Pacer Cars: Real-Time Traffic Shockwave Suppression

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***Abstract*—'Stop-and-go' waves or traffic shockwaves is a well analyzed traffic phenomenon and a known cause of traffic congestion. We propose Pacer Cars, a practical, low-cost and infrastructure-less technique to increase highway traffic capacity by alleviating and preventing traffic shockwaves. Pacer Cars are special cars, such that other cars are prohibited from overtaking a Pacer Car. We show that by injecting Pacer Cars into traffic streams on freeways, we can reduce the inflow of vehicles into a traffic shockwave, and prevent traffic congestion from propagating. We formulate traffic shockwave suppression as a control and scheduling problem and present a generic framework that is both practical and effective in suppressing shock waves. We demonstrate how reducing traffic shockwaves can increase traffic throughput without additional infrastructure investment.**

***Keywords*-traffic shockwaves; real time traffic congestion management;**

I. Introduction

When the traffic demand exceeds the capacity of the roads it results in traffic congestion. According to the 2009 Urban Mobility Report [1], delays due to traffic congestion in the United States cost the nation $87 billion in the form of 4.2 billion lost hours and 2.9 billion gallons of wasted fuel. A marginal improvement in the traffic flow has a significant result on the average amount of time and energy spent in commuting.

Congested traffic is typically characterized by very low vehicular speeds, high vehicular densities, low values of inter-vehicle distances (space-headway) and longer travel times. One commonly observed form of traffic congestion is a traffic shockwave. A traffic shockwave is the boundary on a space-time curve that demarcates one traffic state (flow-density-speed) from another. It is termed as a *wave* because this boundary is not fixed, but travels with time, much like the wavefront of a *pressure wave* [2].

One approach to prevent congestion is to increase the capacity, by building new roads or by adding more capacity to existing roads (i.e. adding new lanes). This is an expensive solution and is only effective up to a certain extent. When new roads are built, the traffic that flows on them also grows, and soon the road reaches its point of saturation [3]. Moreover, adding extra capacity does not always result in an increase in traffic flow, [4], due to uncoordinated driver behavior, who follow individual optimal driving strategies rather than a socially optimal strategy.

Other approaches resolve traffic congestion by regulating traffic flow. These approaches implement a control law to limit the speed of upstream vehicles by the use of Variable Speed Limits (VSL) [5]. Although, it is cheaper than building new roads, implementing a VSL system requires a significant infrastructure cost plus a recurring monitoring and maintenance cost. It also faces the issue of lack of enforcement, as most drivers usually regard the recommended speed as a reference but don't necessarily comply with it.

We aim to solve the problem by injecting Pacer Cars into traffic streams at appropriate locations across a network of freeways based on real-time traffic data and prevent various traffic shockwaves from growing/propagating along the freeway. Pacer Cars are special cars, such that other cars cannot overtake them.

- We determine individual Pacer Car behavior at a microscopic level.
- We explore the macroscopic level behavior of the Pacer Cars across a network of highways.
- We expect that the Pacer Cars approach can improve traffic flow by 8-12 % without any infrastructural requirements.

The microscopic and macroscopic problem formulation is described is the next section.

II. Problem Formulation

The state of the traffic can be characterized by three parameters: speed (v), density (k) and flow (q). Flow is the number of vehicles per unit time and density is number of vehicles per unit length. The fundamental traffic equation (1) relates these parameters:

$$q = k * v \tag{1}$$

A traffic shockwave is formed every time two different states of traffic merge. We can calculate the speed at which the boundary of the wave travels using the equation:

$$V_{shock} = \frac{q_{downstream} - q_{upstream}}{k_{downstream} - k_{upstream}} = \frac{\Delta q}{\Delta k} \tag{2}$$

The sign of the shockwave speed indicates the direction in which the wave travels, with downstream being the

