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Vehicular Traffic Route Selection Based On Traffic Resistance

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Abstract- **In this paper, a new route selection criterion is proposed based on traffic velocity and density. Current route merit models do not characterize traffic at transitions and so cannot be used in situations such as congestion. Mach number, relative trip time, and traffic resistance are considered in this paper. The Mach number characterizes traffic at transitions, the relative trip time denotes the time for a route, and traffic resistance impedes traffic from attaining the maximum velocity. Route merit based on traffic resistance is proposed to identify routes with a small trip time and low variations in the flow. This can be used to reduce emissions and improve air quality by providing better routes for traffic.**

Index Terms-- **fluid theory, velocity, density, Mach number, route, trip time, traffic resistance**

I. INTRODUCTION

Route merit is a criterion that influences the selection of a route by drivers. During transitions, velocity is adjusted according to the forward traffic conditions. The trip time to a destination is lower when the velocity is higher due to a smaller transition time. In congestion, the high traffic density creates more interactions between vehicles resulting in more transitions and greater variations in velocity. This can increase the trip time and thus fuel consumption, so emissions of hydrocarbons such as CO_2 are greater. In free flow traffic, the density is low so the distances between vehicles are large and their interactions can be considered independent. Therefore, traffic transitions are negligible and have little effect on fuel consumption. Route merit based on traffic velocity, density, and transition time is required to reduce the trip time, and improve air quality and traffic flow.

Fluid theory can be employed for the macroscopic characterization of traffic. The change in traffic flow on a road is analogous to the change in fluid flow through a pipe having controlled volume, so traffic on the road is conserved. Changes in traffic are due to velocity resistance parameters such as density, trip time, transition time, road surface and geometry, weather, and driver response [9]. Further, traffic follows leading vehicles so movement is not independent [13].

Traffic congestion has been compared to fluid behavior near the freezing point [9]. In this case, fluid particles near this point tend to move while other particles are fixed. Traffic can be stopped at traffic signs and barricades, and during congestion, which increases the trip time. This increase depends on the traffic flow in the road network. A short trip time is expected when vehicles move freely with few transitions. Conversely, the trip time is long when there is congestion. Three classes of driver response related to trip time have been defined based on fluid theory [12]. Fluid theory was applied in [15] to GPS data and the traffic was shown to have log-linear behavior. This provides a simple and practical traffic model [14]. However, this model is not suitable for traffic dynamics in urban settings such as during congestion.

Changes in velocity change the trip time as well as increase fuel consumption and hydrocarbon emissions. Thus, they are higher in congestion than in free flow traffic [16]. Optimizing the velocity and reducing changes in velocity on a route can improve air quality, reduce trip time, and mitigate congestion. This can be achieved using a route selection criterion.

Route merit is based on parameters such as time [1, 2], distance [3], traffic flow, route familiarity, difficulty, cost, points of attraction, location, geometry, lighting, road surface, quality of service, and road capacity. Route merit has been proposed as a tradeoff between distance, time, congestion, difficulty, and tolls (cost) [1]. Strategies for route control to influence drivers include dynamic traffic signs, automatic cruise control, high tolls for congested routes, automated traffic flow, and dynamic route selection [4]. These measures improve road network utilization and reduce congestion. However, traffic should also be controlled based on hydrocarbon emissions [5]. Electric vehicle routing to charging station is typically based on the trip time and ignores traffic conditions such as congestion [23-24]. The excessive acceleration and deceleration in congestion is a threat to public health and safety. Thus, an improved route merit is required to mitigate congestion, improve trip time, reduce fuel consumption, and improve public health and safety.

In this paper, route resistance based on the Mach number and relative trip time is proposed. This resistance can be used to determine route merit. The Mach number is typically used to indicate aircraft velocity relative to the velocity of sound. In this paper, the Mach number is used to indicate traffic velocity variability.

Traffic resistance impedes traffic from achieving a higher velocity and thus affects route merit. A route with a lower traffic resistance will have a smaller trip time. In this paper, traffic resistance is developed from analogies with fluid pressure. Traffic resistance depends on acceleration and density. Acceleration increases the variations in velocity and thus also traffic resistance. Further, small distances between vehicles increase vehicle interactions and thus variations in velocity. In free flow traffic, the density will be low.

Route merit for routes between an origin and destination is analogous to electrical resistance. Thus, route merit is determined based on the principles of electrical circuits. Further, a Mach number for traffic flow is developed and the relative trip time is defined based on this number. Then, route merit is proposed based on traffic resistance and Mach number. The relative trip time and traffic resistance are evaluated via simulation to show their usefulness. The rest of this paper is organized as follows. The Mach number is presented in Section II and the relative trip time is defined in Section III. Section IV introduces traffic resistance and this is determined in Section V based on electrical resistance. Finally, Section V provides some concluding remarks.

