Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 50 (2020) 458–465

Transportation Research Procedia

www.elsevier.com/locate/procedia

XIV International Conference 2020 SPbGASU "Organization and safety of traffic in large cities"

Estimation of traffic flow parameters of U-turns

Alexander Mikhailov[a], Evgenii Shesterov[b]*

[a]Irkutsk National Research Technical University, 83 Lermontova St., Irkutsk, 664074, Russia
[b]Saint Petersburg State University of Architecture and Civil Engineering, 4 Vtoraja Krasnoarmejskaja St., Saint Petersburg, 190005, Russia

Abstract

U-turns are widely used both on interurban highways and in urban streets. Estimation procedure regarding their traffic capacity was developed over 40 years ago. The calculated parameter values obtained were not specified for several decades. Therefore, we studied the operation of U-turns in order to specify calculation methods. The article considers such characteristics of the major and minor traffic flows as headways and lags. It presents research results as to the traffic volume influence on headways' distribution and critical headway values in cases of U-turn facilities with the acceleration merging lane. We obtained a dependence connecting Erlang coefficient with traffic volume and a relationship characterizing the influence of traffic volume on critical headway values. We also established that minimal lags accepted by minor traffic flow drivers do not depend on traffic volume.

Keywords: U-turns; headway and lag acceptance; traffic volume influence on drivers' behavior.

1. Introduction

U-turns are widely spread and used as a part of incomplete road interchanges as elements replacing at-grade crossings and junctions as well as to provide access to attractions located in the vicinity of major highways. A methodology of calculating the traffic capacity of U-turns was proposed in the Russian Highway Manual 218.2.020-2012 "Methodical recommendations for highway capacity estimation". In this document, the calculation of the traffic capacity of U-turns is based on an assumption that major flow headways follow exponential distribution. Its clauses also imply that the flow headways have a significant range of variation. This methodology was included in the methodical documents published in the Russian Federation during the last decade without any changes. At the same time, an increase in vehicles per capita led to the traffic becoming heavier and denser, which resulted in changes of such characteristics as headway variation range and headway distribution functions. The article presents research results as to the influence traffic volume has on the distribution of traffic flow headways and critical gap values, accepted by minor road drivers in cases of U-turns with the acceleration merging lane.

* Corresponding author. Tel.: +7-914-870-18-40.
E-mail address: eashest@rambler.ru

10.1016/j.trpro.2020.10.054

2. Practical application of U-turns and U-turn capacity estimation in the Russian Federation

The practice of U-turns on Russian urban streets and roads is diverse. U-turns are used in case of partial graded interchanges (Moscow, St. Petersburg, Ulan-Ude, Irkutsk), on urban highways and roads instead of at-grade intersections. For example, in St. Petersburg the 7 km section of Pulkovskoye Highway (between Victory Square and a gas station at 55A Pulkovskoye Highway) has the following characteristics:

- 8 median openings in the central reservation with U-turns equipped with acceleration merging lanes;
- minimal distance between an access point to the major carriageway and a median opening varies from 60 to 510 m;
- turning radius in the median openings is 5–6 m.

In general, U-turns in urban conditions are recommended if the volume of left-turning traffic is between 200 and 250 veh/h as safety improvement of left turns. We should note that Russian specialists do not find U-turns to be accident clusters (Brylev et. al 2018, Danilov et al. 2020, Evtiukov et al. 2018, Ginzburg et al. 2017, Kerimov et al. 2017, Kurakina et al. 2018, Marusin et al. 2018, 2019, 2020, Soo et al. 2020).

To calculate the traffic capacity P of a U-turn, the Russian Highway Manual 218.2.020-2012 "Methodical recommendations for highway capacity estimation" proposes the following equation:

$$P = N\left(\frac{e^{-N/T\left(t_g - 1\right)}}{1 - e^{-N/T\delta t}}\right) \quad (1)$$

where N — major traffic flow volume, veh/h; T= 3600 s, t_g — critical headway in the major traffic flow depending on traffic volume, type of maneuver and intersection design, s; δt — follow-up headway of minor traffic flow.

Equation (1) implies that the 85% percentile value of accepted gaps is a critical gap used in the capacity estimation procedure. Consequently, in the case of U-turn, the specified follow-up headway values are used:

δt = 2.2 s for a U-turn with a stop;

δt = 2.6 s for a U-turn in case of acceleration lane for minor traffic flow merging with the major one.