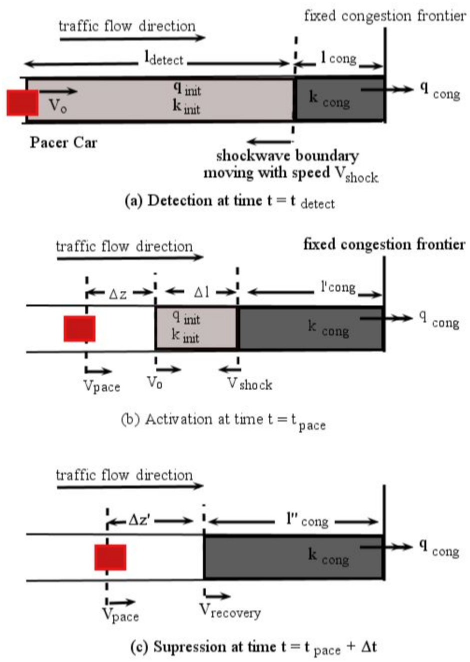

Figure 1. Microscopic view of Pacer Car operation (a)Detection (b)Activation (c)Suppression

positive direction. When high speed traffic ($q_{downstream} < q_{upstream}$) meets slow traffic ($k_{downstream} > k_{upstream}$), the result is a negative value of V_{shock}, i.e. the shockwave boundary travels upstream and the fast moving cars get caught up in the slow downstream traffic.

A traffic shockwave can be either fixed or moving. A stationary shockwave is one whose front end is fixed (caused at bottlenecks, on/off ramps, traffic incidents). In some cases the frontal shockwave boundary also travels with time. Such traffic waves are generally caused due to driver behavior. When a driver suddenly slows down, the fast moving cars behind him also need to apply brakes in order to avoid a crash. Since vehicles take less time to decelerate that to accelerate, the rate at which vehicles in front speed away is less than the rate at which upstream vehicles brake and this flow mismatch causes a traffic shockwave with both its wavefronts traveling upstream.

A. Pacer Car: Microscopic Behavior

In this paper, we only consider resolving traffic congestion for freeways. For simplicity we will assume the following:

1) The freeway is single-lane.
2) There are no on/off ramps in the stretch of freeway under observation.
3) Drivers comply with the no-overtaking rule.
4) Real-time traffic states are known to us.
5) Traffic states, known to us, remain uniform.

We look at the simplest possible case first, where a single Pacer Car suppresses congestion. The behavior of a Pacer Car can be broken down into three stages:

1) Detection: Let us say, at a time t = t_{detect}, we detect a congestion on a freeway, (Figure 1 (a)), which has grown up to a distance of l_{cong} from the point of its inception (fixed). We can calculate the speed, V_{shock}, at which this boundary is propagating, using equation (2). We inject a Pacer Car at a distance l_{detect} from the point of detection. The Pacer Car enters the upstream traffic and moves with the same speed, V_o, as that traffic. It is necessary to determine how far from the detection point we need to inject the Pacer Car. If we inject it too far, then we are allowing the congested region to grow more, whereas, if we inject it too close to the point of detection, then we run the risk that the Pacer Car may not suppress the traveling wave. The distance, l_{detect} is a function of V_{shock}, and we want to find this function. The number of vehicles that are present between the Pacer Car and the frontal wave boundary is given by:

$$N_{init} = (k_{cong} * l_{cong}) + (k_{init} * l_{detect}) \tag{3}$$

2) Activation: Since we need to reduce the flow of vehicles into the congestion, the Pacer Car gradually reduces its speed, but only up to a critical value. If a Pacer Car slows down too much and too fast then we run the risk of causing a new secondary shockwave behind the Pacer Car and if it reduces its speed very slowly then it may fail to suppress the shockwave. The Pacer Car needs to operate within the *deadband* of critical and smooth speed profiles as shown in Figure 2. The minimum speed to which a Pacer Car can slow down, is given by V_{crit}. This speed is estimated based on the traffic state that exists behind the Pacer Car. As shown in Figure 2, the Pacer Car adapts an aggressive speed reduction profile and reduces its speed linearly from V_o to $V_{pace}(> V_{crit})$ in a time t_{pace}(measured from t_{detect} onwards). The scenario will now resemble what is depicted in Figure 1(b), where

$$l'_{cong} = l_{cong} + (V_{shock} * t_{pace}) \tag{4}$$

$$\Delta z = \frac{(V_o - V_{pace})}{2} * t_{pace} \tag{5}$$

Where, Δz is the length of a zero density zone, formed as a result of the relative speed between the Pacer Car and

