Viability and Benefits of Platooning in Automated Transport Systems.

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This work is part of the CyberCars project, which is funded by the IST Programme of the European Commission.

May 21, 2004

Abstract

The potential system capacity benefits of operating automated vehicles in close-spaced platoons has long been known. By using less stringent safety criteria to enable platooning is it possible that flow-rates in lanes can be increased many times over. Whether this method of operation can be practically made sufficiently safe or can be operated at the levels required to gain these benefits is less clear. This report considers the practical safety implications and potential benefits of platooning for both automated highway systems (AHS) and personal rapid transit (PRT) systems.

For safety the key factor is found to be that of the time delay between consecutive vehicles taking action following a vehicle failure. The control and communication methods for platooned vehicles, and their effect on this delay, limit how close vehicles can be spaced and thus the safety of occupants in the platoons. By using risk probabilities and simple vehicle modelling, charts are produced which allow the design and risk assesment of such operations, given known variables such as platoon length, speed and control mode. The work shows that platooning can be of sufficiently low risk on any automated system, so long as control systems are wisely chosen and well designed and that platoon lengths are limited to a set numbers of vehicles.

The capability of utilising the theoretical capacity gains from platooning is strongly affected in practice by the frequency and method of vehicles joining and leaving the platoon. The work shows that with well-chosen operation and control strategies, platooning can increase the capacity of most systems, despite a reduction in overall system utilisation compared to the maximum. The implications of platoon length, average trip distance, system speeds, junction spacing and other factors are demonstrated and discussed.

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Chapter 1

Introduction.

1.1 Why Platoon?

Key to the calculation of lane capacities of transportation systems, both automatic and non-automatic, is the headway or spacing of the vehicles in a lane or guideway. This, combined with the lane speed, will yield the flow rate obtainable on the system in terms of vehicles or passengers every hour. A common rule used for automated systems is that the spacing of vehicles must be such that if any vehicle on the system stops instantaneously, subsequent following vehicles will be able to stop from line speed without colliding with the stationary vehicle.

This has become known as the “brickwall” criterion. Alternatively, it corresponds to a “K-factor” of unity, where [1]:

$$K = \frac{Headway}{Min.SafeHeadway} \tag{1.1}$$

The minimum safe headway will depend on the initial speed, maximum allowable deceleration, control delays and length of the vehicles concerned. Therefore these factors will determine the maximum flow rate on any system.

Although this criteria will ensure a relatively high level of safety, the capacity if this rule is obeyed can be somewhat limited especially, as will be seen, at the higher speeds. This may be particularly true if the allowable decelerations have to be kept relatively low (due to lack of seat restraints). It has been proposed that automatic highway systems (AHS) running under such criteria may be unable to provide the flow rates necessary to meet capacity demands [2].

The platooning of vehicles is one possible strategy which has been proposed to significantly increase lane capacity without a corresponding decrease of safety. Rather than running at the minimum safe headways, vehicles are grouped together in batches (platoons). Each platoon is separated by a safe headway to obey the brickwall criteria, but vehicles in platoons follow each other at relatively small spacings, perhaps around one meter.

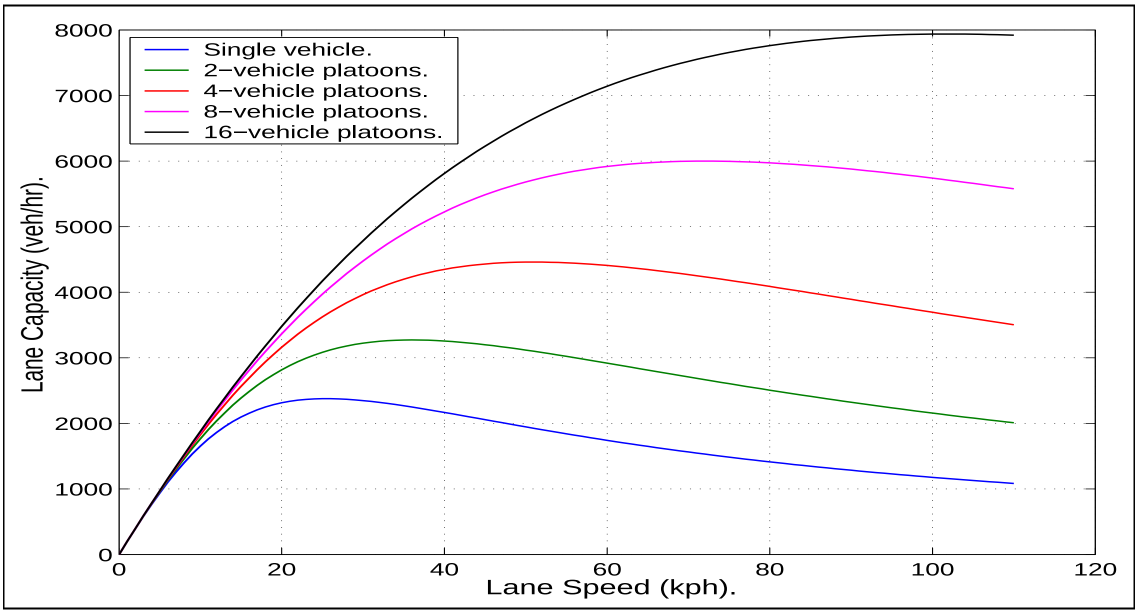

Figure 1.1: Lane Capacity with Speed and Platoon Length.

Figure 1.1 shows the possible benefits to be gained by platooning vehicles. This was calculated for a vehicle length of 5m and intra-platoon spacings and control delays of 0.1-seconds. It is interesting to note that the highest capacities do not occur at the highest speed unless many vehicles are platooned together. This is because the minimum safe headway (inter-platoon headway) increases proportional to the square of the speed. As longer platoons are used this effect is reduced by the average headway becoming closer to the intra-platoon headway and hence less dependent on speed.

It is also interesting that the benefits of platooning many (more than eight) vehicles at the lower speeds are significantly smaller than at the higher speeds. At 20kph there is very little increase of capacity between running eight and sixteen-vehicle platoons while the same increase in platoon length at 110kph increases capacity by over 40%. This is an important consideration which will be returned to as the benefits and praticalities of platooning are considered for different types and speeds of systems.

1.2 Platoon Safety Concepts.

The argument for safety in platooned vehicles is that, contrary to the brickwall criterion, the lead vehicle cannot or will not stop instantaneously, and that subsequent vehicles follow at separations so as to not collide with significant relative speed [3]. Suggested failed vehicle decelerations are usually in the range $10 - 20m/s^2$ [2, 4]. Figure 1.2 shows the collision speeds between two vehicles running initially at 20m/s with a 0.1-second actuation delay and assuming the second vehicle decelerates at a constant $5m/s^2$. Four variations of lead vehicle failure deceleration are shown from the brickwall

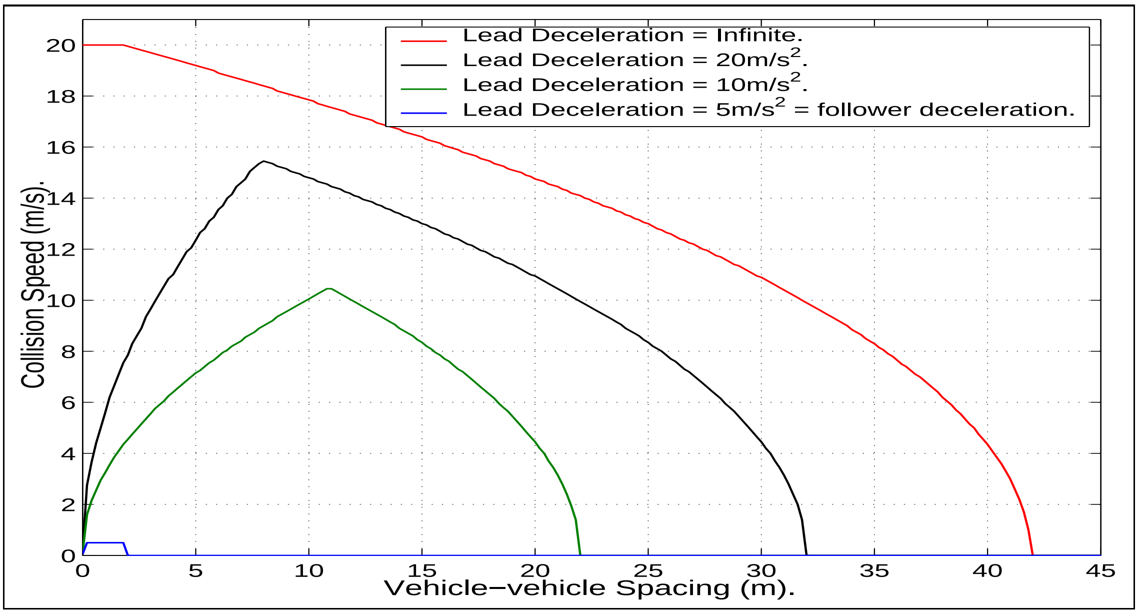

Figure 1.2: Collision Speed with Spacing and Lead Deceleration.

stop to a deceleration equal to that produced by the following vehicle. All vehicle-to-vehicle spacings used in this report represent the distance or time between the rear of the leading vehicle and the front of the following vehicle. Such graphs have been used before to demonstrate platoon safety concepts [2, 4]. At the far right of the plot is the intersection of the instantaneous lead vehicle stop plot with the horizontal axis. This value (42m in this case) is the brickwall spacing which makes up part of the safe minimum headway.

The other plots intersect the same axis at equivalent safe spacings with the assumption of reduced lead vehicle deceleration as shown. This leads to a conclusion about a third possibility for vehicle spacing, which will be discussed later. In terms of platooning and close vehicle spacing, the plots show that to significantly reduce collision speeds the desire must be to drive the spacings down as low as possible.

Whilst this proves the theoretical concept of vehicle platooning, these are very small spacings to run at, especially with respect to the time delays in the system. The graph shows that, even if the vehicles have the same decelerations, they will collide (albeit with low collision speed) if the spacing is less than 2m. Key to determining the practicalities of platoon safety will be the consideration of how small the vehicle spacings can be made and what constitutes a safe collision speed.

1.3 Platoon Control Design and Experiments.

While Shladover considered both the need for and potential safety of platooning [1, 2], work was also carried out regarding the control systems required for platooning operations [5]. This work used simple dynamic longitudinal vehicle models to produce a feedback controller for vehicle spacing and dynamic entrainment. The controller was designed to entrain the vehicle (from safe minimum headway to close spacing), reverse the process or hold the vehicle at either position. The transition between each of these states is a critical "non-safe" period and should therefore be minimised. By use of spacing-scheduled gains the specified dynamic characteristic could be maintained in each state. For a 48kph system the suggested intra-platoon spacing was 0.3 to 0.6-metres (0.023 to 0.046-seconds).

