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Towards investigating vehicular delay reductions at signalised intersections with the SPA System

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1 INTRODUCTION

The Simple Platoon Advancement (SPA) model describes a conceptual system where a combination of roadway infrastructure and in-vehicle systems controls the longitudinal progression of vehicles through signalised intersections. The primary objectives of the SPA system are two-fold. The first is to increase – compared to traffic behaviour of today – the throughput of vehicles through signalised junctions and thereby reduce vehicular delays. The second is to improve safety at intersections by automating the decision task required of drivers on their approach.

The impetus for the SPA system is apparent when looking at the areas of possible improvement in signalised intersection efficiencies achievable in the traffic signal systems of the current road network (Clement, 1996; Clement, 1998). In general there are two systems controlling the progression of vehicles through intersections. The first is the right-of-way system that gives stop and go permissions to particular movements in a safe manner. The second is the motion system that controls using both longitudinal and latitudinal components the actual movement of vehicles through the intersection.

The right-of-way system has been the focus of improvement changes such as that from human control (the pointsman on duty) to mechanised systems (signals) over the last one hundred years. Latterly there has been significant improvement in control and optimisation techniques that have increased efficiencies (increased throughput, reduced delays, etc) for vehicles (Clement, 1996). While development focusses solely on the right-of-way mechanisms there is unlikely to be another overall improvement as dramatic as the move from fixed time to demand-responsive and automatic control (eg SCATS). Continued small efficiency gains will be made due to improvements such as the implementation of localised, flexible operations engineered for particular intersections. A possible development is therefore to automate the longitudinal motion of vehicles through signalised intersections in such a way that the two systems, right-of-way and motion, cooperatively produce significant efficiency gains.

The SPA system is a suggested method of achieving these gains. This paper reports on recent developments of the theoretical models and outlines the next stages in the investigation of the reductions in delays that are likely if vehicles and roadways are kitted with SPA system technologies.

2 THE CONCEPT OF SPA

The concept of the SPA system is that as a vehicle approaches a signalised intersection on a movement showing the red traffic signal, the vehicle receives a communication signal from the roadway infrastructure that instructs the vehicle to slow down and stop in a particular queue density configuration. The longitudinal control of the vehicle is therefore automated from some distance upstream of the stopline, thereby increasing safety at the junction by dramatically reducing the possibilities of the vehicle running the red light. At the start-of-green, the queue is moved *en masse* as a single unit (a technologically-connected platoon) retaining the spatial density of the stationary queue. This is achieved through vehicles having on-board acceleration and deceleration control systems linked to on-board sensors that provide information about the proximity and relative speed of the preceding vehicle. These mechanisms along with other Intelligent Transport Systems (ITS) technologies are becoming more available in production cars around the world. The SPA system uses the same mechanisms but in an innovative manner to achieve throughput and safety improvements at signalised intersections.

The platoon dispersion mechanism (Clement and Taylor, 2001) allows the longitudinal control of the vehicles to be safely transferred from the infrastructure to the driver of each vehicle. After initial acceleration, each vehicle (except the head vehicle in the platoon) travels for some period at a fixed speed (the velocity limit). Then the vehicle is 'released' by the controlling SPA system to the control of its driver so that the driver can accelerate the vehicle to a predetermined target speed (the target velocity). The time of release between successive vehicles occurs when the headway (desired headway) is at least a predetermined safe value.

The institutional, technical, legal, societal and economic aspects of the implementation and operation of the SPA system are not discussed in detail here though these will necessarily be addressed before such a system can become part of our roadway landscape. For example, in a working SPA system, the distance between successive vehicles in the queue awaiting the green light (known as the jam spacing which is adopted from Akçelik, Besley and Roper (1999) and is the space density with which vehicles are packed in the queue) is likely to be considerably shorter than that exhibited by today's drivers. The jam spacing in a SPA system may need to be set at a distance with which drivers are comfortable with staged reductions over time until the desired optimal value is reached.

The development of the models describing the conceptual SPA system has taken two paths as explained in detail in Clement (2002). The first path developed the constant acceleration model while the second incorporated the notion of jerk to the acceleration characteristics of vehicles and is termed the smooth acceleration model.