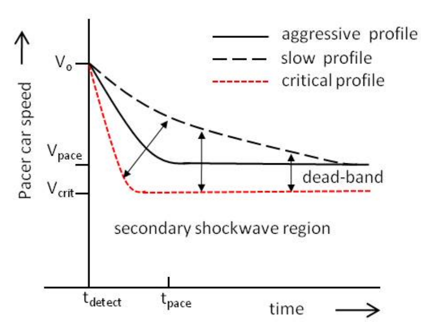

Figure 2. Pacer car needs to operate within the deadband of critical speed profile and smooth speed profile.

the downstream cars. The distance,Δz in equation (5) is:

$$\Delta z = (V_o * t_{pace}) - \int V_o + \frac{(V_o - V_{pace})}{t_{pace}} * t \, dt \qquad (6)$$

Also, Δl, the stretch of the freeway consisting of *unaware* cars (cars in between the Pacer Car and the shockwave boundary), is given by

$$\Delta l = l_{detect} - ((V_o + V_{shock}) * t_{pace}) \qquad (7)$$

At this point, the number of cars between the Pacer Car and the fixed frontal boundary is,

$$N' = N - (q_{out} * t_{pace}) \qquad (8)$$

3) Suppression: Once the Pacer Car has reached the speed V_{pace}, it will continue to travel with this speed. Eventually all the *unaware* cars that were traveling ahead of the Pacer Car will hit the shockwave boundary, get stuck in congestion, and gradually clear out. The instant of time when this happens is shown in Figure 1(c). After the Activation stage, the time it takes for the remaining unaware cars (traveling in the Δl stretch) to hit the shockwave boundary can be anticipated:

$$\Delta t = \frac{\Delta l}{(V_o + V_{shock})} \qquad (9)$$

The zero density zone will grow to from Δz to $\Delta z'$, where

$$\Delta z' = \Delta z + ((V_o - V_{pace}) * \Delta t) \qquad (10)$$

and l''_{cong} (the length of the congested region) is given by

$$l''_{cong} = l'_{cong} + (V_{shock} * \Delta t) = l_{cong} + (V_{shock} * (t_{pace} + \Delta t)) \qquad (11)$$

The rear end of the shockwave will stop growing any further, because there are no more cars left to join the congestion (due to the zero density zone $\Delta z'$). If we re-apply the shockwave equation (2) at the congestion boundary, we observe that the speed of the shockwave is now given by:

$$V_{recovery} = \frac{q_{cong} - 0}{k_{cong} - 0} = \frac{q_{cong}}{k_{cong}} \qquad (12)$$

which is positive, implying that it travels downstream, and is actually a recovery wave. The value of $V_{recovery}$, could have been calculated at the detection stage itself, since it depends on the congestion density and outflow. Since the speed of the Pacer Car, V_{pace}, is greater than the shockwave recovery speed, $V_{recovery}$, we want to ensure that by the time the Pacer Car hits the congestion boundary, the boundary itself ceases to exits, i.e all cars stuck in traffic are cleared before the Pacer Car catches up with them. This will be possible *iff*,

$$\frac{\Delta z'}{(V_{pace} - V_{recovery})} \geq t_{supp} \qquad (13)$$

Figure 3. Macroscopic view of Pacer Cars operation along freeways leading to the city.

where, t_{supp} is the time it takes for remaining cars to clear out and is equal to

$$t_{supp} = \frac{N''}{q_{cong}} = \frac{l''_{cong}}{V_{recovery}} \qquad (14)$$

where, N”(cars stuck in congestion) is given by

$$N'' = N' - (q_{cong} * \Delta t) \qquad (15)$$

Getting back to our initial question, the effectiveness of inserting Pacer Cars depends on where we insert it and how it behaves thereafter. Using equations (5), (10),(11), we can see from equation (14) that:

$$\Delta t > \frac{l_{cong} + t_{pace} * (V_{shock} - (\frac{V_{recovery}}{V_{pace} - V_{recovery}}) * (\frac{V_o - V_{pace}}{2}))}{((\frac{V_{recovery}}{V_{pace} - V_{recovery}}) * (V_{shock} - V_{pace})) - V_{shock}} \qquad (16)$$

Using (7) and (9) we know the relation between l_{detect} and Δt, so we can re-write (16) as:

$$l_{detect} > (V_o + V_{shock}) * (f + t_{pace}) \qquad (17)$$

where f is the RHS of equation (16). This indicates, that we can calculate the point of insertion of the Pacer Car from the congestion boundary, at the time of detection.