Connolly and Hedrick [6] suggest a similar control method for platooned vehicles. These controllers are generally of a type known as multiple surface control. One set of algorithms controls the speed or acceleration demand on the vehicle, based on the position and spacing, whilst another set controls the actual response of the vehicle to reach the required speed and acceleration. In this study an adaptive feed-forward control element (drag force estimate) is used to improve the velocity tracking at spacings between 28 and five metres.

One successful demonstration of platoon operation is that which took place in 1997 in San Diego as described by Rajamani et. al. [7]. This again involved a two-layer controller but this time using both spacing distance and vehicle-to-vehicle communication to share speed and acceleration data between vehicles. This can help the stability of the platoon (reduce propagation of errors toward the rear of the train of vehicles). The tests saw over one thousand visitors ride in the eight-vehicle platoon over a 7.6 mile two-lane highway. It also involved en-train and ex-train manouevres.

Other studies also indicate the possible importance of platoon control involving both feedback and shared data / feedforward elements. Lu et. al. [8] implements vehicle-to-vehicle communications for speed calculation and synchronisation purposes. Both Rao et. al. and Tongue and Yang emphasise the need for communicated information within the platoon to prevent collisions [9,10] and Seto and Inoue also design a platoon controller involving Laser headway feedback components and acceleration and speed components via inter-vehicle communications [11].

1.4 Strategies and Manoeuvres.

Of primary importance when considering the benefits platooning may provide and platooning safety are the strategies and manoeuvres which occur, mainly around junctions, of vehicles leaving or joining platoons and the platoon response after such an event. Shladover [2] suggests that the key to successful and efficient platoon operations is dynamic entrainment. That is, the formation of platoons at line speed, rather than off line or in a holding area. In terms of safety it has already been noted that for this to be accomplished vehicles may have to spend time at non-safe spacings between running as individual units and platoons. How vehicles enter and leave both the automated lane and platoons will determine both the length of time in these non-safe states and how well the lane is utilised.

In any transportation system there is a difference between the theoretical lane capacity and that which is practically achievable. The theoretical capacity of any lane depends purely on the headway and speed of vehicles if they continue along the lane without disturbance. In reality there will be disturbance from vehicles entering and leaving the lane and there will always need to be spaces left in the traffic flow to accommodate vehicles entering the system and allow manouevres within the lane, whether platooning is used or not. Although this utilisation will be highly system specific, values between 65% and 80% have been suggested [2, 9, 12].

In [5] the manoeuvre of a vehicle joining a platoon from the rear is considered. This is the simplest idea of platoon formation where vehicles enter, leave and run on the automated lane as individual units at safe spacings and are then manoeuvred into and out of platoons while on the running lane. Connolly and Hedrick [6] consider the same procedure with vehicles spaced at 28m (line speed 20m/s) to run individually, join or leave the automated lane and closing to 5m (0.25-seconds) when platooned. This is also an option simulated by Rao et al. [9] with 30m spacings ahead and behind the leaving or joining vehicle reducing to 1m (0.04-seconds) when platooned at 25m/s.

An alternative is that of “virtual platooning”. This operation, proposed and demonstrated by Lu et. al. [8], controls the vehicles entering the automated lane, whether from a slip-road or parallel lane, such that the speed and acceleration are matched to the platoon before the vehicle joins. The vehicle is also controlled to the correct longitudinal position prior to entry. This means that a vehicle is effectively platooned in a longitudinal sense, before merging with the rest of the platoon. The merge of a vehicle into the platoon (or the exit of a vehicle) can take place from platoon spacings rather than requiring platoon manoeuvres to allow a vehicle to join or exit. This system was successfully demonstrated at two speed ranges (21 - 28kph and 56 kph), although intra-platoon spacings were rather larger than ideal (8 - 12m).

A similar system is proposed by Tsao et. al. [12] using a system of slots, each the length of a vehicle plus the intra-platoon spacing. Vehicles in adjacent slots are therefore platooned, while an empty slot either alone or between two full slots, is sufficiently big for a vehicle to enter it and not effect the flow of the lane. Vehicles must be next to the slot before moving into the lane: i.e. "virtually" platooned.

Rao et. al. [9] suggested this kind of method only for vehicles joining the platoon. It is suggested that all vehicles join platoons at the rear but at a spacing of only twice the usual platoon spacing. The same initial spacing is suggested by Hitchcock [13]. Here, platoons can only be formed away from the running lane but vehicles can come and go from these platoons once on the lane. They do this from close spacings, which are greater than the normal intra-platoon spacing but no greater than an increase of around 0.5m [14]. The extra spacing is required to give room for the vehicle to run out from or into the lane and also for the potential additional control errors due to the changing or aerodynamic forces involved.

The same kind of theory was applied when the eight-car platoon was implemented by Rajamani et. al. [7]. Once again the nominal intra-platoon spacings were relatively large (6.5m or 0.24 seconds) but vehicles, when leaving, spaced (both front and rear) to 13m (0.5 seconds). Unlike some of the other systems described, vehicles required to join the platoon did so at the safe headway distance of 41m and then closed up from the rear.

Other ideas involve the sorting of platoons before entering the guideway. Hall and Chin [15] suggest that platoons are formed at junctions depending on their destination such that no platoon formation occurs on the guideway and vehicles only ever leave from the rear of the platoons. Rao et. al. [9] consider a similar option, although platoons can be formed on-line, they are assembled to ensure vehicles only leave from the rear.

1.5 Project Aims.

A significant amount of work has been carried out looking at various aspects of platooning, some of which has been considered in this chapter. This work has shown that the possible benefits of platooning with regards to system and lane capacities are large and that there is a theoretical argument that platooning can be both safe and efficient. Practically, there has been much investigation and demonstration of the control methods and strategies which can be used to platoon two or more vehicles at reasonable highway speeds and spacings.

The aim of the work presented here is to ascertain whether platooning is a viable and practical means of increasing the capacities of automated transport systems. This will particularly focus on the two main areas already discussed.

First, the safety of platooning. The fact that platoon safety is justified only by a relaxation of the brickwall criteria makes it inherently less safe than single-vehicle operations and more so when platooning, exit and entry manoeuvres also involve passing through non-safe states. Consideration must be made of the effect of failure for multiple-vehicle platoons, what the risks are, how this relates to passenger injury and whether control systems can be specifically used to reduce these risks.

Secondly there is the question of what effect the implementation of platoon operations has on the utilisation of an automated lane. How will the nature of the operating strategies and platooning manoeuvres effect the drop in capacity from the theoretical level and will this make platooning as beneficial as predicted? It will also be of interest to determine how specific system characteristic may influence how beneficial platoons are and what length platoons it may be best to operate.

Ultimately, it is intended that this work will present a realistic view of the viability of platooning as a means to achieving higher system and lane throughput and design guidelines to aid the planning risk assessment of such systems.

1.6 Methods and Example Systems.

The aim of the study is to obtain general facts about the practicalities of platoon operation, and demonstrate these by way of examples or possible case studies. Therefore much of the initial work will be addressed by means of kinematic algorithms rather than simulation. This will mainly take place in the MATLAB environment. During the development of these ideas and also once a set of design guidelines are established, MATLAB with SIMULINK will be used for some system specific demonstration of possible platoon behavior.

For the examples considered through the report, and demonstrations, three specific systems will be considered. System 1 represents a possible low-speed personal rapid transit (PRT) system. This utilises four-person automated vehicles running on a dedicated single-lane guideway with a lane speed of 22kph (6m/s). This is similar to the proposed ULTra system [16] but with a low speed for possible use in high-demand, short journey situations. System 2 is based entirely on the ULTra PRT system. It involves the same guideway and vehicle types as System 1 but with a lane speed of 40kph. S

System 3 represents an Automated Highway System (AHS). This is designed to utilise less specific vehicles with on-board automation systems. The vehicles would run on a dedicated "automated" lane possibly self contained or as part of a standard highway structure. Lane speed is set at 113kph (British Motorway speed of 70mph) and while single lane operations will primarily be considered for comparison, multiple lane affects will also be investigated.

Chapter 2

Platoon Safety.

2.1 Collision Speeds.

To gauge the safety of platoon operations the situation is considered whereby a vehicle fails such that it decelerates at the highest possible rate (without external influence). Given the likely lack of, or low aerodynamic downforce produced by PRT vehicles or passenger automobiles, this is set at an instantaneous $10m/s^2$ for this study, which is unlikely to be exceeded even in full four-wheel lock-up. Although this vehicle will often be referred to as the failed or lead vehicle, it can be any of the vehicles in the platoon (although the rear vehicle will not cause any collision).

Assuming that all vehicles following the failed vehicle have a (possibly) time-delayed response and then a constant emergency deceleration the collision speeds can be determined between subsequent vehicles subject to the following assumptions: For simplicity, the vehicles do not crumple or shorten after collision. All vehicles have the same spacing and speed before collision. When a following vehicle collides with the vehicle ahead of it, it instantly assumes the speed and deceleration of that front vehicle. This is similar to the methods used by Shladover and Szillat [2, 4].

It has already been shown that there will still be a collision when the lead and follower decelerations are equal. As well as considering the case when the emergency follower decelerations can match the lead failure deceleration, it is interesting to consider when the decelerations are equal but lower. This would occur when the leader in a platoon detects a stationary vehicle or object ahead and undertakes a controlled emergency stop (note that inter-platoon spacings obey the brickwall criteria with headway determined by the emergency deceleration). This shall be called the Platoon Emergency Stop and is also worth consideration - logically, vehicles in the platoon should not collide under such a controlled procedure.