Briefly, the first model developed was that of the homogeneous SPA model with constant acceleration. That is, all vehicles behave the same and the transitions between stages of acceleration (either zero or a constant value) are instantaneous. This model is described in Clement and Taylor (2002) where stopline throughput performance is compared with an Exponential Queue Discharge (EQD) model of Akçelik, Besley and Roper (1999). The EQD model is a valid representation of queue discharge behaviour at signalised intersections in the current road system. This paper showed that the SPA model can reasonably progress up to 45 per cent more vehicles past the stopline in the same period of time compared with behaviour on today's roads.

The addition of the jerk component produces the second model known as the homogeneous SPA model with smooth acceleration. The consideration for jerk brings more realistic behaviour to the theoretical motion of vehicles travelling under a SPA system than the constant acceleration model. The smooth acceleration model, like its predecessor, is homogeneous in its behaviour over the fleet of light vehicles that is modelled (consideration of the effects of heavy vehicles with their different progression characteristics is a topic for further research). The distance – time curves for the first five vehicles that approach a SPA intersection, stop and are progressed in the manner described by the smooth acceleration model are shown in Figure 1.

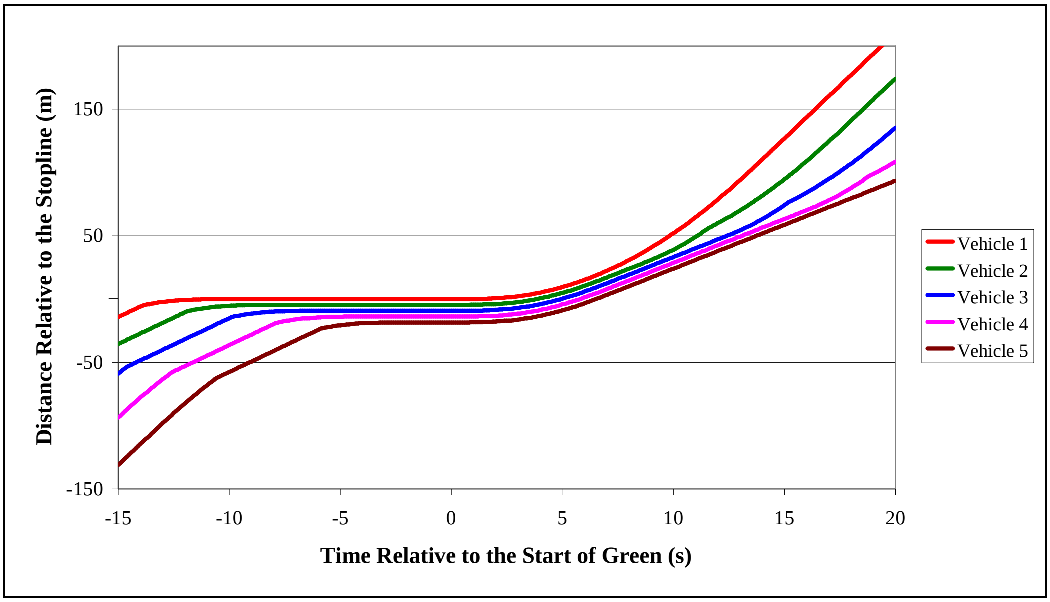

Figure 1 Distance - time diagram for the first five vehicles in the platoon

Investigations reported in Clement (2003) and Clement, Taylor and Yue (forthcoming) show that throughput improvements of 85 per cent are possible. At such levels the SPA system would be impractical due to the excessive length travelled before vehicles are released into driver control. The distance from the stopline at which a particular vehicle is released into driver control is known as the vehicle's 'release distance'. The stopline throughput graph of Figure 2 shows the performance of the constant and smooth acceleration models with the given governing parameter values. The performances of the SPA models are compared with the throughput in the same time period of today's roadway system as represented by the EQD model. Figure 2 shows even greater throughput than that reported above but again must be discounted for being impractical due to the excessive lengths required for dispersal operation.

Why are there so many seemingly different throughput performance improvement figures? This is because different sets of SPA governing parameter values (jam spacing, platoon acceleration, velocity limit, target velocity, desired headway and jerk) produce different vehicle motion characteristics and not all of the combinations of parameter values have been modelled and analysed. This paper describes the motion characteristics or profiles possible within a given range of values for each governing parameter and describes the next steps in the development of the analytical methods for determining the delays experienced by vehicles travelling in the conceptual SPA system. Delays for a single set of parameter values are investigated in Clement and Taylor (2002) and Clement and Taylor (forthcoming). These investigations show that the rise in delay experienced by SPA system vehicles at signalised intersections experiencing increasing demand is slower under these parameters than that of today's roadway as modelled by aaSIDRA.