B. Pacer Car: Macroscopic Behavior

The above equations, ((14) and (16)), resemble the equations of timing constraints in real time scheduling theory as they are of the form that a task must execute before its deadline, where the notion of a task resembles the Pacer Car’s action and the deadline is the instant of time when the Pacer Car hits the shockwave boundary. If we look at the situation on a macroscopic level (network of freeways), then we see that resolving a local congestion does help, but wont be much effective if the cars that managed to avoid congestion eventually hit a congested area downstream. Therefore we need to have multiple Pacer Cars spread across the network of highways. This is also a good point to discuss one of our assumptions that the traffic state is known to us at the time of detection of congestion. One of the ways of doing this is to make use of smart hand-held devices. 3G technology allows us to obtain real time traffic information based on data received from the smart phones, and this data is reasonably accurate. Such applications for smart phones already exist, where knowledge of downstream traffic conditions is known to the driver.

Given the real-time traffic information, we can decide where Pacer Cars need to be inserted and how often. An example of this is shown in Figure 3, where you see Pacer Cars in action, in places of traffic congestion. With this network wide coordination among pacer cars, we hope to achieve better traffic flow conditions during rush hours, thereby utilizing the existing capacity more efficiently.

III. Expected Results

We now analyze the improvement in travel times and traffic capacity. In traffic theory, travel time is considered a good measure of highway performance. Faster travel times indicate freely flowing traffic whereas traffic congestion and shock-waves tend to increase the travel times by adding delays. To see the effect of a Pacer Car, consider the stretch of a freeway shown in Figure 4. We observe the velocity profiles of cars as they pass through this stretch, which extends from 0 to x.

As shown, in the *non-pacer* case, high speed cars have to suddenly slow down to a very low speed as they hit the congested region at point x_2. They continue to move slowly through the jam till the point x_3, after which they gradually increase their speed and exit the freeway stretch. The average speed of these cars equals $< V_{non-pacer} >$. On the other hand, the speed profile with the Pacer Car starts decreasing from point x_1 onwards, since it already knows about the downstream congestion. The speed decreases up to a level, which is much higher than the speed of the cars that were caught in traffic. The platoon of cars, led by the Pacer Car travels through the entire stretch with a much larger average speed, $< V_{pacer} >$. Consequently, the travel time along the freeway stretch, for the cars with the Pacer Car in front decreases by a factor of, $\frac{V_{non-pacer}}{V_{pacer}}$ (< 1). The decrease

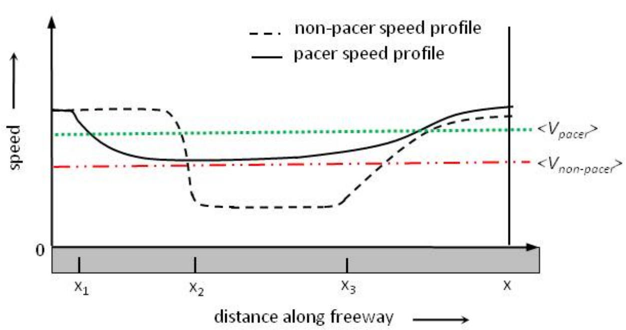

Figure 4. A comparison of speed profiles and average speed of cars along a freeway stretch, for with and without Pacer Car case.

in travel time corresponds to an increase in the traffic flow along the stretch. If we aggregate the effect of Pacer Cars in the network then we can potentially increase the traffic flow by 8-12%, without any additional infrastructure.

IV. Conclusions and Future Work

The idea of resolving traffic congestion using real-time traffic information on very fast time scales is very promising. Pacer Cars, provides us with means of achieving an improvement of 8-12% in traffic flow without any infrastructure cost. As a physical Pacer Car controls the traffic behind it, it is more effective in terms of *enforceability* as compared with other speed control measures like Variable Speed Limit. Future work involves,

- Simulating traffic scenarios with fixed and moving shockwaves to observe Pacer Car behavior.
- Relaxing the assumption about non-existence of on/off ramps.
- Analyzing multi-lane highways with multiple Pacer Cars.
- Establishing a Pacer-to-Pacer protocol for cooperative behavior in a network.
- Evaluating the best and worst case traffic scenarios for the Pacer Car to operate and determining the region of operation.
- Incorporating the effect of non-uniform traffic flows (traffic states change with time)
- Relaxing the no-overtaking assumption by specifying a non-compliance factor.

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