To demonstrate these points a System 3 (AHS) platoon of eight vehicles is considered. As these are highway vehicles and passengers are possibly restrained the Platoon Emergency Stop takes place with a constant deceleration of $7m/s^2$. Figure 2.1 shows the collision speeds with spacings for the following vehicle assuming a vehicle-to-vehicle time delay of 0.2-seconds. Also shown are the collision speeds for lead failure deceleration of $10m/s^2$ and follower decelerations of 5, 7, 9 and $10m/s^2$. For likely emergency

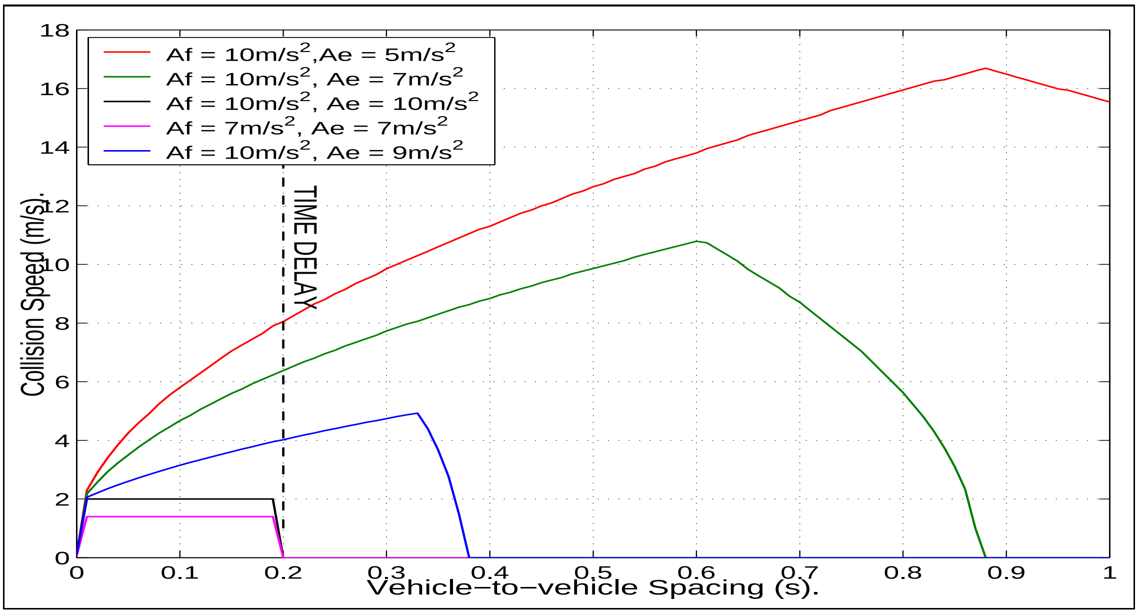

Figure 2.1: Collision Speed with Selected Lead and Follower Decelerations.

decelerations (5 or $7m/s^2$) it is clear that it is vital to run vehicles as close as possible. At a one-metre (0.033-second) spacing, the collision speed at the lower follower deceleration is 3.5m/s but at a spacing equivalent to the time delay it is over 8m/s.

The closer the two deceleration are, the lower the collision speed between the two vehicles. However, as stated, there is still a collision if the two decelerations are equal. This can be simply proven by calculating the distance (S) and velocity (V) of the lead (l) and follower (f) vehicles given the decelerations of each (D) and the time spacing (Ts), time delay (Td) and initial lane speed (V):

$$V_l = V - (t + Td) \times D_l \tag{2.1}$$
$$V_f = V - t \times D_f \tag{2.2}$$

$$S_l = V \times t - \frac{t^2 \times D_l}{2} - Td \times t \times D_l + V \times Ts \tag{2.3}$$
$$S_f = V \times t - \frac{t^2 \times D_f}{2} \tag{2.4}$$

At the time of contact t (that is time since follower starts deceleration), and if failure and emergency (lead and follower) decelerations are equal then the distances must be equal and so the contact time can be found to be:

$$t = \frac{V \times Ts}{Td \times D_l} \tag{2.5}$$

If the separation (Ts) is zero then the collision occurs immediately and both vehicles are still at line-speed. Otherwise, up to the point where separation equals the time delay:

$$V_{collision} = Td \times D_{f/l} \tag{2.6}$$

When the separation delay and control delays are equal then the contact time is:

$$t = \frac{V}{D} \tag{2.7}$$

And so the following vehicle is stationary at the point of contact and the collision speed is zero. Beyond this the following vehicle is stationary before the collision time and, as the lead vehicle does not continue to decelerate once stationary (does not reverse) there are no collisions at this or any higher initial separations.

This leads to a fundamental point about platoon control. In order to avoid all vehicle-to-vehicle collisions under controlled situations (including the Platoon Emergency Stop) the vehicle-to-vehicle spacing cannot be less than the controller actuation delay in time. The delay between consecutive vehicles obtaining similar rates of acceleration or deceleration becomes vital in determining the safety of platooning as it limits how close vehicles can be run together and therefore how low potential collision speeds can be made. This key element is the Minimum Spacing Requirement.

2.2 Minimum Spacing Requirement.

The important parameter to determine this requirement is the time between similar actuation of consecutive vehicles, that is the time between consecutive platooned vehicles reaching similar, or maximum, braking levels. This will strongly depend on the nature of the control systems used in platooning, of which three types can be defined.

2.2.1 Feedback Control.

The most basic method of vehicle control is to rely entirely on vehicle to vehicle distance sensing between consecutive vehicles, usually by means of lasers. This is suggested by Shladover [2] with a total time for vehicles to reach equivalent braking levels of 0.2-seconds and [5] where a non-linear feedback control is used to increase gains at close spacings. For controller lag time constants of 0.1-seconds or less this can minimise spacing errors during low acceleration manoeuvres to 0.25m and so 0.3m is suggested as a minimum intra-platoon spacing (0.03 seconds at the average speed shown). This does not consider controlled emergency operations.

Connolly and Hedrick [6] suggest feedback with adaptive control (modification of drag force estimate) to minimise spacing errors when following. Although no specific delays are considered, the intended spacing at 20m/s is 5m (0.25-seconds) which is at least similar to the other delays suggested above.

In another study Shladover [17] presents a more detailed break-down of the possible components of the delays. For the feedback only case ("Automatic - Autonomous") the time to sense problem and initiate action in a severe failure (0.5g) is 0.2-seconds with a further 0.1-second actuation delay with the most advanced braking system predicted. This gives a total of 0.3-seconds. A figure for spacing of just 0.225m is suggested to ensure that the second vehicle has at least begun braking before impact. For a controlled emergency stop it might be reasoned that the time delay between consecutive vehicles taking similar action would be just the sensing delay of 0.2-seconds.

Tongue and Yang [10] consider delays of 0.2 to 0.5-seconds but assume a 1m ($\leq$ 0.1-second) spacing even with just feedback control. Seto and Inoue [11] show that effective delays with feedback can be up to one second between vehicles reaching similar speeds. This gives headway errors of over 1m but the headways used are 15m and so the accuracy of vehicle spacing is not as significant. Finally Hitchcock [18, 19] suggests a delay of 0.09 seconds between consecutive vehicles applying brakes.

These studies all appear to indicate that, with a pure feedback system, the minimum lag between subsequent vehicles braking could be as low as 0.1-seconds but that realistically it will be greater. It is possibly more reasonable to set the Minimum Spacing Requirement to around 0.2-seconds.

2.2.2 Feedback with Lead Vehicle Information.

Although not running vehicles in tight platoons, Lu et. al. [8] emphasises the importance of vehicle-to-vehicle communication. Providing information to each vehicle about the vehicle directly ahead of it is suggested as a means of reducing the spacing errors and hence, the required intra-platoon spacing.

For the platoons which were successfully tested and described in Rajamani et. al. [7] the spacings were around 0.24-seconds but communication was used to share vehicle speed and acceleration data within the platoon. This system is assumed by Rao et. al. [9] in their simulations. The communication delay is supposed to be 0.1-seconds and the actuation delay 0.2-seconds but the vehicle-to-vehicle spacing is set at 1m (0.04-seconds). This can only be possible due to communication between vehicles. Indeed, it is said:

> communicated information should keep platoon parties from hitting each other, even in sudden braking. [9]

As this type of communication removes total reliance on the sensing of the vehicle (and hence significant changes in the spacing before any actuation) the effective delay between vehicles reaching similar states of operation will be reduced. Tongue and Yang [10] showed this by modifying a platoon simulation to include communication from the lead vehicle and reduced both collision speeds and the number of vehicles in the platoon that collided.

Seto and Inoue [11] also demonstrated that the inclusion of feed-forward terms in the longitudinal control algorithm (from the lead vehicle acceleration) reduced lag times by around half and the spacing / headway error by significantly more.

Whilst this method does appear to make some significant difference in these examples, there are still some inherent problems and delays involved. If the lead vehicle undertakes a controlled emergency stop with only speed and acceleration communicated to the following vehicle, the delay between lead and following vehicle will still consist of the time the lead vehicle takes to reach significant deceleration, any lag due to filtering, and the communication delay.

Any system that relies on real time dynamic information about the vehicles in the platoon will have such lags. While this method of feedforward may help reduce the lags from the feedback system, the lag is likely to still be significant and necessitate larger than ideal platoon spacing in normal conditions.

2.2.3 Full Platoon Communication.

By communicating both real-time dynamic and more qualitative information between vehicles there is the possibility to reduce the overall time lags between vehicle actions further. Tsao and Hall suggest that:

> when a vehicle decelerates due to failure, all the trailing vehicles within a reasonable range receive simultaneously the distress signal and start decelerating at a common and constant target rate (after a common delay). [12]

The reaction delay (communication plus brake actuation) is set at 0.1-seconds. This would be the time lag between lead vehicle failing and second vehicle starting to decelerate. However, between the second and all subsequent vehicles there would be no time lag and so even in the event of collisions (for this failure mode) the 3rd and subsequent vehicles are likely to have significantly lower collision speeds than expected under pure feedback control.

Taking this idea through to normal operating conditions the communication could be used to indicate either qualitative changes of operating mode between constant speed and standard or emergency acceleration or deceleration modes or to provide the trailing vehicles with the speed or acceleration control demands on the lead vehicle. This would effectively reduce any lag between the start of actions to just that of the communication delay, be it lead vehicle to all in the platoon or vehicle to vehicle down the platoon.

Shladover [17] describes something similar as an "Automatic - Co-operative" system. For a severe failure he suggests just 0.06-seconds to sense the problem and communicate it to the next vehicles. For a controlled emergency situation this is the only delay time as there is no failure and so the actuation time is part of the action. Therefore, if these figures are realistic, it suggests that sub 0.1-second intra-platoon spaces are possible.

Hitchcock [18, 19] proposed that this is how platoon vehicles operate where each vehicle is warned to brake (rather than waiting to detect braking) by a signal passed back vehicle to vehicle. Although the actuation delay may be 0.09-seconds, the delay between vehicles taking similar actions is only that of the communication time, which is proposed to be 0.01-seconds. In the case of a vehicle failing, the delays are likely to be bigger (the communication may actually be the system which fails) and collisions are likely. But if the communication allows vehicles to run closer together in nominal operation, the collisions should be at lower relative speeds.

It has been shown [5] that other aspects of the dynamic control will limit the minimum spacing a little and so around 0.3 to 0.6m is likely to be a minimum, depending on the speed. 0.03-seconds seems a reasonable figure. If vehicles are to run at sub 0.1-second spacings, as may be necessary to increase safety, and yet avoid contact in all controlled running, including high braking rates, then this extra communication appears to be necessary.

2.3 Multiple Collisions.

Although close spacing may minimise the collision speed of the the vehicle directly behind a failed vehicle it is important to consider that there may be multiple vehicles in the platoon and therefore multiple collisions in the event of failure. As any vehicle in the platoon may fail, or any vehicle be the leader in an emergency stop, the spacing between all vehicles must be equal and obey the Minimum Spacing Requirement.