II. MACH NUMBER

The Mach number is a measure of the velocity of an object relative to the velocity of sound [17] and is given by

$$M = \frac{v}{w}, \qquad (1)$$

where v and w are the velocity of the object and sound, respectively. M is a dimensionless quantity. This number gives relative information about an object in its environment. It is used here to provide relative information about the velocity of traffic on a road. If v is the traffic velocity and v_m is the maximum velocity, then the Mach number is defined as;

$$M = \frac{v}{v_m} \qquad (2)$$

The maximum velocity occurs with free flow traffic so that $v = v_m$ and $M = 1$, otherwise $v < v_m$ and $M < 1$.

In free flow traffic, the density is low so the distances between vehicles are large and there are negligible interactions between vehicles. As the density increases, the distances between vehicles decrease so the velocity decreases. When the density is maximum, these distances are minimal and the velocity is zero so $M = 0$. Thus, the bounds on the Mach number are;

$$0 \le M \le 1.$$

For $M = 1$, the traffic flow is smooth whereas $M \approx 0$ indicates congestion. Thus, the Mach number is a good criterion to estimate the trip time to reach a destination. The trip time in free flow traffic will be small as a vehicle can approach the maximum velocity. As the Mach number decreases, the trip time increases.

III. RELATIVE TRIP TIME

The time taken by a vehicle to reach a destination from the origin with a speed other than the maximum speed is called the relative trip time. The distance to the destination can be expressed as;

$$d = vT_{tr}, \qquad (3)$$

where v is the velocity and T_{tr} is the relative trip time. If the distance d is covered in time t_m with maximum velocity v_m, then (3) becomes;

$$T_{tr} = \frac{v_m t_m}{v}, \qquad (4)$$

and substituting (2) in (4) gives

$$T_{tr} = \frac{t_m}{M}, \qquad (5)$$

For $M = 1$, the trip time is minimum and the relative trip time is

$$T_{tr} = t_m, \qquad (6)$$

whereas in congestion $M \approx 0$ and the trip time is large.

Figure 1 illustrates the trip time versus velocity, v, based on (4). The maximum velocity is v_m = 33.33 m/s and the minimum trip time is t_m = 0.03 s. This figure shows that as velocity decreases the trip time increases, as expected.

IV. TRAFFIC RESISTANCE

Traffic resistance impedes traffic from achieving the maximum velocity. In this section, traffic resistance is developed using analogies with fluid pressure. The fluid pressure per unit length is

$$p = \rho a, \qquad (7)$$

where a is acceleration and ρ is density. Fluid pressure varies with changes in acceleration and density. The traffic resistance is large in congestion and small when the density is low as in free flow traffic. In free flow, vehicle interactions are largely independent and it is easier to attain a high velocity.

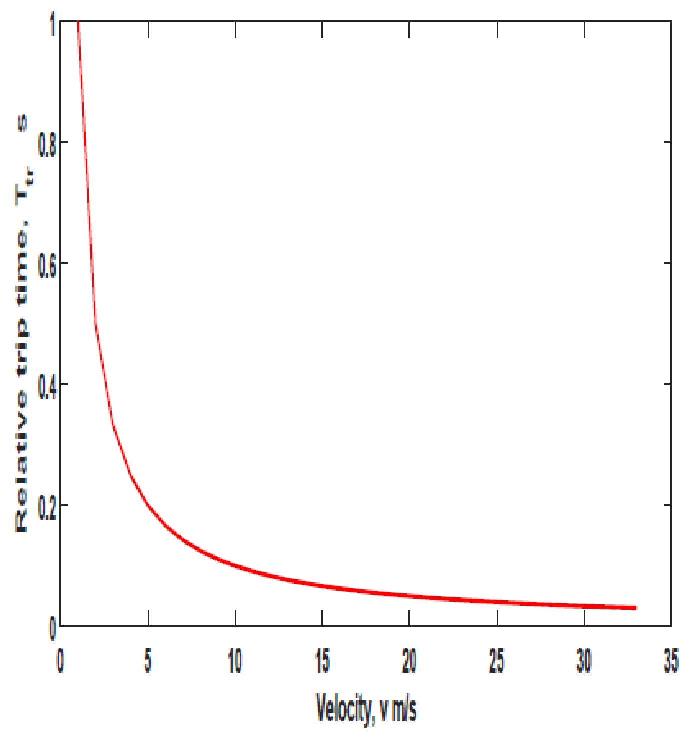

FIGURE 1: Relative trip time versus velocity for a maximum velocity of 33.33 m/s.