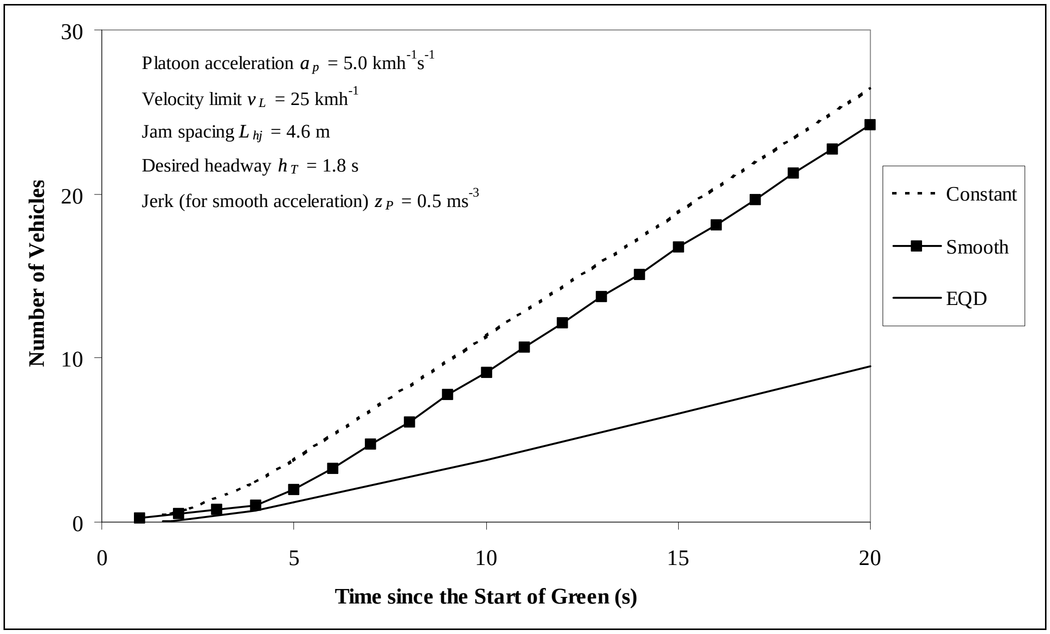

Figure 2 Stopline throughput of the constant acceleration and smooth acceleration SPA models compared with a valid representation of current road network performance (reproduced from Clement, 2002)

3 STAGES OF MOTION

3.1 THE CONCEPT OF JERK

One of the features of a comfortable ride for passengers in a vehicle is a low perceived jerk. Jerk is characterised by a large acceleration transition in a short period of time. In mathematical terms jerk is the third derivative of distance with respect to time (Vuchic, 1981). Comfortable ride is experienced when the value of jerk (expressed by the letter *z*) is relatively low. Of course complete comfort occurs when *z* is very small but this results in a very long period of time to reach any significant acceleration, hence speed and distance. Jerk has the SI units of metres per second cubed (ms^{-3}). Vuchic recommends that maximum values of jerk should be between 0.5 and 0.6 ms^{-3} when designing the movement characteristics of public transport vehicles. Vuchic recommends these values with consideration for the riding comfort of standing passengers on public transport vehicles in accelerating and braking actions. The SPA models are concerned at this stage only with light vehicles where presumably drivers and passengers are seated and in the Australian context wearing seat belts. The Vuchic values for jerk are extended to 0.8 ms^{-3} in the analysis of possible profiles for the second vehicle as described later in this paper. The values for jerk are applied homogeneously to the vehicle fleet investigated in the SPA models presented here. There will of course be some stochastic variation in the values tolerated by a range of drivers on our road system and this variation is the subject of future research.

3.2 EIGHT STAGES

There are eight distinct stages of motion associated with an accelerating vehicle progressing in a SPA system. The first period is when the acceleration changes from zero to the platoon acceleration value with a rate of change of acceleration equal to the positive value set for jerk (Stage F). The vehicle then proceeds for a time at the platoon acceleration (Stage G). Another transition occurs when the acceleration reduces to zero (a negative value of jerk, Stage H) at which point the vehicle is travelling at the velocity limit (Stage I). At the end of this stage – when the headway is sufficient – a further transition occurs as the acceleration increases once again (Stage J) to the platoon acceleration (Stage K). At the end of this period the acceleration decreases (Stage L) and the vehicle proceeds at the target velocity (usually the cruise speed, Stage M).