With the assumptions previously stated, and assuming that feedback only control is in operation (delay of 0.2-seconds), figure 2.2 shows the collision speeds of seven following vehicles with emergency deceleration of $7m/s^2$ after a failure deceleration of $10m/s^2$ and with initial speed once again 113kph (System 3). Here the significant

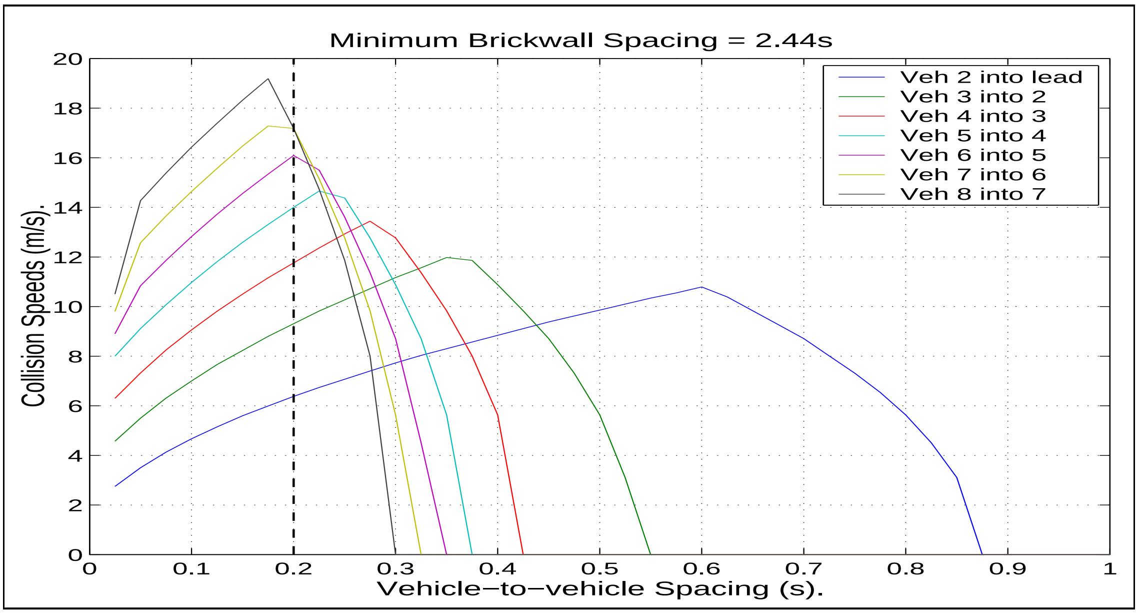

Figure 2.2: Collision Speeds of Multiple Vehicles.

affects of multiple collisions and minimum spacing requirement are clear. While the first collision is at relatively low speed, subsequent collisions are each at higher speeds. The eighth vehicle in the platoon would have an even higher collision speed if the spacing could be slightly lower, but generally all collisions could be reduced if the spacing could be set below the minimum spacing requirement.

The argument for the safety of platooning is to push vehicles close together to minimise collision speeds. It has been seen that the requirement for a minimum spacing may prohibit the effectiveness of this but it is interesting that for multiple vehicle platoons increasing the spacing will reduce the collision speeds for the sixth-vehicle onwards in this case. In fact, for a spacing of 0.3-seconds and above, the eighth vehicle (and any other vehicles for longer platoons) would not be involved in collisions at all. At

0.4-second spacings and above only four vehicles (including leader) would be involved. This is interesting, but the spacings required to produce this result (9.4 - 12.6m) would not produce the high capacity benefits expected from platooning. It does, however, lead to another possible operating strategy, also demonstrated by Figure 2.2.

2.3.1 Free-agent Operation.

This is a third possibility for automated operation which has also been considered by Tsao et. al. [12, 20]. The vehicles run closer spaced than at the brick-wall criteria but not as close together as in a platoon. For the purposes of presenting a case for safe platooning it has been suggested that a failed lead vehicle will decelerate at a finite level ($10m/s^2$) and that vehicle to vehicle collisions are safe at low relative speeds. If this is regarded as acceptable for safe operation then the same rules could surely be applied to non-platooned vehicles.

In the case shown in figure 2.2 vehicles could theoretically run at 0.87-second spacings (or slightly less) with small or no collisions in the case of failure. As stated, the safe brickwall spacing is 2.44-seconds. This suggests that if the platoon safety rules are applied throughout then individual vehicles could run at these lower spacings and increase capacity by over 250%.

This concept of free-agent vehicles might also have other benefits in reducing control complexity [20] and eliminating special manoeuvres for forming, joining and leaving platoons. Also, the problem of controller delay and control tightness will not be as significant. If the failure and emergency decelerations become very similar as is expected on a motorway, the free agent and platoon capacities will converge and vehicles will again need tighter platooning control.

2.4 Risk of Casualty and Fatality.

To determine safety and risk of platooned operations the vehicle-to-vehicle collision speeds likely to cause passengers injury need to be determined. Tsao and Hall [20] use values of 3.55m/s for a safe collision while any above 7.10m/s run a high risk of causing serious injury or death. The lower of these figures is similar to other suggestions of a cut off velocity to avoid anything other than mild or moderate injury. These include Shladover [17] who suggests 3.3m/s, and Huang and Chen [21] who suggest a slightly lower figure of 3.0m/s.

More precise information comes from Hitchcock [18, 19] where data from the National Highway Traffic Safety Administration (US) [22] is used to estimate probability curves for casualties rated on the Abbreviated Injury Scale (AIS) against front - on collision speeds. AIS ratings are:

Table 2.1: Abbreviated Injury Scale Ratings.

Severity	AIS
Minor	1
Moderate	2
Serious	3
Severe	4
Critical	5
Unsurvivable	6

Combined with a more general rule for the risk of fatality in a crash, based on similar data [23], some of the key general curves can be plotted for collision speeds in the region of interest: Whilst minor injury (a small amount of bruising but no broken

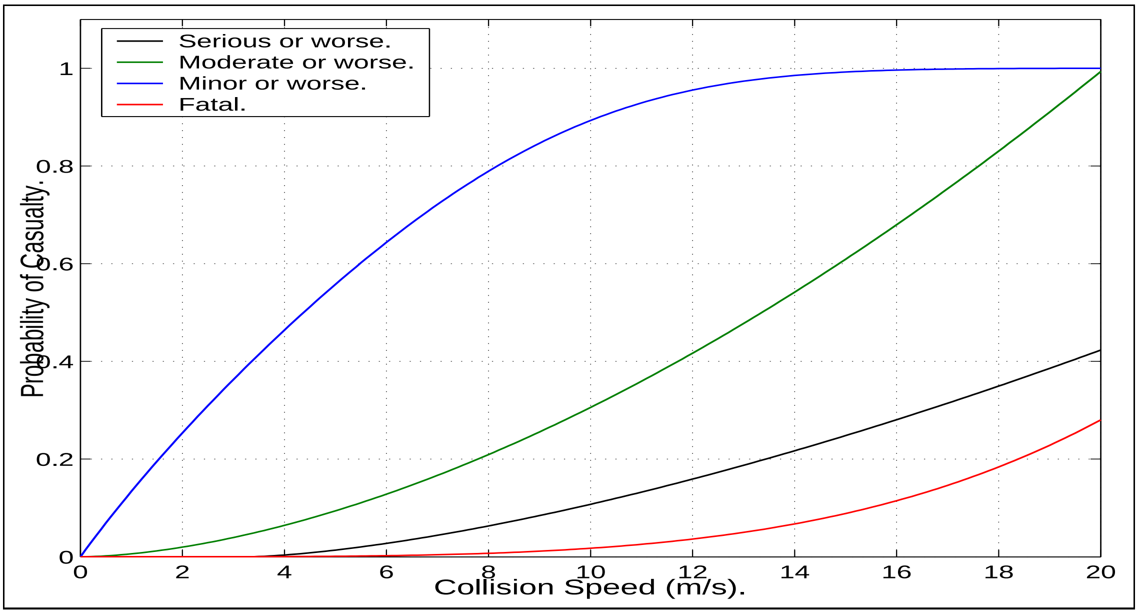

Figure 2.3: Probability of Casualties.

bones) is possible at any speed, the cut off for serious injury is around 3.5 to 4m/s as suggested. The chance of any more than a moderate injury is very low at 6m/s and fatalities almost impossible. The chance of fatality is around 1 in 44 at 40kph but rises to 1 in 4 at 20m/s. However, if collisions are kept below 4.85m/s the chance of fatality is only 1 in 1000 crashes. This seems a reasonable figure to consider when looking at platoon collisions.

2.5 Casualty Risk in Platoon Failure.

The probability of casualty at collision speeds can now be used to consider overall likelihood of casualty within a platoon when the lead vehicle fails by combining the trends in figure 2.3 with the calculation of the collision speeds as shown (for this example) in figure 2.2.

For each collision at each spacing the probability of casualties based on collision speed are calculated. These are then summed for all the vehicles (it is assumed that the lead vehicle of an eight-vehicle platoon fails) and multiplied by 1.4, which is said to be comparable to current automobile occupancy [2, 16]. What is then derived is the probability of a particular injury occurring in the whole platoon after a failure. The probabilities shown are limited to a maximum of unity. This implies an "almost"

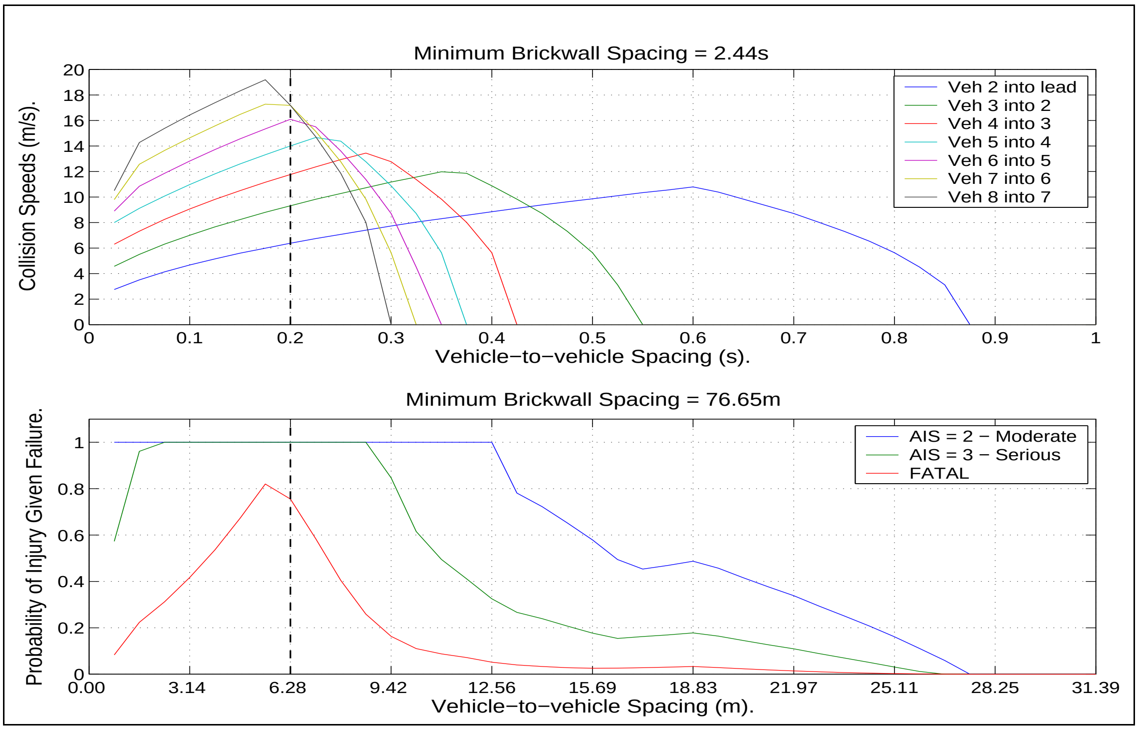

Figure 2.4: Injury Risk in 8-vehicle Platoon Failure.

certain chance of this injury occurring in the platoon. Values of greater than unity are possible as this implies a good chance of more than one passenger per platoon being injured at a particular level but the main concern is the chance of injury per failure.