Traffic resistance changes with velocity and density. In this paper, it is defined as

$$R = \rho a. \qquad (8)$$

From the kinematic equation of motion

$$a = \left(\frac{v_m - v}{t}\right), \qquad (9)$$

where v_m is the maximum velocity and v is the velocity during a transition. Substituting (9) in (8) gives

$$R = \rho \left(\frac{v_m - v}{t}\right). \qquad (10)$$

When $v = v_m$, R=0 and the trip time is minimum while v = 0 denotes maximum resistance. Multiplying and dividing the numerator in (10) by v_m results in

$$R = \rho v_m \left(\frac{1 - \frac{v}{v_m}}{t}\right). \qquad (11)$$

and substituting (2) gives

$$R = \rho v_m \left(\frac{1 - M}{t}\right), \qquad (12)$$

For $M = 0$ (v = 0), we have

$$R = \left(\frac{\rho v_m}{t}\right) \qquad (13)$$

and for $M = 1$, the traffic moves with maximum velocity ($v = v_m$), so that

$$R = 0. \qquad (14)$$

Thus, the maximum velocity corresponds to minimum resistance and trip time.

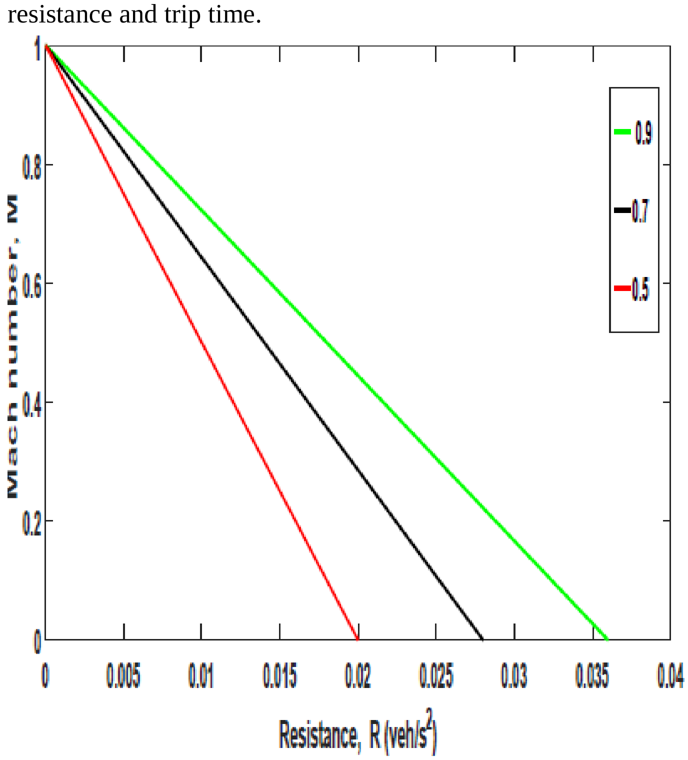

FIGURE 1a. Traffic resistance versus Mach number for a transition time of 25 s.

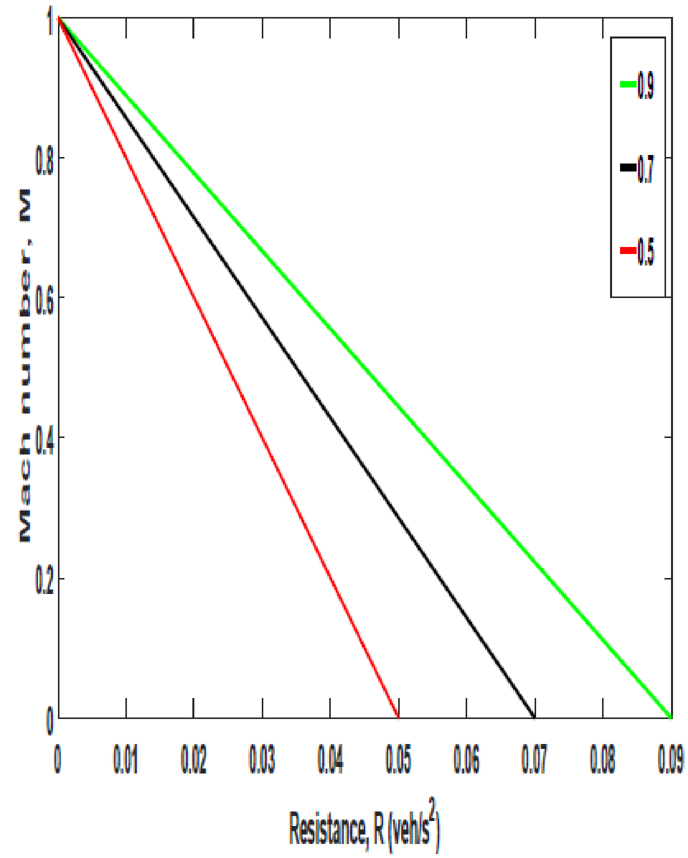

FIGURE 2b. Traffic resistance versus Mach number for a transition time of 10 s.

