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$M/G/c/c$ state dependent travel time models and properties

J. MacGregor Smith [a,*], F.R.B. Cruz [b]

[a] Department of Mechanical and Industrial Engineering, University of Massachusetts Amherst, MA 01003, United States

[b] Departamento de Estatística, Universidade Federal de Minas Gerais, 31270-901 - Belo Horizonte - MG, Brazil

HIGHLIGHTS

- $M/G/c/c$ models provides a quantitative foundation for three-phase traffic flow theory.
- $M/G/c/c$ travel time function is S-shaped (i.e. logistics curve).
- The S-shaped curve captures the phase transition from Free Flow to Congested Flow.

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ABSTRACT

One of the most important problems in today's modeling of transportation networks is an accurate estimate of travel time on arterial links, highway, and freeways. There are a number of deterministic formulas that have been developed over the years to achieve a simple and direct way to estimate travel times for this complex task. Realistically, however, travel time is a random variable. These deterministic formula are briefly reviewed and also a new way to compute travel time over arterial links, highway, and freeways, is presented based on an analytical state dependent queueing model. One of the features of the queueing model is that it is analyzed within the context of the theoretical three-phase traffic flow model. We show that the model provides a quantitative foundation alternative to qualitative three-phase traffic flow theory. An important property shown with the model is that the travel time function is not convex, but a sigmoid S-shaped (*i.e.* logistic curve). Extensive analytical and simulation experiments are shown to verify the S-shaped nature of the travel time function and the use of the model's method of estimation of travel time over vehicular traffic links as compared with traditional approaches. Finally, it is shown that the point-of-inflection of the S-shaped curve represents the threshold point where the traffic flow volume switches from Free Flow to Congested Flow.

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1. Introduction

"Therefore, queueing theories cannot be relied upon for a correct description of congestion on un-signalized freeways, and the term 'queue' will henceforth not be used to describe traffic on freeways", Boris S. Kerner, *The Physics of Traffic*, p. 85, Springer-Verlag, Berlin, 2004.

Most design and analysis studies of transportation networks need to estimate in some way the travel time over the traffic network segments. This is a fundamental but difficult problem because of congestion, natural variability of rates of travel, time of day, road and weather conditions, driver characteristics, and vehicle types. The traffic flow process is essentially a stochastic (random) process. Since this is a random process, one needs to estimate the probability distribution of the number of vehicles along a roadway in order to compute the desired performance measures of the roadway such as throughput, queueing delays, average number of vehicles along the segment and the utilization of the roadway segment.

* Corresponding author. Tel.: +1 14135454542.
E-mail addresses: jmsmith@ecs.umass.edu, jmacgregor.smith@gmail.com (J. MacGregor Smith), fcruz@est.ufmg.br (F.R.B. Cruz).

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It is important to have an accurate formula since the use of this formula is critical to transportation planning and traffic assignment activities.

1.1. Motivation and purpose

In this paper, we illustrate the special properties of a state dependent queueing approach to traffic modeling. Part of the reason for this is to show that through the queueing approach, it helps explain the often frustrating experience that drivers face when there is severe congestion on roadways. On another account, with the queueing approach, it begins to explain quantitatively some of the fundamental assertions of Kerner's three-phase traffic theory [1].

Another feature of this paper is to develop an approach to understanding what type of travel time calculations will result from the queueing approach. This is motivated by the following situations and examples.

For example, in estimating the amount of fire insurance for a community's fire protection, insurance companies often utilize a simple formula to estimate the response time for an engine company to respond to a fire. While the fundamental response time is a stochastic process, the insurance companies will often use a deterministic formula to estimate this response time. In fact, one formula often used is based upon linear-regression research by Hausner et al. [2] and is the following:

$$T = 0.66 + 1.77D,$$

where:

T := time in minutes to the nearest 1/10 of a minute;
0.66 := a vehicle acceleration constant for the first 1/2 mile traveled;
1.77 := a vehicle speed constant validated for response distances ranging from 1/2 miles to 8 miles;
D := Euclidean distance based upon two-dimensional Cartesian coordinates from the engine company location to the fire location.

This formula was derived in a RAND Corporation study in New York city and is still used as a predictive tool. The formula is somewhat dated and is derived from empirical data in Yonkers, New York, but appears to be a very practical one [3].

Another situation is in the traffic planning area, which is considered a crucial component since stable transportation systems are one of the main factors that contribute to a higher quality of life. Indeed, Buriol et al. [4] propose an algorithm to solve a user equilibrium model (which describes the behavior of users on a given traffic network), while maintaining the system optimum model solution (which describes a traffic network operating at its best operation). This algorithm is based on a convex *approximation* to represent the cost of traveling along each arc, as a function of the flow on the arc (more on traffic assignment models on the classical book of Sheffi [5]). This is a relevant area of research since any improvement is significant because of the many millions of dollars that are spent every day on traffic issues [6,7].

There have been many formulas developed over the years for estimating roadway traffic travel times. Why is there any need for another formula? First of all, it is important that the theoretical formula reflects as closely as possible what happens in reality. If the understanding of the travel time phenomenon is not empirically and theoretically sound, then all the models based on the formula are deficient.

Secondly, if one can easily compute a more accurate estimate of travel time in congested environments, then this will be an important boost to its application in traffic modeling and traffic network design. As might be expected, one does not get something from nothing. In order to achieve a more accurate estimate, the tradeoff is that more computation work has to be done, yet the real benefit here will be a better approximation to the quantitative measure for congested highway traffic. With the advent and proliferation of powerful computer processors (even in cell phones and their web inter-connectivity), the computation times should not become extraordinary.

1.2. Outline of paper

Section 2 presents a survey of relevant literature about travel time models and discusses two-phase and three-phase traffic theory of Kerner [1] in contrast to the theory which derives from the state dependent approach. Section 3 presents the state dependent model and its derivation and computation of travel times along highway segments. Section 4 presents a comparison of the computation of travel times in particular the Bureau of Public Roads [8] formula and a formula by Akçelik [9] along with the state dependent model. Section 5 examines some incidents and bottlenecks and compares the state dependent approach with the other travel time models. Section 6 summarizes and concludes the paper.

2. Problem and literature review

In traffic assignment and evacuation planning models, a travel time delay function is necessary in order to express the relationship between the traffic flow volume and the expected delay on the traffic link. Numerous formulas have been constructed over the past 40 years for this purpose, among some of them are the contributions by the following authors: Bureau of Public Roads [8]; Davidson [10]; Rose et al. [11]; Spiess [12]; Akçelik [9]; and Dowling et al. [13]. From a physics-oriented approach, there is the thorough review by Chowdhury et al. [14] in which the authors explain the detailed basic

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