3. Theory of calculating traffic capacity in the area of merging flows

Foreign researchers (Al-Masaeid, 1999, Haştemoğlu 2016, Luttinen 2003, Liu et al. 2008, 2009, Transportation Research Board 2000) employ a generalized equation to estimate maximum ramp capacity:

$$c = q\sum_{i=1}^{\infty}(i+1)P\left[t_c + it_f \le t \le t_c + (i+1)t_f\right] \quad (2)$$

where c — maximum ramp capacity, veh/h; q — main through flow traffic volume in the area of merging flows, veh/h; t_c — critical headway, s; t_f — follow-up time, which is minimal headway with regard to a minor road vehicle following a minor road vehicle merging into the main flow, s; $P[t_c+i\ t_f \le t \le t_c+(i+1)t_f]$ — the probability of time headway t between values $t_c+i\ t_f$ and $t_c+(i+1)t_f$; i = 1, 2, 3...

According to equation (2), the minor traffic flow capacity c is the function of the main traffic flow headways' distribution t. Researchers consider exponential or Erlang distribution as an alternative to such a distribution (Ashworth and Green 1966, Brilon et al. 1997, McGowen and Stanley 2012, Sullivan and Troutbeck 1994). Erlang density distribution has the following form:

$$f(x) = \frac{1}{\Gamma(k)\theta^k} x^{k-1-\frac{x}{\theta}} \tag{3}$$

where k and θ — distribution parameters; $\Gamma(k)$ — Euler gamma function.

Erlang coefficient k is inversely proportional to the coefficient of variation V. In accordance with the theory of interrupted traffic flow in case of Erlang coefficient values k = 1 and k = 2, the following equations of capacity estimation are used (Jenjiwattanakul et al. 2013):

$$\text{at } k = 1 \quad c = \frac{qe^{-qt_c}}{1-e^{-qt_f}} \tag{4}$$

$$\text{at k} = 2 \quad c = \frac{qt_f e^{-2qt_c}}{1-e^{-3qt_f}}\left[1+2qt_c+\frac{2qt_f e^{-4qt_f}}{1-e^{-2qt_f}}\right] \tag{5}$$

It should be noted that equation (3) is similar to equation (1) used in the Russian Highway Manual 218.2.020-2012. We intended to reveal situations, in which we need to use equation (5) instead of equation (1). That implied investigating patterns of traffic flow volume vs. variation of major traffic flow headways.

4. Results of the experiment

We considered the interaction of the major traffic flow with the minor traffic flow using a case study of a U-turn of a partial clover leaf graded interchange at Lermontova St. in Irkutsk. The minor traffic flow uses an acceleration merging lane 95 m long, while the left turn is performed from the left lane into the left lane of dual carriageway (Fig. 1).

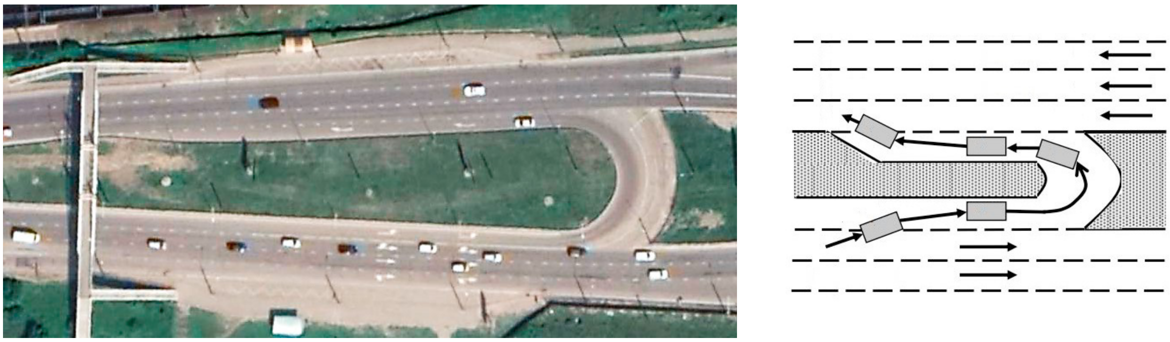


Fig. 1. U-turn facility under consideration and schematic representation of traffic from the left lane into the left lane.