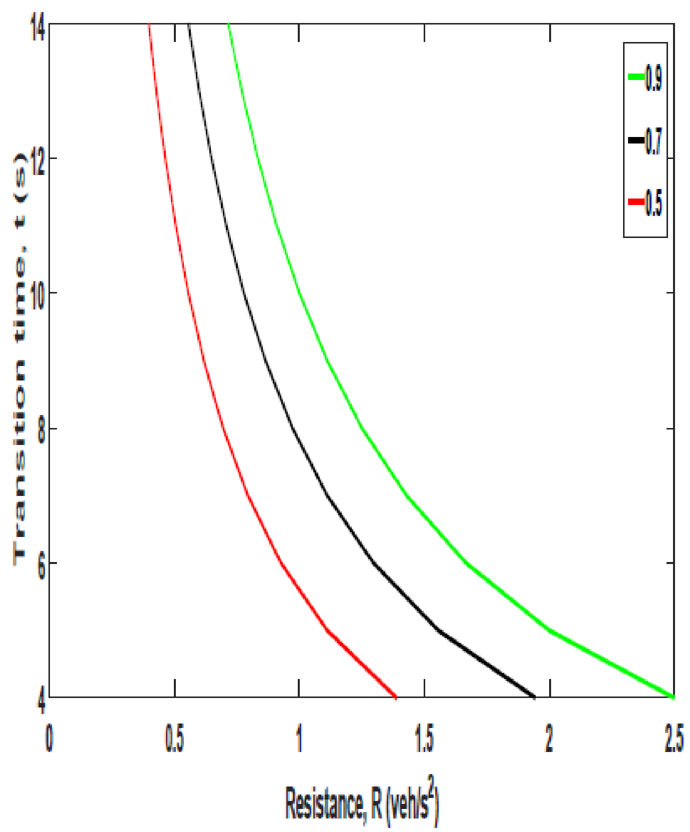

FIGURE 2. Traffic resistance versus transition time for a maximum velocity of $\boldsymbol{v_m = 22.22}$ m/s and an average velocity of 11.11 m/s.

TABLE 1
SIMULATION PARAMETERS

Parameter	Variable	Value
Mach number	M	0 to 1
Maximum velocity	v_m	22.22 m/s
Normalized traffic density	ρ	0.5, 0.7, 0.9
Transition time	t	10 s, 25 s
Average velocity	v	11.11 m/s

Figures 2 and 3 illustrate the traffic resistance from (13) with different Mach numbers and transition times and the simulation parameters given in Table II. Figure 2 shows the traffic resistance for Mach numbers between 0 and 1. The transition time in Figure 2a is t = 25 s whereas in Figure 2b it is t = 10 s. The curves from left to right correspond to normalized densities of 0.5, 0.7, and 0.9. The maximum velocity is v_m = 22.22 m/s. As expected, the resistance is minimum for M = 1 and maximum for M = 0. In Figure 2a, the maximum resistance for ρ = 0.5, 0.7, and 0.9 is 0.45 veh/s^2, 0.62 veh/s^2, and 0.8 veh/s^2, respectively. In Figure 2b, the maximum resistance for ρ = 0.5, 0.7, and 0.9 is 1.1 veh/s^2, 1.55 veh/s^2, and 2 veh/s^2. Thus, a decrease in transition time increases the resistance. Further, an increase in density also increases the resistance.

Figure 3 gives the traffic resistance as the transition time is varied from t = 5 s to 14 s. This shows that for a higher density, the change in resistance is greater when transition time increases. For a given density, the resistance is higher for smaller transition times. Thus, there is greater resistance to attaining the maximum velocity over a shorter time period. For ρ = 1, R = 2.25 veh/s^2 with t = 5 s whereas with t = 14 s, R = 0.62 veh/s^2. For ρ = 0.1, R = 0.25 veh/s^2 with t = 5 s whereas with t = 14 s, R = 0.05 veh/s^2. Thus, traffic resistance varies less when the density is low.