For this example the risk of injury and fatality appear alarmingly high. In the likely desired (capacity wise) spacings of 0.2 to 0.3-seconds there is an almost certain risk of serious injury and a fatality is likely in up to 75% of failures. To significantly reduce the risk of serious injury or fatality but maintain genuine platoon operation the spacing would have to be reduced to around a metre (co-incidentally a spacing commonly suggested) but this would violate the minimum spacing requirement and even then only reduce fatality risk to around 1 in 10.

Figure 2.4 once again emphasises the possible safety advantages of running vehicles in the free-agent mode. Fatality risk is reduced to below 1 in 20 at 0.4-seconds and approximately 1 in 1000 at a point which would still offer a potential three-fold capacity increase over brickwall spacings.

It appears practically that this type of control system is not capable of making close platoon operation viable at such speeds. While the safety calculations must be further enhanced to account for the probability of vehicle failure and the number of likely follower vehicles, it appears from this study that it is the more complex control and communication systems which are required to ensure safe platoon operation.

2.6 Fatality Risk in Journey.

To gain comparable insight into the safety of platoon operations, or automated transport systems in general, the best gauge is that of the fatality risk to any passenger during a journey. While there will be other potential risks involved from other types of vehicle failure and external forces, this work considers the collision between vehicles as the significant risk.

Using the calculations explained in the previous sections the risk of fatality, given a vehicle failure, can be determined for a lead vehicle failure in a platoon of any length. This platoon length could alternatively represent the number of vehicles involved in an incident as it is reasonable to assume that any vehicle in a platoon has an equal chance of failure. Any vehicles ahead of the failed vehicle will not collide and so the risk of fatality in these is zero.

For any platoon length the risk of fatality, given that a vehicle within the platoon fails, can be calculated by averaging the risks for a failure in each vehicle - again assuming 1.4 passengers per vehicle. Furthermore, if the probability of vehicle failure is known then the overall risk of fatality during a journey can be calculated. This is most easily evaluated as the expected number of journeys per fatality.

Figure 2.5 shows this for another example of an AHS system. This has the same characteristics as the previous examples but models a system which uses some shared vehicle communications during platooning. The actuation delay (and minimum spacing requirement) is reduced to 0.03-seconds. The collision speeds of subsequent vehicles following lead vehicle failure are shown and below the expected journeys per fatality for operation with between two and eight-vehicle platoons. The probability of vehicle failure is 10^{-6}. The reduced actuation delay significantly reduces the collision speeds

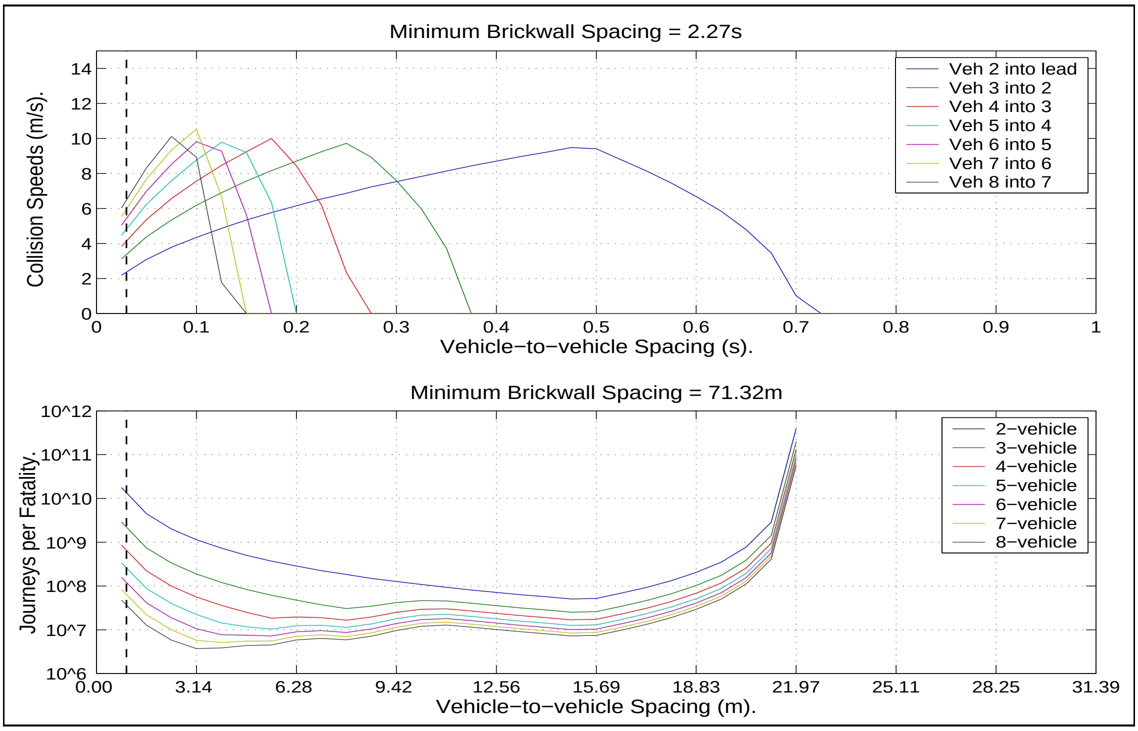

Figure 2.5: Collision Speeds and Fatality Risk for AHS Example.

throughout the platoon compared to Figure 2.4. It is interesting to compare the areas of highest risk (low journeys per fatality) for different platoon lengths. Logically, the highest risk if two-vehicle platoons are used throughout corresponds to a spacing of 0.5-seconds: the highest collision speed. For eight-vehicle platoons the risk is highest much nearer the minimum spacing requirement, at 0.1-second spacing, but reduces by a factor of 10 if the minimum spacing is used.

It should be noted that the data used for determination of the risk of fatality compared to collision speeds is supposed to be for unrestrained occupants. Although this may only have complete relevance to the PRT systems considered, it is wise to use these figures for the AHS system as there is no guarantee that passengers will be restrained and it is useful to usually consider the “worst case scenario”.

The final stage in assessing the practicalities of platoon safety is to determine what an acceptable risk of fatality is, and how safety is related to system capacity (something considered by Hitchcock [18]) given the system characteristics and operations considered. This allows the production of useful design charts to aid such an assessment.

2.7 Design for Safety: Effect on Capacity.

2.7.1 Vehicle Failure Rate.

In the previous example the failure probability of the vehicle was set at 10^{-6}. This is similar to aerospace levels of reliability and a reasonable aim for automated transport systems. However while this is presumed to be the most significant type of failure with regards to platoon safety, it is also a very specific failure mode which would produce such a result.

If the vehicle fails but decelerates at anything up to and including the emergency deceleration rate then the Minimum Spacing Requirement will ensure that no collisions take place. Similarly, a vehicle failure due to some other fault may not render the vehicle incapable of longitudinal control and may just initiate a controlled emergency stop. Otherwise, brake failure would cause a different set of problems beyond the scope of this study.

Given these facts it may be that the chance of this specific failure, which causes the vehicle to decelerate significantly above the emergency braking levels is only a fraction of the overall probability of failure. The difference between the failed and emergency decelerations used in the calculation will probably have some influence on what this fraction is (if the emergency deceleration is limited to $5m/s^2$ for PRT systems the chance of a failure exceeding this will be higher).

Although, once again, it may be useful to consider 10^{-6} as a worst case scenario, both the possible seat restraints and the chance of vehicle failure and failure type lend yet more probabilistic uncertainty to the exact safety ratings of operations. It may be wise to consider journeys per fatality rates by a factor of 10 above and below the calculated figure.

2.7.2 Tolerable Risk: Hazard Ranking.

The work covered has determined the possible risk of fatality under platooning operations in terms of the predicted number of journeys per fatality. To determine platooning safety the tolerable risk needs to be considered. One fatality for every 1000 failures, or one per 10^9 journeys seems extremely low but makes no particular sense in itself, without a measure of the frequency of journeys.

A method developed for engineering safety management [24] provides a risk assessment table known as the Hazard Ranking Matrix. The frequency of events are rated between one and six (one being an event every 25-years and six being around 30 events per year) and the severity one to ten (one being negligible injury and ten multiple fatalities). The product of each gives a ranking which determines the risk, and whether action is required. Table 2.2 shows some selected examples of risk level, converted back into descriptive forms of risk level.

Table 2.2: Hazard Matrix - selected examples.

-	1 event > 25yrs	1 event > 5 years	1 event/yr
Injury Level			
Serious	**Acceptable**	**Tolerable**	**Tolerable**
Major	**Acceptable**	**Tolerable**	**Moderate**
Fatal	**Tolerable**	**Moderate**	**Unacceptable**
Fatalities	**Moderate**	**Unacceptable**	**Unacceptable**

A tolerable risk is defined as one which is acceptable but should be monitored for any increase. A moderate risk is one which should be examined for ways in which it could be reduced. Therefore the safety level to aim for is tolerable safety. From a more detailed look at the values involved it appears that one fatality every ten years in a reasonable value to consider for tolerable safety.

One the basis of a tolerable risk of one fatality in ten years, acceptable safety levels can be established for platooning based on the operation of a system. This is simply calculated on the basis of the number of hours of operation of the system in one day and the number of trips in one hour (based on 365 day/year operation).