In order to obtain the characteristics of the major and minor flows interacting, presented in Fig. 2, we performed eight sessions of video recording with 10–15 minutes duration. The camera was installed 5 m above the roadway, which provided a good view of both major and minor traffic flows.

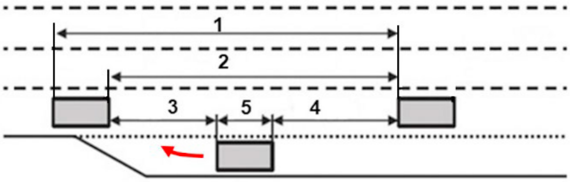


Fig. 2. Characteristics of the traffic flows interaction in the merging area (1 — accepted headway; 2 — accepted gap; 3 — lead gap; 4 — lag gap; 5 — occupancy).

We defined major flow headway as the time between the crosses of the front bumpers of two successive vehicles at a designated point:

$$h_i = \tau_{i+1} - \tau_i \tag{6}$$

where h_i — headway between successive vehicles i and i +1; and τ_i+1 — designated point crossing time by the front bumpers of two successive vehicles i and i +1.

Lag gap (Fig. 2) was defined as the time between the passage of the rear bumper of a minor flow vehicle, which accepted the headway, and the passage of the front bumper of a major flow vehicle, closing up the accepted headway. Further in this article, we use the term lag instead of lag gap. Since we did not use a detector, the occupancy (Fig. 2) is determined as the ratio of considered vehicle length to considered current vehicle speed.

The critical headways were determined using Raff's method (Guo et al. 2014, Nemchinov et al. 2018, 2020). Processing of the experimental data proved the influence of traffic volume on the headway variation range and the accepted headway values (Tables 1, 2, Fig. 3). An increase in traffic volume from 600 to 1700 veh/h resulted in variation range dropping down by 75%.

Table 1. Values of headways accepted by minor flow drivers.

Major flow traffic volume in the left lane, veh/h	Headway values, s						Standard deviation
	Average	Minimum	Maximum	15% occurrence	85% occurrence	Variation range	
1224	3.02	0.49	14.74	1.14	5.00	14.25	2.45
1728	2.15	0.52	11.65	1.14	3.31	11.13	1.49
1188	3.03	0.67	15.88	1.22	5.24	15.21	2.45
672	5.35	0.75	23.56	1.14	10.38	22.81	5.36
594	5.87	0.63	47.65	1.32	9.66	47.02	6.70
1002	3.72	0.21	22.95	0.96	7.09	22.74	4.11
1236	3.14	0.40	16.49	1.05	5.95	16.09	2.91
792	4.60	0.41	22.16	1.18	8.71	21.75	4.40

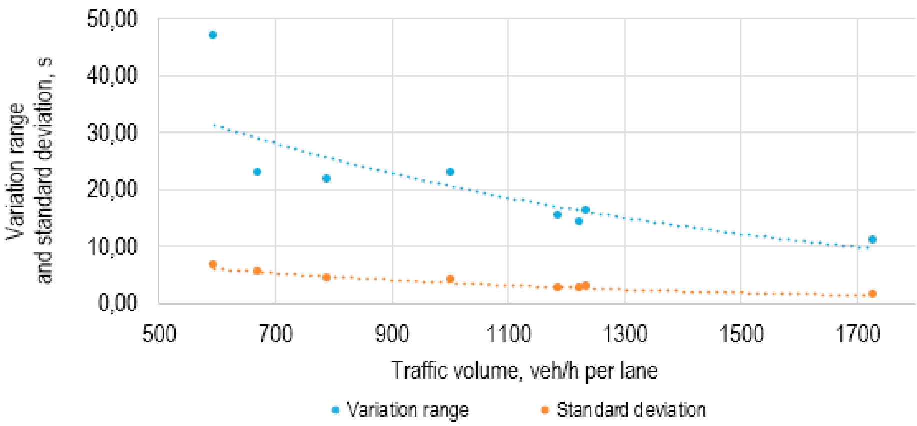


Fig. 3. Variation range and standard deviation of headway values depending on major flow traffic volume.