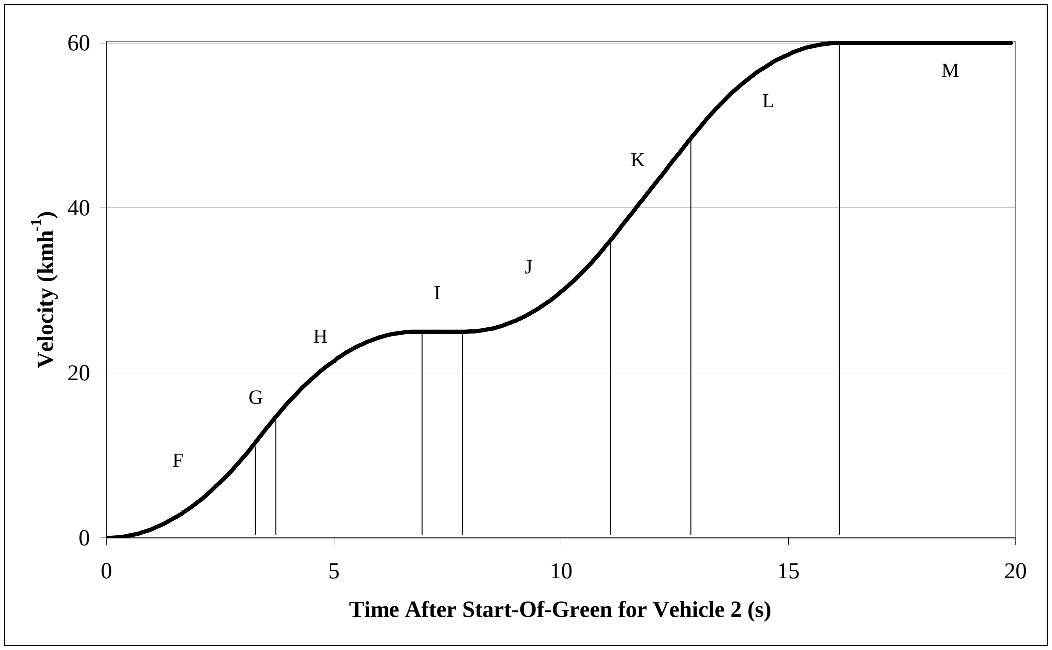

Figure 3 Velocity - time profile for vehicle 2

3.3 HEAD VEHICLE MOTION

The above description applies to all vehicles except the head vehicle since this does not experience travel at the set velocity limit. This results in four distinct stages of motion for the head vehicle as it accelerates to its target velocity. Its velocity – time profile is shown in Figure 4.

The first period is when the acceleration changes from zero to the platoon acceleration value with a rate of change of acceleration equal to the value set for jerk. The vehicle then proceeds for a time at the platoon acceleration. Another transition occurs when the acceleration reduces to zero at which point the vehicle is travelling at the velocity limit. At the end of this stage a further transition occurs as the acceleration increases once again to the platoon acceleration. At the end of this period the acceleration decreases and the vehicle proceeds at the target velocity.

Figure 4 Velocity - time diagram for the head vehicle of a platoon

4 MOTION PROFILES

4.1 WHAT IS A MOTION PROFILE?

A motion profile is the term given to the characteristics of the velocity – time curve of any vehicle in the platoon. Here we will concentrate on describing the possible profiles for the second vehicle. Profiles are determined by sets of SPA governing parameter values (jam spacing, platoon acceleration, velocity limit, target velocity, desired headway and jerk). In the development of the SPA models so far, all vehicles experience the same governing parameter values (homogeneous models). It is appreciated that some of these values will in the future require an element of stochasticity to more appropriately model behaviour of the real world.

4.2 THE STANDARD PROFILE

The standard profile of any but the head vehicle is characterised by the vehicle experiencing some travel at the platoon acceleration (Stage G), at the velocity limit (Stage I) and in the free acceleration period of Stage K (see Figure 3). While this profile is the most likely to occur and the focus of the initial model and analysis, it is by no means the only profile possible for vehicles 2 and later. Clement (2003) identifies 23 separate profiles for SPA vehicles. Different profiles occur due to different sets of SPA governing parameter values (jam spacing, platoon acceleration, velocity limit, target velocity, desired time headway and jerk) having an effect on the velocity reached by a vehicle before a change of stage is occasioned.