2.7.3 Design Charts.

Figures 2.6 show the charts which combine all the safety and risk information on the AHS-type system (System 3) given the characteristics described. After consideration of the data plotted in figures similar to Figure 2.5 four operation types are chosen. These are the “free-agent” operation with actuation delay of 0.2-seconds and spacing of 0.87-seconds, the feedback controlled platooning operation with actuation delay of 0.2-seconds and spacing of 0.3-seconds, the operation involving some vehicle-to-vehicle communications with delay and spacing of 0.03-seconds and a full platoon communication system similar to the previous system but with all follower vehicles responding simultaneously when a failure occurs.

The uppermost plot shows the risk of fatality for the four operation modes if the

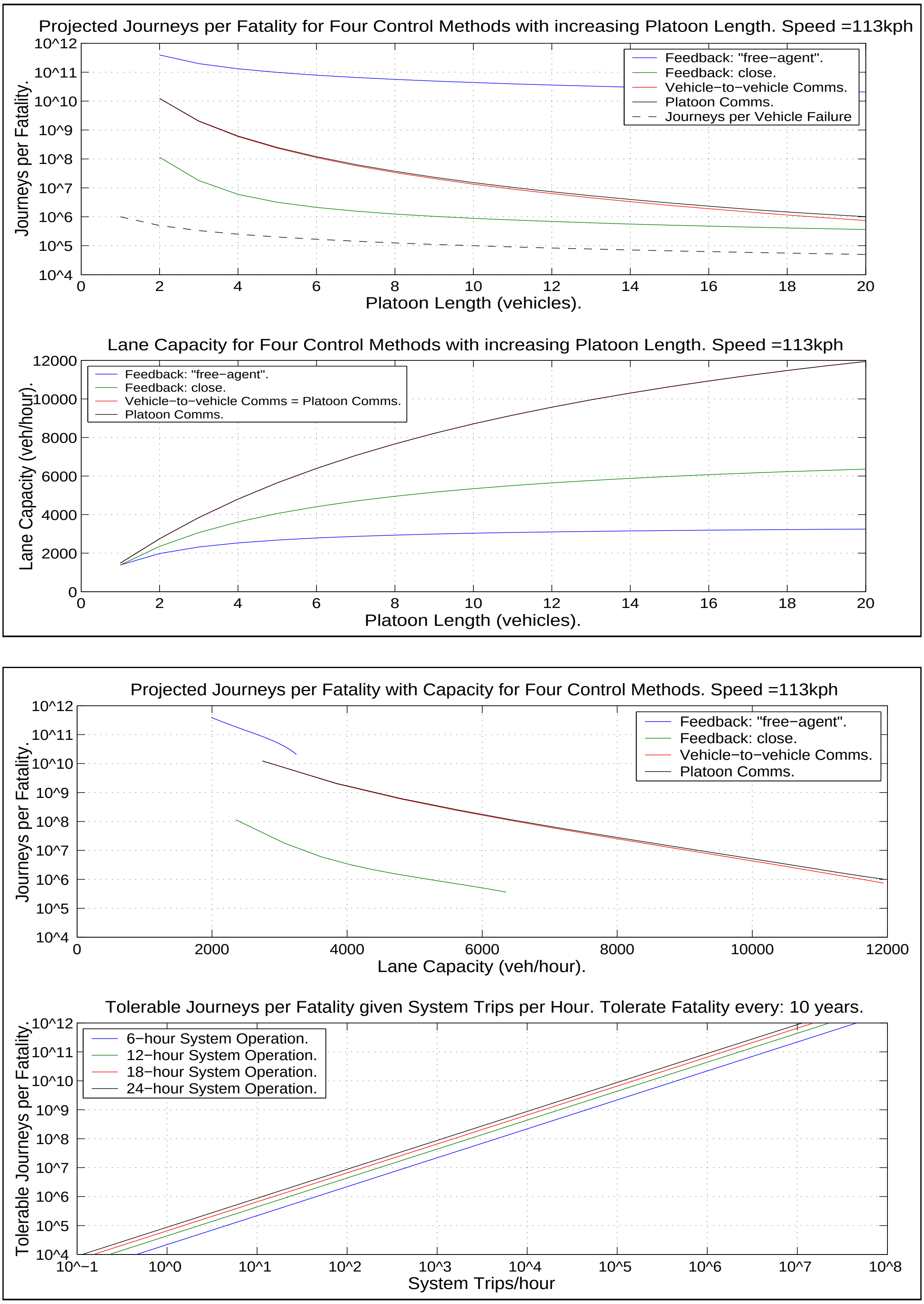

Figure 2.6: Safety and Risk Design Charts for System 3 Example.

average platoon length used on the system is between two-vehicles and twenty-vehicles. Below this the maximum theoretical lane capacity of the system under each operation mode is shown.

As expected, the free-agent operation is the safest, but yields the lowest capacity. The third and fourth modes yield the same capacity (intra-platoon spacings are identical) but the full-platoon communication mode is marginally safer at the higher platoon lengths. Considering this appears to indicate that the benefits of this extra complexity is minimal and that any communicated information may only be from vehicle-to-vehicle through the platoon, rather than simultaneously to every vehicle.

The dashed line indicates the expected number of journeys per vehicle failures. It should be noted that the chance of a platooned vehicle failing is higher with longer platoons, so if the average platoon length is ten vehicles, the chance of a vehicle failing in a platoon increases to 10^{-5}.

For the third mode of operation the effects of platooning on safety are very significant. With two-vehicle platoons the journeys per fatality is 10^{10}. This decreases by two orders of magnitude if the platoons are six-vehicles long and by another two orders of magnitude for twenty-vehicle operations (to one fatality every million journeys). The second plot shows that these increases in platoon length still provide reasonable gains in capacity while, although significantly safer, the free-agent operation has little gain in capacity above ten-vehicle platoons.

In some ways the free-agent case is a little mis-leading. If spacings were increased to 0.9-seconds then there would, by these safety criteria, be no chance of collision in failure and vehicles are not practically platooned. While this gives a potentially safe and less complex way of at least doubling capacity, the system becomes one of a fixed headway of around one second - providing a maximum capacity of 3600 vehicles/hour - less than achievable by running platoons of three vehicles under the third or fourth operation modes.

The third chart in Figure 2.6 compares the risk of all these modes to the capacities available while the fourth allows consideration of the likely tolerable risk given a projected number of trips per hour. For simplicity in this example it is assumed that the trips per hour matches the available capacity and that the system operates on an 18-hours a day basis. Capacities of interest range between 1000 and 12000 vehicles an hour, giving tolerable risk of between 10^8 and 10^9 journeys per fatality.

The platooned feedback mode provides relatively low capacity gains at high risk and appears not to be a viable mode of operation. As stated, the free-agent operation an extremely low risk operation and it looks likely that the maximum capacity of 3600 vehicles/hour could be obtained without violating the limit of tolerable safety.

The tighter platoon modes appear to be reasonable with a six-vehicle platoon length returning a 10^8 journeys/fatality risk while providing capacities upwards of 6400 vehicles/hour. However, the problem is that at this higher capacity and therefore potential trips/hour the required safety threshold is lower. It may be necessary to reduce platoon lengths to five-vehicles to satisfy the tolerable risk and hence capacity to approximately 5600 vehicles/hour.

2.8 Conclusions.

By building up a set of calculations and models of vehicle behaviour, collisions in failure, casualty risk and tolerable safety it has been possible to create design charts to compare different possible modes of operation and strategies for automated transport systems.

Although only one example has been shown, and some parameters chosen for simplicity, the process allows any system of any speed and characteristic to be considered and options compared and evaluated in terms of effectiveness and safety. Later in this report, the other two example systems will be considered in a similar way and effective modes of operation suggested.

In the final section the capacity was compared to the risk and also used to gauge the possible number of journeys which would be undertaken in an hour. Exactly how the risk in journeys/fatality relates to the tolerable risk levels is a complex and interesting subject, which will not be fully covered here. In some ways the actual definition of risk is important. If a single AHS or PRT system is considered then it may be realistic to assumed that the number of journeys/hour is a single-digit multiple of the system capacity and so long platoons may be acceptable.

If AHS or PRT systems become Nationwide or World-wide then some re-scaling needs to take place as many more journeys will be undertaken every hour and every day. In this case the required risk either becomes impossibly small to meet or the tolerable level of one fatality in ten years must be re-addressed. For AHS systems it might be more useful to compare the risk to that on a manual road network where for a country like Britain multiple fatalities may occur every week - which based on the Hazard Ranking Matrix is “unacceptable”.

Having considered the theoretical capacities obtainable with various modes of platooning, it is now important to consider whether these increased flow rates can be practically obtained, or to what extent does the necessary increase in complexity of control systems reduce the utilisation of the system's full potential. Determining a better understanding of the practical benefits of platooning is key to the process of deciding if the inevitable reduction of safety is worthwhile and the overall viability of such operations.

Chapter 3

Effect of Platooning on System Capacity.

3.1 Utilisation and Schedule Efficiency.

In all transportation systems there is inevitably a difference between the maximum throughput, or capacity, that is theoretically possible on a lane or a network, and that which is practically achievable. This difference shall be represented by the lane or system utilisation and be expressed as a percentage of the theoretical capacity for each case. The drop from maximum throughput may be due to a number of issues.

Vuchic [25] states that operation at maximum capacity places strain on most transport systems as they must run to their maximum abilities. It is suggested that operation is feasible at around 80% of capacity. When considering capacity models based solely on system speed and headway considerations Vuchic states:

> theoretical capacities are often quite different from practical capacities....
> ...Factors exist in the real world which are not included in these models. [25]

These factors include the problems when two routes converge and continuous arrivals of vehicles at minimum headway cannot possibly be achieved. Also the throughput must depend on standing times at stations (or rate at which vehicles can be put onto the network) which is likely to involve significant variation. There will also be variation in braking and acceleration rates which will inevitably create irregularities and decrease capacity.

Shladover [2] suggests that with a slot-based system only 80% can be occupied if merging conflicts are not be become unacceptable. This is mainly the basis of the schedule efficiency. There must always be sufficient spaces in the lane for a joining vehicle to ensure that the delay to the vehicle joining is not too large. Otherwise the rate of entry to the lane will not be sufficient to sustain the throughput and so this will drop. This is difficult to quantify generally as it is somewhat dependent on the layout of entry and exit ramps and the proportion of vehicles leaving and entering at any point.

Rao et. al. [9] used simulation to investigate achievable capacities in an AHS system. Three methods were tried for platooning operations on a system where, rather than having pairs of entry and exit ramps, four entry points were followed by the exit point. The first method required all vehicles to be at safe spacings before entry and exit. Sufficient capacity was obtained on the lane, following all entry points, but the manoeuvres caused too many uncomfortable accelerations and decelerations while spacing all vehicles to allow exit caused a significant drop in flow rate.