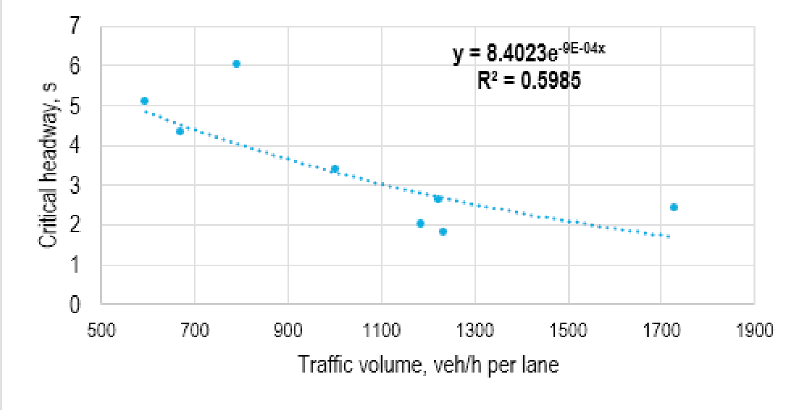
When traffic volume exceeds 1000 veh/h per lane, Erlang coefficient value exceeds 1, therefore, we need to use the second equation presented in Table 2, which is not included in the Russian highway capacity manuals. This can be regarded as one of the most important results of this study. We received a regression equation connecting the Erlang coefficient value with traffic volume (veh/h per lane):

$$y = 0.0005x + 0.6264; \quad R^2 = 0.7586 \tag{7}$$

Table 2. Recommended equations to calculate the traffic capacity of the merging area.

Traffic volume, veh/h per lane	Erlang coefficient value	Recommended equation to calculate traffic capacity
672	1.00	$c = \frac{qe^{-qt_c}}{1-e^{-qt_f}}$
594	0.88	
1002	0.90	
1224	1.23	$c = \frac{qt_f e^{-2qt_c}}{1-e^{-3qt_f}}\left[1 + 2qt_c + \frac{2qt_f e^{-4qt_f}}{1-e^{-2qt_f}}\right]$

In addition to establishing critical headway values, one of the most important parts of this study consisted in testing a hypothesis of the influence of major flow traffic volume on minor flow drivers' behavior and critical headway values. Based on the experimental data, we noted that an increase in traffic volume from 600 to 1700 veh/h per lane results in critical headway value dropping down by 50%. The influence of traffic volume on the critical headway value is approximated by an exponential function (Fig. 4).



Traffic volume, veh/h per lane	Critical headway, s
1224	2.6
1728	2.4
1188	2.0
672	4.3
594	5.1
1002	3.4
1236	1.8
792	6.0

Fig. 4. Influence of traffic volume on the critical headway value.

Lags as a characteristic of major and minor traffic flows interaction were not considered in Russian specialist literature, but they are studied by foreign specialists (Devarasetty et al. 2012). Therefore, in our study, in addition to critical headway, we also determined lag (lag gap, Fig. 2), measured as the time between the passage of the rear bumper of a minor flow vehicle, accepting the headway, and the passage of the front bumper of a major flow vehicle, closing up the accepted headway. The results of field surveys show that in contrast to the average and 85% percentile values of accepted lag, the minimal accepted lag and 15% percentile of accepted lag values are not subject to the influence of main traffic volume (Table 3 and Fig. 5). In this context, the drivers accepting lags of less than 15% percentile value can be classified as aggressive. On average, 15% percentile value of accepted lags is 1.5 s.

Table 3. Values of lag duration accepted by minor flow drivers.

Major flow traffic volume in the left lane, veh/h	Lag duration value, s				
	Average	Minimum	Maximum	15% percentile	85% percentile
1224	7.05	0.87	29.67	1.90	14.34
1728	3.79	0.94	18.99	1.39	4.89
1188	4.11	0.77	14.14	1.22	7.69
672	5.69	0.53	14.01	1.62	10.77
594	10.55	0.83	46.24	1.68	20.05
1002	5.51	0.33	22.24	1.48	9.31
1236	3.52	0.67	14.93	1.31	6.67
792	3.52	0.67	14.93	1.31	6.67

