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Traffic flow on pedestrianized streets

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ABSTRACT

Giving pedestrians priority to cross a street enhances pedestrian life, especially if crosswalks are closely spaced. Explored here is the effect of this management decision on car traffic. Since queuing theory suggests that for a given pedestrian flux the closer the crosswalk spacing the lower the effect of pedestrians on cars, scenarios where pedestrians can cross anywhere should be best for both cars and pedestrians. This is the kind of pedestrianization studied.

Analytic formulas are proposed for a pedestrianized street's capacity, free-flow speed and macroscopic fundamental diagram. Of these, only the free-flow speed formula is exact. The analytic form of the capacity formula is inspired by analytic upper and lower bounds derived with variational theory for a version of the problem where cars are treated as a fluid. The formula is then calibrated against microscopic simulations with discrete cars. The MFD for the fluid version of the problem is shown to be concave and have a certain symmetry. These two geometrical properties, together with the formulae for capacity and free-flow speed, yield a simple approximation for the MFD.

Both the capacity and MFD formulae match simulations with discrete cars well for all values of the pedestrian flux – errors for the capacity are well under 0.2% of the capacity before pedestrianization. Qualitatively, the formulas predict that the street's capacity is inversely proportional to the square root of the pedestrian flux for low pedestrian fluxes, and that pedestrians increase the cars' free-flow pace by an amount that is proportional to the pedestrian flux.

1. Introduction to the problem

In urban environments, traffic flow is affected by the external influence of pedestrians. If pedestrians are regulated by traffic lights the only disruptions to flow are the traffic light themselves. This situation is simple and formulas to predict delay already exist; see e.g. Daganzo (1977). Therefore this paper focuses on the unsignalized case. The subcase in which cars have priority over pedestrians is not interesting because (i) pedestrians have no effect on traffic flow and (ii) the ensuing pedestrian delays have already been described with queuing theory (Tanner, 1951). Therefore the focus is narrowed to the subcase in which pedestrians have priority at all crossings.

We want to understand the effect of these crossings on the traffic stream. The effect of a single crosswalk is already well understood. Queuing formulas, in which the cars are customers served by the crosswalk, exist for both the street capacity

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and the expected traffic delay (Daganzo, 1997; Hawkes, 1965; 1968). These formulas predict that splitting the pedestrian flow of a single crosswalk among several widely separated crosswalks always increases the street's capacity and reduces car delay; i.e., that a street design with crosswalks, say, every 25 m is better for cars than one with crosswalks every 100 m. We conjecture that this continues to be true if the crosswalk separation tends to zero; i.e., if we allow pedestrians to cross anywhere. Since crossing anywhere is also good for pedestrians, it is probably the best thing to do if pedestrians are to have priority. This pedestrianization shall be the scenario considered in this paper.

A street with multiple pedestrian crosswalks can be modeled as a serial queuing system. However, when the crosswalks are very closely spaced, car queues will spill back over upstream crosswalks, "blocking" service. Unfortunately, queuing theory does not provide easy answers to problems with spillbacks – the solution with only two servers is already very complicated; see Newell (1979). For this reason, our crossing-anywhere scenario will not be studied here with the tools of queuing theory, but with a combination of symmetry arguments, dimensional analysis, simulation and traffic flow theory.

We shall consider an infinitely long homogeneous street with cars and crossing pedestrians. It is assumed that cars behave according to the kinematic wave theory (KWT) of traffic flow (Lighthill and Whitham, 1955; Richards, 1956), and that the fundamental diagram relating flow q, and density k, is triangular as proposed in Newell (1993). The fundamental diagram (FD) relationship is denoted $q = Q(k)$. As is well known, kinematic wave theory is equivalent to two other representations of traffic that will be used in this paper: (i) the variational theory (VT) of traffic flow with a linear cost function (Daganzo, 2005; 2005a; 2006); and (ii) Newell's simplified car-following model (Newell, 2002). Pedestrian arrivals are assumed to be homogeneous in space, stationary in time and mutually independent. Each pedestrian is assumed to interrupt traffic for a fixed amount of time, which is equal for all pedestrians. We are interested in seeing how these random interruptions modify the macroscopic fundamental diagram (MFD) of the street, and in particular how much they reduce the street's capacity and its free-flow speed.

To answer these questions the paper is organized as follows. Section 2 formulates the problem in the continuum world of KWT/VT in which cars are treated like a fluid, and then shows that a one-parameter family of curves depicts the MFDs for all scenarios. Section 3 derives an expression for the maxima of these curves, i.e., the pedestrianized street's capacity, and compares it with discrete car-following simulations. Section 4 then presents an exact formula for the free-flow speed and an approximate analytic formula for the MFD that is also compared with simulations. Finally, Section 5 presents some conclusions

2. Formulation

This section formulates the problem in a continuum framework where cars are treated like a fluid. After some simplifications, described in Section 2.1, the problem is stated in the context of variational theory.

2.1. Simplifications

The MFD of a generic pedestrianized street is sought. To define an instance of the problem one needs to characterize the street and the pedestrians. Since the street has a triangular FD, three parameters suffice to describe it. We shall use: (i) the street capacity without pedestrians, q_o; (ii) the jam density k_j; and (iii) the optimum density, k_o. Other FD features can be derived from these three parameters. This paper will use: (a) the free-flow speed, $v_f = q_o/k_o$; (b) the backward wave speed, $w = q_0/(k_j - k_o)$; and (c) and the flow-intercept of the congested branch, $r = k_j q_0/(k_j - k_o)$.

To describe the pedestrians two parameters suffice. We shall use: (iv) their arrival flux f in pedestrians per unit time per unit length of street; and (v) the time, τ, that each pedestrian blocks the street. Thus, an instance of the problem is defined by five parameters in total.

To simplify the formulation we shall choose the units for time, distance and vehicle number (u_t, u_x, u_n) such that the values of τ, q_o and k_j equal 1. The reader can verify that this is always possible by choosing ($u_t \equiv \tau$, $u_n \equiv q_o\tau$, $u_x \equiv q_o\tau/k_j$). For example, if $q_o = 1800$ v/h, $k_j = 200$ v/km and $\tau = 5$ s then $u_t = 5$ s, $u_n = 2.5$ v and $u_x = 12.5$ m. Thus, from now on and without any loss of generality: $\tau = q_o = k_j = 1$ so that these parameters are eliminated.

In order to eliminate one additional parameter from the problem (the value of k_o), we shall work in a system of asynchronous time-space coordinates such the the clock is started at every location, x, with the passage of an observer moving at speed u; i.e., so that in our chosen coordinate system time is defined by:

$$t' = t - x/u. \tag{1}$$

As explained in Daganzo (2002), this transformation preserves the KW character of the traffic problem regardless of the chosen u. (The special case with $u = v_f$ was previously used in Newell, 1993). The reader can verify that (1) leaves invariant the flow but changes the speed and density variables as follows:

$$1/v' = 1/v - 1/u, \tag{2}$$

and

$$k' = k - Q(k)/u. \tag{3}$$

To eliminate k_o choose any desired constant, $c \in [0, 1]$, and let the observer pace be $1/u = k_o - c$. Then, as shown by (3), the optimum density becomes $k'_o = k_o - Q(k_o)(k_o - c) = k_o - (k_o - c) = c$. The value $c = 1/2$ is adopted in this paper as it