The second method used an improved merge and lane change similar to the proposed "virtual platooning". This greatly improved the entry of vehicles into the lane but the significant problem still remained the requirement to space vehicles off for exit especially when more than one vehicle in a platoon needed to leave. In this case vehicles toward the rear of the modeled set became nearly stationary. The third method allowed vehicles only to leave the platoon from the rear. This meant that initial sorting was necessary on entry to the lane. While this makes the exit of the lane significantly less disruptive, it restricts entry flow and so overall throuput is reduced.

Whilst simulation is a useful tool, the aim of this work was to try and obtain more general equations which can represent any system characteristic. The basis of the method used to obtain this was a study by Hall [26] in which equations for the workload, throughput and utilisation of an automated lane are derived.

3.2 Workload and Throughput.

The definition of workload, as stated by Hall, is:

> the total longitudinal space requirement within a lane (measured per length of highway), accounting for vehicles engaged in purely longitudinal movement, as well as vehicles engaged in lateral movement. [26]

For every vehicle journey, the vehicle requires a certain amount of space on the lane (vehicle length plus headway) for the time of the journey. In addition there is extra space required for certain amounts of time for entry and exit manoeuvres and (for this study but not included by Hall) any on-line manoeuvres to place the vehicle in a platoon.

In simple terms, the workload equations calculate an average space for each vehicle in a journey, given the characteristics of the system operations. This can then be compared to the ideal space for each vehicle (assuming purely longitudinal movement) and so the throughput (capacity) of the system can be calculated, normalised by the ideal throughput. This then gives the utilisation U_S and practical capacity of the system. In [26] the full derivation is provided. Adopting slightly different terms the key equations can be simplified to:

$$U_S = \frac{1}{\sum_{i=1}^{L} W_i} \tag{3.1}$$

Where L is the number of lanes and W_i the workload of each lane. For a single lane it is found that:

$$W_i = p_i + (2\beta + 2\gamma) \sum_{j=i}^{L} \frac{p_j}{r_j} - (\beta + 2i\gamma) \frac{p_i}{r_i} \tag{3.2}$$

p is the proportion of flow in each lane and r the ratio of the average trip length in the lane to the overall average trip length of the system. The sum of p and r across all lanes is therefore, by definition, always unity. For multi-lane systems it is assumed in this work that r_i is unity and the initial flow distribution is defined as equal ($p_i = \frac{1}{L}$). The equations for workload then must be iterated until the ratio of workload in any lane to overall workload is equal to the proportion of flow in the same lane to the overall flow.

γ represents the waiting time to execute a lane change as a proportion of the average trip travel time while β is the primary parameter which accounts for the additional time and space required for the vehicle to undergo the lane-change, entry and exit manoeuvres. The equations work on the basis that a lane-change manoeuvre (leaving one lane and entering the next) is identical to the manoeuvre when entering the first lane in the system added to the manoeuvre when leaving the system.

$$\beta = \frac{o_M \times V_L}{\eta \times S_L} \tag{3.3}$$

V_L is the lane speed of the system and η the average trip distance for the system (therefore β is significantly effected by the average journey time). S_L is a calculation of the average space requirement for each vehicle on the lane. This is the first term on which platooning, and specifically the length of platoons, has a direct affect. If N is the average platoon length on any system then:

$$S_L = \frac{[(N-1)\,x_1 + x_2]}{N} \tag{3.4}$$

x_1 is the intra-platoon headway (vehicle length plus vehicle-to-vehicle spacing) and x_2 the inter-platoon headway which is the same as a single vehicle headway meeting the brickwall criterion. Hence with no platooning (single vehicle platoons) $S_L = x_2$ while for long platoons S_L will approach x_1, the smaller value, and β will increase.

This only leaves o_M and γ to be fully defined. These are both directly effected by platooning and, more specifically, the nature of the platooning operations used. The method of operation, or overall control laws, need to be defined and then the parameters calculated based on the manoeuvres that they entail.

3.3 Platoon Operation and Strategy.

In section 1.4 previous work in defining possible aspects of platoon control was described. Assuming that the formation of platoons must take place on the running lane to provide any benefit [2] there are two basic concepts behind platoon formation. First there is the concept of all vehicles entering and leaving the guideway at the safe minimum headway [5, 6, 9] while the alternative consists of vehicles manoeuvring into the correct longitudinal position before joining the lane (so called "virtual platooning" [8, 12]).

The tightest form of virtual platooning strategy is most obviously going to deliver the highest guideway capacity. In its purest form, where vehicles enter and exit from platoons at the intra-platoon spacing, vehicles are only ever running on the network or lanes at correct spacings, be they independent or platooned. Therefore no manoeuvres are undertaken on the lane itself and entry and egress can be carried with almost no affect on the other vehicles and hence little reduction in system capacity.

Conversely, if vehicles must always leave the lane or network from safe-spaced positions, both ahead and behind, then capacity must be significantly effected around junctions as many vehicles will have to pass through as individuals, even if their state prior to and after the junction is platooned. This is particularly well demonstrated by Rao et. al. [9] as described in section 3.1 where in order to separate before an exit point vehicle decelerations in the lane propagate upstream until vehicles must almost stop to allow spacings to be created. The benefits of the system, however, is that every vehicle entering the system does so in a totally safe state (under the brickwall criterion) and can be, if the upper control system deems it sensible, left in a non-platooned state.

Whilst virtual platooning offers a much more space-efficient method of extraining and entraining vehicles, there is the drawback that vehicles must be both at line speed and have had time to adjust position before entering the automated lane. This may no be so critical in highway systems with a dedicated transition lane but may require much larger slip-roads at junctions or stations on PRT systems, increasing the cost and size of infrastructure and the land required. There is also much tighter longitudinal control required based on actual guideway position at the point of merging, especially if it occurs at the front or rear of the platoon.

While all these systems are certainly possible, and virtual platooning appears the most ideal system, in reality some compromise solution is the most likely to be practical and allow the system to reach useful capacities. The next section presents one possible solution that includes many of the benefits of virtual platooning while aiming to keep off-line manoeuvres and infrastructure to a minimum.

3.3.1 Example Strategy.

This is one possible strategy for platooning which combines elements of both the safe spacing and virtual platooning approach. The following rules and guidelines are applied to the system or lane:

1. For each system the ideal or target platoon length is set. A rolling block-length system is used with the length defined as the distance between the lead vehicles of consecutive target-length platoons.
2. When leaving a lane the vehicle must have a spacing of at least twice the normal intra-platoon spacing front and rear.
3. When entering a lane the vehicle always enters behind the platoon it intends to join.
4. A vehicle must enter a minimum of twice the normal intra-platoon spacing behind the vehicle directly ahead of it.
5. When entering a lane the vehicle must have a spacing of at least the free-agent spacing between it and the next vehicle immediately behind it in the lane.
6. A vehicle can close up to join with a platoon as long as the platoon in question contains less than the target number of vehicles and the distance to the lead vehicle of the platoon is less than the block-length. Otherwise it should be positioned at the start of the next block length to become the leader of a new platoon.

7. Once a vehicle leaves a platoon the remaining vehicles should close-up to re-form the platoon. If the lead vehicle leaves the next remaining vehicle moves up to the head of the block to become the leader.

This offers the minimum amount of disturbance on leaving the lane, as the spacing off required means only small manoeuvres just before exit. The entry strategy means that the exact position and speed of vehicles is not compulsory on entry and, although there will be some manoeuvres through non-safe spacings, use of the more realistic safety requirement of free-agent spacing minimises these whilst increasing the safety of entering vehicles.

Whilst not every detail of the strategy can be accounted for in the workload equation, it can lead to a reasonable concept of the length and space required for such operations and hence the affect they might have on the overall effectiveness of operating with platoons of different target lengths.

3.4 Manoeuvre Parameter Calculation.

3.4.1 Wait Time.

The γ term in equation 3.2 represents the time for which a vehicle has to wait before making a lane change, normalised by the average trip travel time. It can be shown that the γ terms cancel in the equation if only a single lane is modeled. γ is calculated:

$$\gamma = T_{WAIT} \times \frac{V_L}{\eta} \tag{3.5}$$

Defining T_{WAIT} is difficult. Hall [26] suggests that realistically γ should not exceed 0.05. For likely journey times of zero to ten-minutes this would mean a maximum waiting time of 30-seconds, which is relatively large.

For this study it is assumed that the likely maximum waiting time is the time taken for one block-length to pass a point on the lane and therefore the average waiting time is:

$$T_{WAIT} = \frac{x_2 + (N-1)\,x_1}{2 \times V_L} \tag{3.6}$$

Where the numerator in this equation is the block length, dependent on the number of vehicles in the platoon. The concept is that any vehicle entering the system may have to wait for a complete platoon to pass before joining the next. Although this is an extremely simplified idea and does not necessarily hold for lane-change manoeuvres (where lanes run at the same speeds with accelerating or slowing just for position correction) it does at least provide reasonable values for γ which increase as platoon length increased - a likely scenario. It is found that the exact values of γ are not significant, compared to β, and as this term is not used for single lane systems, the primary focus of this study, a more accurate definition is not essential.

3.4.2 Lane Change, Entry and Exit.

As previously stated, the combination of system entry and exit is also the total occupancy of the lane change manoeuvre. Hall [26] defined this occupancy as the space required in the lane the vehicle is leaving added to the space required in the lane the vehicle is joining multiplied by the total time of the manoeuvre. This makes the assumption that the space in both lanes is maintained for the vehicle during the entire manoeuvre process, which errs on the side of safety but is a reasonable scenario.

In this study, terms are added to represent the fact that before exit and after entry to each lane the vehicle will probably have to make some adjustment manoeuvre to space-off from other vehicles or close-up into a platoon. Therefore, the total manoeuvre occupancy, for each lane change or entry and exit is:

$$o_M = o_{change} + o_{join} + o_{leave} \tag{3.7}$$

As with the pure longitudinal space requirement S_L, the terms all represent the average values for each vehicle and so are dependent on the platoon length.

$$o_{change} = T_{change} \times (S_{exit} + S_{entry}) \tag{3.8}$$

The time for the lane change is approximated based on the allowable lateral acceleration combined with one second at either end of the manoeuvre to account for lateral jerk. To exit the guideway/lane all following vehicles require only the intra-platoon headway (x_1) plus an additional two intra-platoon spaces (to obey the second platoon operation rule). The lead vehicle must maintain a full inter-platoon spacing ahead of it with an additional intra-platoon spacing to the rear. Therefore:

$$S_{exit} = \frac{(N-1)(x_1 + (2 \times D_S)) + (x_2 + D_S)}{N} \tag{3.9}$$

Where D_S is the vehicle-to-vehicle intra-platoon spacing.