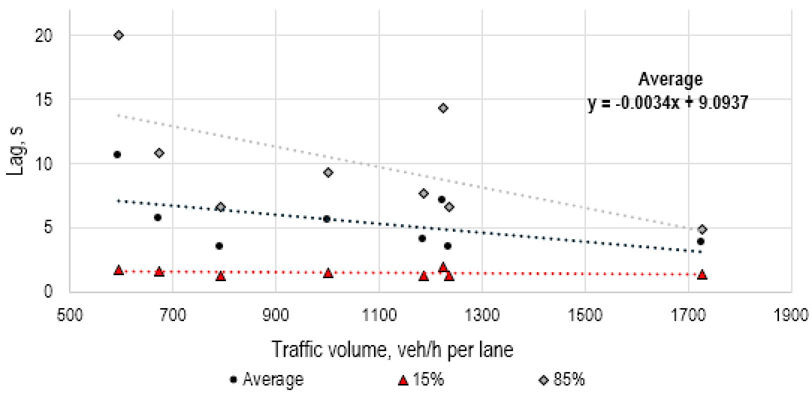


Fig. 5. Influence of major flow volume in the left lane on the accepted lag values: average; 15% percentile; 85% percentile.

In 2019, the considered U-turn was reconstructed and equipped with an acceleration merging lane. Thus, we had an opportunity to compare the results of this study with the field surveys of 2018 to estimate the effect of the acceleration merging lane. In the range of traffic volumes on the left lane of the major road between 600 and 1000 veh/h, the critical gap values were:

- without the acceleration merging lane — 4.5–6.4 s;
- with the acceleration merging lane — 3.4–6.0 s.

The critical headway value reduction reaches 10–25%.

5. Conclusions

The conducted study of major and minor traffic flows interaction in the areas of U-turns equipped with an acceleration merging lane, allows us to make the following conclusions:

1. An increase in traffic volume causes a reduction of the variation range of gap values. If the left lane traffic volume of the major flow exceeds 1000 veh/h per lane, a model based on Erlang distribution should be applied.
2. The survey results prove that the critical headway is heavily influenced by traffic volume of the major flow. An increase in the main traffic volume from 600 to 1700 veh/h per lane results in critical headway value dropping down by 50%. The influence of major traffic volume can be represented by an exponential function.
3. The similar effect of the major flow traffic volume has been revealed in case of the average accepted lag and 85% percentile value of accepted lag. An increase in the main traffic volume from 600 to 1700 veh/h per lane results in 50% percentile accepted lag value dropping down by 40%. In contrast to the average accepted lag, the minimal accepted lag value was not affected by major traffic flow volume and averaged 1 s. Besides, 15% percentile value of accepted lag was not influenced by main traffic flow volume and averaged 1.5 s.

References

Al-Masaeid, H.R., 1999. Capacity of U-turn at median openings. ITE Journal 69 (6), 28–30.

Ashworth, R., Green, B.D., 1966. Gap acceptance at an uncontrolled intersection. Traffic Engineering and Control 7 (11), 676–678.

Brilon, W., Koenig, R., Troutbeck, R.J., 1997. Useful estimation procedures for critical gaps. Transportation Research Part A: Policy and Practice 33 (3–4), 161–186. DOI: 10.1016/S0965-8564(98)00048-2.

Brylev, I., Evtiukov, S., Evtiukov, S., 2018. Problems of calculating the speed of two-wheeled motor vehicles in an accident. Transportation Research Procedia 36, 84–89. DOI: 10.1016/j.trpro.2018.12.047.

Danilov, I., Marusin, A., Mikhlik, M., Uspensky, I., 2020. Development of the mathematical model of fuel equipment and justification for diagnosing diesel engines by injector needle displacement. Transport Problems 15 (1), 93–104. DOI: 10.21307/tp-2020-009.

Devarasetty, P.C., Zhang, Y., Fitzpatrick, K., 2012. Differentiating between left-turn gap and lag acceptance at unsignalized intersections as a function of the site characteristics. Journal of Transportation Engineering 138 (5), 580–588. DOI: 10.1061/(ASCE)TE.1943-5436.0000368.

Evtiukov, S., Karelina, M., Terentyev, A., 2018. A method for multi-criteria evaluation of the complex safety characteristic of a road vehicle. Transportation Research Procedia 36, 149–156. DOI: 10.1016/j.trpro.2018.12.057.

Ginzburg, G., Evtiukov, S., Brylev, I., Volkov, S., 2017. Reconstruction of road accidents based on braking parameters of category L3 vehicles. Transportation Research Procedia 20, 212–218. DOI: 10.1016/j.trpro.2017.01.054.