V. ROUTE MERIT

In this section, traffic resistance is calculated based on electric circuit theory, and the resistance for a route from origin to destination is used as the route merit. In an electric circuit, the resistance offered to the flow of current can be in series or parallel [20]. For n resistances in series, the total resistance is

$$R_t = R_1 + R_2 + \cdots + R_n \qquad (15)$$

For n resistances in parallel, the total resistance is given by

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}. \qquad (16)$$

The current will be largest in the smallest resistor

$$R_{\min} = \min(R_1, R_2, \ldots, R_n) \qquad (17)$$

Traffic resistance is analogous to electrical resistance. A larger traffic resistance means fewer vehicles can traverse a road. The velocity is analogous to electric current. Velocity is low with a high traffic resistance. A road can be viewed as an electric conductor and the traffic resistance based on the resistances along the road is given by (15). The traffic resistance for multiple roads between the origin and destination is given by (16).

Consider a road network with three routes leading to a destination as shown in Figure 4. One is a direct route (resistance R_4), while the others have multiple branches. For the top route, there are three parallel branches with resistance R_{2eq} which from (16) is given by

$$\frac{1}{R_{2eq}} = \frac{1}{R_2} + \frac{1}{R_9} + \frac{1}{R_{10}}. \qquad (18)$$

The resistance for this route from (15) is

$$R_{1eq} = R_1 + R_{2eq} + R_3. \qquad (19)$$

For the lower route, the resistance for the two parallel branches is R_{6eq} which is obtained from

$$\frac{1}{R_{6eq}} = \frac{1}{R_6} + \frac{1}{R_7}, \qquad (20)$$

and the resistance for the route is

$$R_{5eq} = R_5 + R_{6eq} + R_8. \qquad (21)$$

The minimum traffic resistance for the three routes is then

$$R_{\min} = \min(R_{1eq}, R_4, R_{5eq}). \qquad (22)$$

This route will provide the minimum trip time. The probability of selecting a route is defined as

$$P_{r=} \frac{1}{R_r}, \qquad (23)$$

where R_r is the route resistance. The route having the lowest resistance will then have the highest probability of being used. The probabilities for a route can be defined at intersections along the route.

VI. CONCLUSION

Route merit models in the literature consider trip time, distance, and/or delay and ignore traffic changes due to velocity and density. However, vehicle trip time depends on velocity. Thus, traffic resistance based on analogies with electrical resistance was proposed in this paper based on variations in velocity and this was used to determine the route merit. Free flow traffic has a small route merit. In this case, fuel consumption and vehicle emissions are low. Traffic routing based on the proposed route merit is realistic as it is a function of density, velocity variations, and transition time. This route merit can be used for road selection. Future work can consider traffic routing based on real data for a road network in an urban environment.

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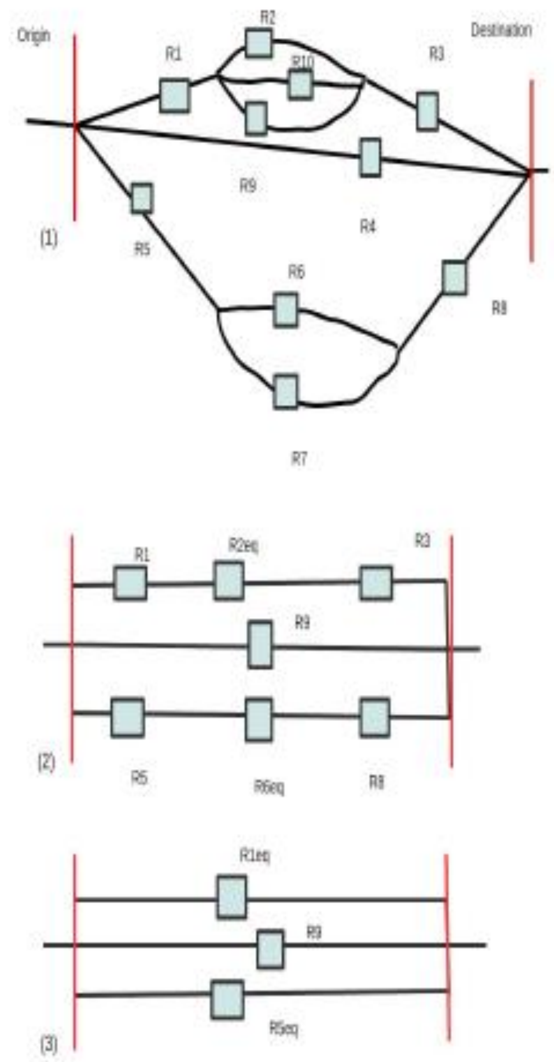

FIGURE 4. Traffic routes from origin to destination with resistances.