4.3 TRUNCATED PROFILES

Some sets of values result in truncated Stages F and H and no travel in Stage G at the platoon acceleration. In the initial acceleration period of Stage F, the rate of change of the acceleration is governed by the jerk. If the acceleration does not reach the platoon acceleration before it has to be decreased (Stage H) in time for the vehicle to be travelling at the velocity limit at the precise moment that the acceleration is zero, the stage is referred to as being velocity-truncated. For example, a low value of jerk (0.5 ms^{-3}) and a high platoon acceleration (8.0 $kmh^{-1}s^{-1}$) will in almost all cases result in Stage F being terminated before the platoon acceleration is reached.

4.4 RELEASE-TRUNCATED PROFILES

A further complication is occasioned by the release mechanism. Release occurs at the precise moment when there is sufficient headway (desired headway) between a vehicle and that in front. While release in the standard profile occurs during the period that the vehicle is travelling at the velocity limit, this is not always the case though the probability of it being so increases rapidly for vehicles further back in the platoon. Again focussing on vehicle 2, the moment of release cannot occur in either of its Stages F or G regardless of the motion profile. This is because the motion of both the head vehicle and the second vehicle are identical up to the time when vehicle 2 finishes its Stage G period of acceleration. The corollary to this is that if Stages F and H of vehicle 2 are velocity-truncated, the moment of release cannot occur before the start of Stage H of reducing acceleration. The complicating factor is that vehicle 2 can be released before its Stage H finishes regardless of whether or not the stage is velocity-truncated. In such a situation, Stage H is referred to as release-truncated.

4.5 OCCURRENCES OF MOTION PROFILES

For vehicle 2, there are four possible motion profiles up to the point when it is released to begin its final acceleration stages towards its target velocity. These four possibilities are listed in Table 1 with the first column showing whether or not Stages F and H are velocity-truncated.

Table 1 Possible profiles and the number of occurrences for each

F & H Velocity-truncated?	H Release-truncated?	Number of cases
Y	Y	8,602
Y	N	1,142
N	Y	3,138
N	N	11,814

Do all of these profiles occur for likely value ranges of the governing parameters? The third column of Table 1 gives the number of occurrences of the particular combination of velocity-truncation and release-truncation found by iterating through a range of possible governing parameter sets. While the target velocity was set at 60 kmh^{-1}, the other five parameters were varied in the manner indicated by the ranges and the step sizes contained in Table 2. The reasons for choosing the ranges of the parameters shown in Table 2 are given in Clement (2003) with some values guided by the results in Akçelik and Besley (2002).

Table 2 Governing parameter ranges and step sizes

Parameter	Min	Max	Step	Units
Jerk	0.5	0.8	0.1	ms^{-3}
Acceleration	3.0	9.0	1.0	$kmh^{-1}s^{-1}$
Velocity Limit	10	30	1	kmh^{-1}
Jam Spacing	4.6	7.2	0.2	m
Desired Headway	1.8	2.0	0.1	s

The standard motion profile is shown in Table 1 as Stages F and H being not velocity-truncated and Stage H also not release-truncated. Over the ranges of parameter values and step sizes chosen, the standard profile is the most likely to occur. Other profiles can occur and are detailed in the list of 23 analysed in Clement (2003). These include those parameter values that result in exactly zero travel in Stage G; Stages F and H are therefore not velocity-truncated. Using the parameter ranges and step sizes of Table 2, such a profile did not occur though in a working SPA system it is indeed possible.

5 MOTION PROFILES AND DELAY INVESTIGATIONS

Similar development and analysis of motion profiles for the third and subsequent vehicles is being conducted. Once these are completed the next investigation is to look at the possible reductions in delays over an entire intersection in a similar manner to that reported in Clement and Taylor (2002). Here, precise delays for the SPA system vehicles were calculated from the moment they began to decelerate to the time they reached their target or cruise speed after negotiating the intersection. Delays included the times when arrival occurred during a red period and when progress was impeded by a departing platoon. The SPA system governing parameter values were set and the delays produced were compared with the delays calculated by aaSIDRA for the same demand. It was the aaSIDRA signal settings that were used in the SPA delay calculations. Once the delays for vehicles using a signalised intersection can be calculated for any set of governing parameter values (hence any pattern of motion profiles over the entire platoon) the next investigation will be to find the most optimal set of values that result in a desired outcome. This desired outcome will initially include only minimising delays and release distances and maximising throughput and will be extended to include the number of stops.

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