Guo, R.-J., Wang, X.-J., Wang, W.-X., 2014. Estimation of critical gap based on Raff's definition. Computational Intelligence and Neuroscience 6, 236072. DOI: 10.1155/2014/236072.

Haştemoğlu, H., 2016. Estimation of critical gap of U-Turns road in Turkey. Journal of Transportation Technologies 6 (3), 131–138. DOI: 10.4236/JTTS.2016.63012.

Jenjiwattanakul, T., Sano, K., Nishiuchi, H., 2013. Capacity of U-turn junction at midblock median opening on urban arterial based on balancing volume-to-capacity ratio. Journal of the Eastern Asia Society for Transportation Studies 10, 1670–1686. DOI:10.11175/EASTS.10.1670.

Kerimov, M., Safiullin, R., Marusin, A., Marusin, A., 2017. Evaluation of functional efficiency of automated traffic enforcement systems. Transportation Research Procedia 20, 288–294. DOI: /10.1016/j.trpro.2017.01.025.

Kurakina, E., Evtiukov, S., Rajczyk, J., 2018. Forecasting of road accident in the DVRE system. Transportation Research Procedia 36, 380–385. DOI: 10.1016/j.trpro.2018.12.111.

Liu, P., Lu, J.J., Cao, B., 2009. Capacity of U-turns at unsignalized median openings on six-lane streets. Transportation Research Record: Journal of the Transportation Research Board 2130 (1), 59–65. DOI: 10.3141/2130-08.

Liu, P., Lu, J.J., Hu, F., Sokolow, G., 2008. Capacity of U-turn movement at median openings on multilane highways. Journal of Transportation Engineering 134 (4), 147–154. DOI: 10.1061/(ASCE)0733-947X(2008)134:4(147).

Luttinen, R.T., 2003. Capacity at unsignalized intersections. TL Consulting Engineers Ltd., Lahti.

Transportation Research Board, 2000. Highway Capacity Manual 2000 (HCM 2000). Transportation Research Board, Washington.

McGowen, P., Stanley, L., 2012. Alternative methodology for determining gap acceptance for two-way stop-controlled intersections. Journal of Transportation Engineering 138 (5), 495–501. DOI: 10.1061/(ASCE)TE.1943-5436.0000358.

Marusin, A.V., Danilov, I.K., Khlopkov, S.V., Marusin, A.V., Uspenskiy, I.A., 2020. Development of a mathematical model of fuel equipment and the rationale for diagnosing diesel engines by moving the injector needle. IOP Conference Series: Earth and Environmental Science 422, 012126. DOI: 10.1088/1755-1315/422/1/012126.

Marusin, A., Marusin, A., Ablyazov, T., 2019. Transport infrastructure safety improvement based on digital technology implementation. Atlantis Highlights in Computer Sciences, Vol. 1. International Conference on Digital Transformation in Logistics and Infrastructure (ICDTLI 2019), 353–357. DOI: 10.2991/icdtli-19.2019.61.

Marusin, A., Marusin, A., Danilov, I., 2018. A method for assessing the influence of automated traffic enforcement system parameters on traffic safety. Transportation Research Procedia 36, 500–506. DOI: 10.1016/j.trpro.2018.12.136.

Nemchinov, D., Mickhailov, A., Kostsov, A., Martiyahin, D., 2018. Determining the critical headways by observation the roundabout's traffic flows in Russian Federation. In: Lakušić, S. (ed.). 5th International Conference on Road and Rail Infrastructure. Zadar, Croatia. https://doi.org/10.5592/CO/cetra.2018.724.

Nemchinov, D., Martiyahin, D., Mikhailov, A., Kostsov, A., Nemchinov, M. 2020. Research of accepted headways and visibility conditions on intersections. Transportation Research Procedia 45, 13–20. https://doi.org/10.1016/j.trpro.2020.02.057.

Soo, S., Abdel Sater, K.I., Khodyakov, A.A., Marusin, A.V., Danilov, I.K., Khlopkov, S.V., Andryushenko, I.S., 2020. The ways of effectiveness increase of liquid fuel with organic addition appliance in aerospace equipment. Advances in the Astronautical Sciences 170, 833–838.

Sullivan, D.P., Troutbeck, R.J., 1994. The use of Cowan's M3 headway distribution for modelling urban traffic flow. Traffic Engineering and Control 35 (7/8), 445–450.