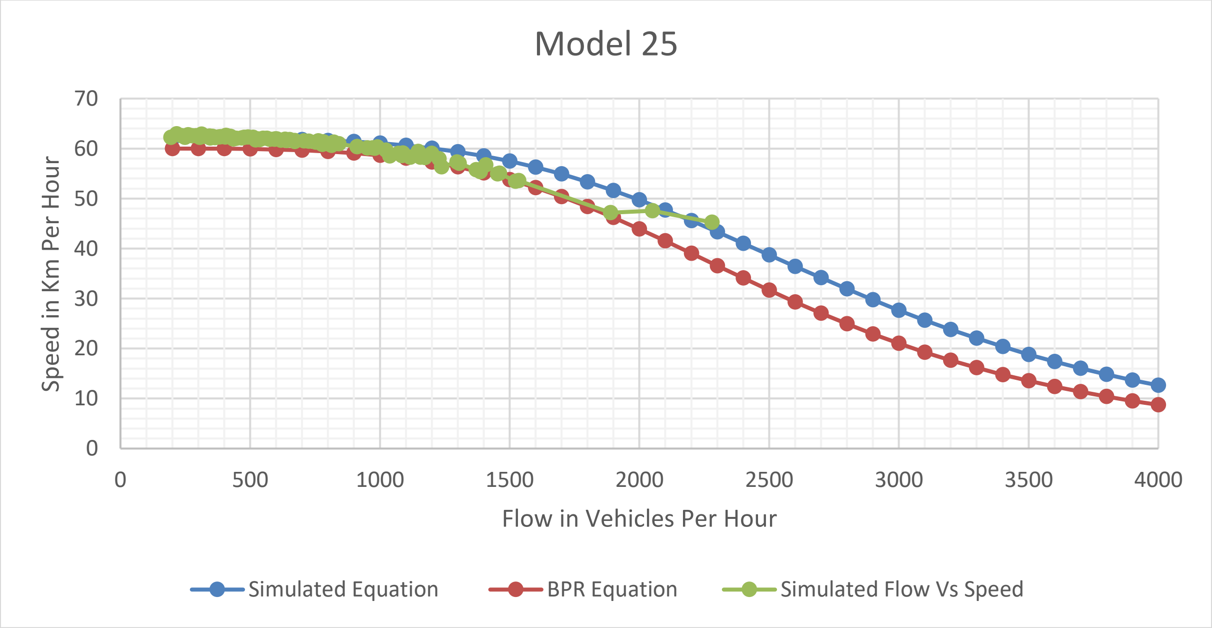

Figure 3: Model 25 fitted VS standard BPR equation parameters

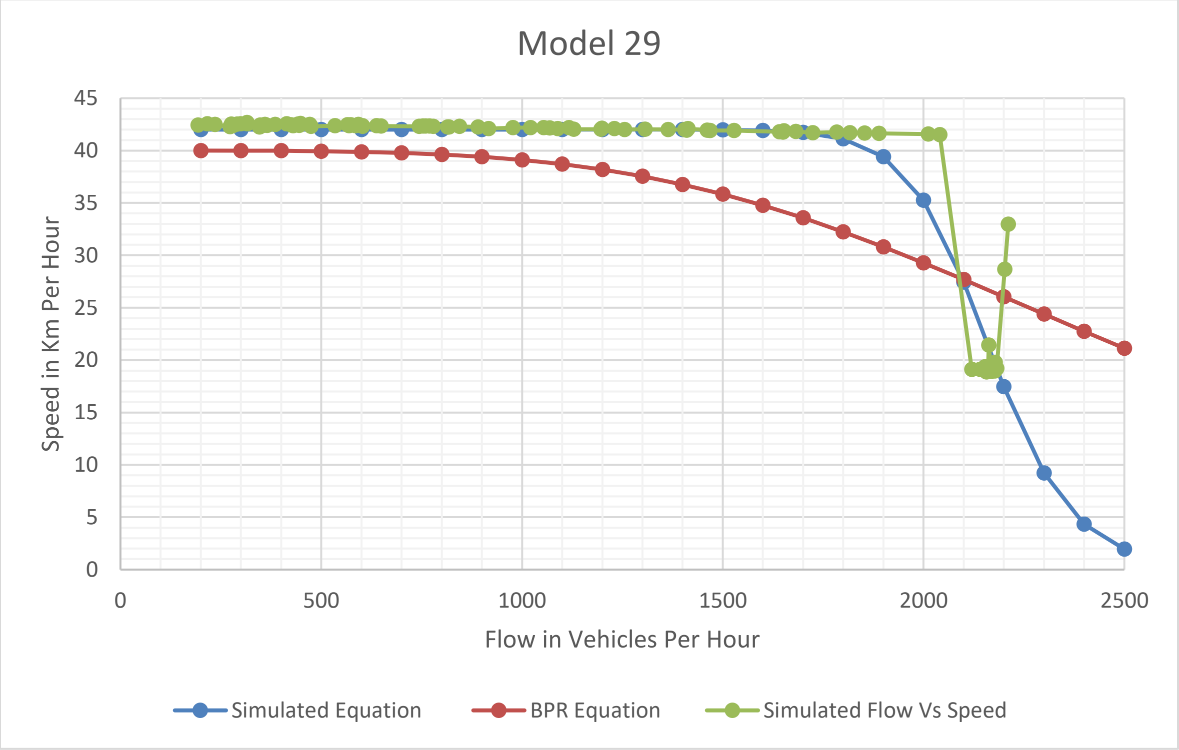

Figure 4: Model 29 fitted VS standard BPR equation parameters

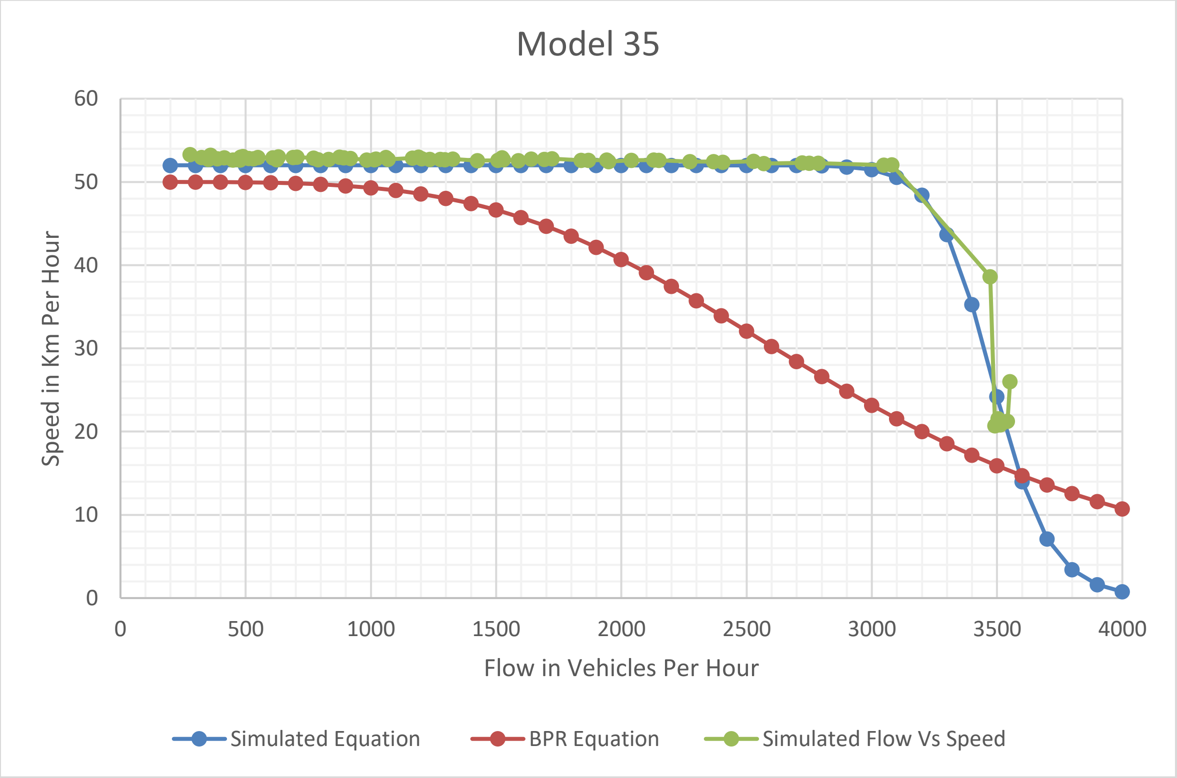

Figure 5: Model 35 fitted VS standard BPR equation parameters

6 CONCLUSIONS

The microsimulation-based analysis can be used to enhance the inherent resilience of transportation corridors with different characteristics. Still, more models need to be developed in order to produce a predictive model to solve the interrelations of a, b, and serving capacity of transportation corridors. The current models yielded a satisfactory R^2. Significant findings are the capacity of a corridor is affected the most by the number of lanes, left turn on the intersection, and the availability of left turn bay; followed by speed limit, green time and segment length. Segment length of 100 m has a flow speed of less than that of the posted speed limit. Field data is required to estimate the fluctuation of flow speed in longer segment length to produce a better-simulated result. The coefficients of (b) are larger than the standard coefficient used in the BPR equation (4) which implies that the BPR equation predicts lower speed for v/c < 1 and higher speed for v/c >1. In addition, the study indicated that capacities of corridors are underestimated, and flow speed deteriorates faster with the increased flow than standard BPR equation. More models need to be developed to account for changes in corridors characteristics and to draw better estimates of parameters.

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