On entry to the lane an average of one vehicle for each platoon will have a full headway ahead of it and, to meet the fifth operation rule, a free-agent length spacing behind it. This is the spacing required such that under the less stringent platoon safety criteria, two vehicles would not collide after the lead vehicle fails. This will be spacing x_3. The other vehicles will usually have a space on entry to the lane of between the normal longitudinal requirement plus an additional intra-platoon space and the full inter-platoon headway. Assuming an approximately even chance of all spacings:

$$S_{entry} = \frac{(N-1)\left(\frac{(x_1+x_2+D_S)}{2} + x_3 - x_1\right) + (x_2 + x_3)}{N} \tag{3.10}$$

Once in the lane vehicles must close up to join a platoon. For an average of one vehicle per platoon it is likely that little or no manoeuvre will be required (it will enter alone, at the correct spacing). For the other vehicles the maximum distance to close up will be the inter-platoon spacing minus the vehicle length (L_V) and vehicle-to-vehicle spacing and the minimum distance will be just the vehicle-to-vehicle spacing.

The time taken to do this will depend on the allowed over-speed. The average overspeed (V_{OS}) is used so that acceleration and jerk levels are ignored. During the manoeuvre, the space occupied falls, and so considering the average spacing needed to be closed and the average occupied space during the manoeuvre, the average occupancy for joining a platoon can be approximated as:

$$o_{join} = \frac{(N-1)\,(x_2 - L_V)^2}{8 \times V_{OS} \times N} \tag{3.11}$$

Thus with single vehicles there are no manoeuvres as vehicles will only enter the lane if there is a slot available. In a similar way, the average occupancy of the manoeuvre to space-off (leave) the platoon can be approximated. The manoeuvres are smaller than those when joining. Front and rear vehicles only require one extra intra-platoon spacing and the other vehicles two spacings. However, once spaced, the vehicles will remain in those positions (occupying more lane space) for the time they wait to make the manoeuvre (T_{WAIT}). Therefore the average additional occupancy for a vehicle leaving a lane can be approximated as:

$$o_{leave} = \frac{((N-2) \times 2 \times D_S^2) + \frac{D_S^2}{2}}{V_{OS} \times N} + T_{WAIT}\frac{((N-2) \times 3 \times D_S)}{N} \tag{3.12}$$

As single vehicle operation should also result in this occupancy being zero the calculation is limited to zero and above for all values of platoon length (N).

Figure 3.1 shows some typical occupancy values for vehicles in a System 2 (40kph PRT) lane. As expected, the occupancy during the platoon leaving manoeuvre is very small but increases marginally with platoon length (mainly due to the time spent at

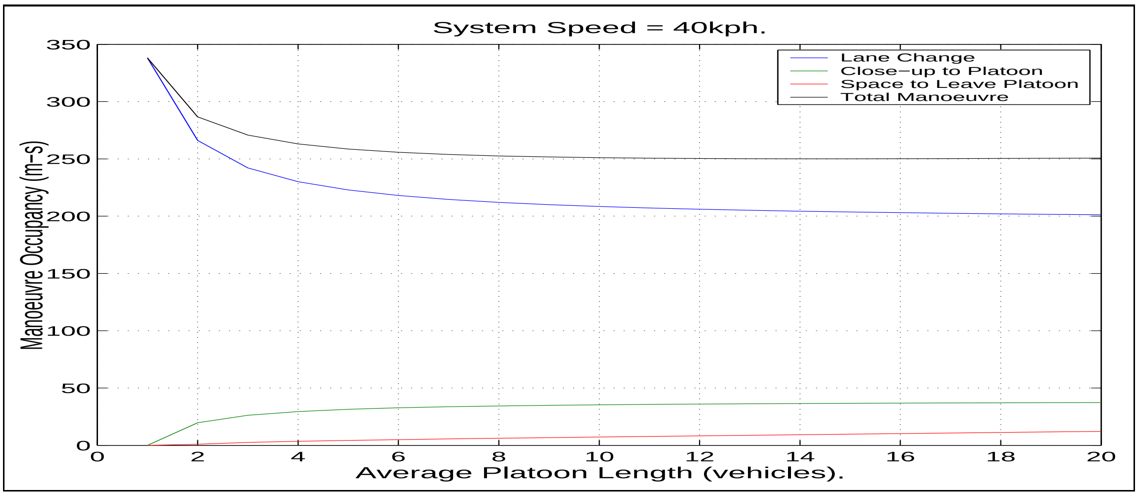

Figure 3.1: Average Manoeuvre Occupancy for Vehicle in 40kph PRT System.

the larger spacings waiting to make the manoeuvre). Similarly, the average occupancy for a vehicle joining a platoon will increase with platoon length as a higher percentage of vehicles do not enter at the correct spacing.

The reverse is true for the lane change manoeuvre (which requires the highest occupancy) as in single vehicle operation a large amount of space is required in both lanes during the transition. As average platoon length increases more a higher proportion of vehicles are changing lane with smaller space requirements, so the occupancy drops.

In this example, the total occupancy for a vehicle for all manoeuvres drops from single-vehicle operation but then reaches almost a constant value for all platoon lengths above ten vehicles. This has potentially beneficial consequences and it implies that up to this point platooning reduces the time and space required for vehicle manoeuvres on, onto and off the lane. A more detailed look shows that occupancy is at a minimum at around 14-vehicle platoons and then begins to rise. In this case the rise is not significant, but for other systems it may provide an indication of a reasonable upper limit of platoon length.

3.5 Single Lane Utilisation.

With the parameters of the workload equation defined it is now possible to consider how the utilisation of a lane or system will be effected. In the case of a single lane, which is directly applicable to most proposed PRT networks (Systems 1 and 2), the total system workload W_S, from equation (3.2) reduces to:

$$W_S = 1 + \beta \tag{3.13}$$

and so the workload and utilisation is fully dependent on the β parameter. As equation 3.3 shows this is derived from the manoeuvre occupancy, the space required for each vehicle once in the lane, the system speed and average trip length.

3.5.1 Effect of Trip Length and System Speed.

From equation 3.3 it can be deduced that β is directly proportional to V_L/η, in other words, the inverse of the average trip time. Figure 3.2 shows this for the 40kph system. In this case it is clear that a journey time of only five minutes is sufficient to significantly

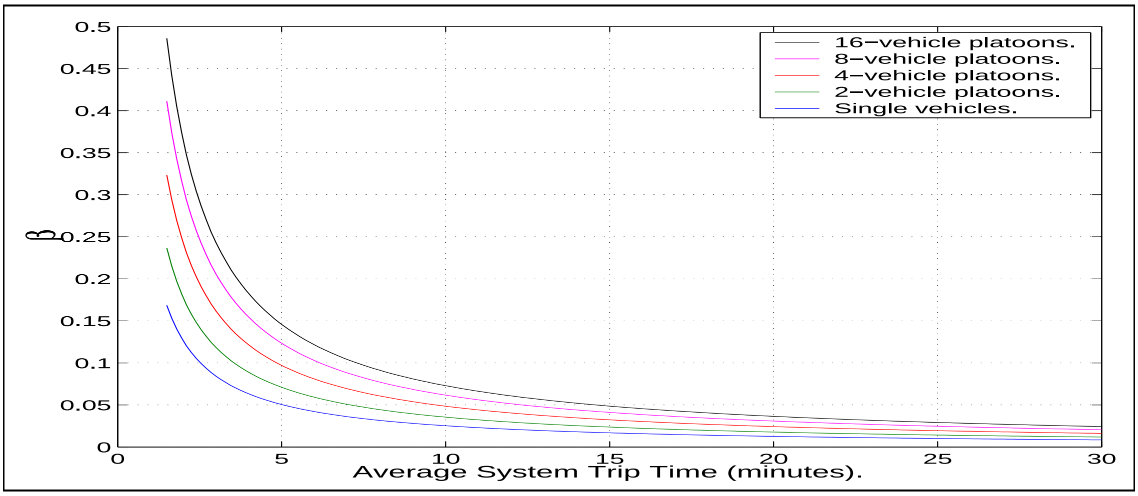

Figure 3.2: Effect of Average Trip Time on β with selected Platoon Lengths.

lower the β parameter (note for single lanes β of 0.15 implies a utilisation of 87%). The reasons behind the relationship are relatively simple to explain. For any system speed and characteristics a certain number of manouevres (lane entries and exits) must take place and this must be proportional to the troughput of the system. The shorter the average trip length, and therefore time, the more manoeuvres must take place in a shorter time and space.

For example, consider a simple two-junction linear system. If the journey time is short (a matter of minutes) then by the time vehicles have entered the lane and possibly manoeuvred into platoons it is probable that the manouevres required for leaving the platoon and lane will have to begin. Overall, vehicles may spend very little time in purely longitudinal running and, on average, will take up more than the ideal space on the guideway. This is demonstrate in further work by Hall, where a highway in Florida is studied. The frequent entries and exits and short trip lengths lead to a high workload and so a very limited capacity [27].

If the journey time is significantly longer (up to an hour) then vehicles will enter and platoon at the start of the journey and then spend most of the journey running with the ideal space requirement before having the leave the lane. For a large percentage of the journey the traffic flow will be continuous and undisturbed, leading to a very high throughput and utilisation.

Based on these conclusions it may be the case that, especially for tailor-made PRT systems, the speed of the system can be adjusted to best account for predicted average trip lengths to increase the utilisation and capacity of the system.

3.5.2 Effect of Discrete Entry and Exit.

One of the potential limitations of the workload equations is that it does not bring into consideration the usually discrete nature of entry and exit points at junctions or stations. It is argued [26] that it is not clear whether this may substantially alter highway capacity but it may cause an increase of workload in the first lane (which is the only consideration in a single-lane system). This is because all the manoeuvres would have to take place over a short segment near the junctions, as described in the previous section.

There is an argument for scaling the β parameter upwards due to all vehicles having to enter and leave at one point, rather than having a significant length of parallel lane to run along before merging but exact quantification of this is difficult. Whilst discrete entry and exit may cause more localised disturbance at certain points, the advantage is potentially large sections of undisturbed traffic flow between these points which is not possible with continuous entry and exit.

A more quantifiable value is the flow-rate at the lane entrances if they are discrete. The flow-rate of any system cannot exceed the supply to the system and if entrances are discrete then this could act as another limit to the capacity. This will be dependent on both the average flow rate of the entry lane (C_{entry}), the number of lanes (L) and the relationship between the average trip length (η) and the average spacing of entry points thus (η_{entry}):

$$C_{LIMentry} = L \times C_{entry} \times \frac{\eta}{\eta_{entry}} \tag{3.14}$$

This is again simply explained by considering that if all vehicles entered at one point and left at the next point then the flow on the lane could not exceed the rate of entry. This is approximately the case where the average trip distance is equal to the average spacing of entry points. If the trip distance is twice the entry spacing then, on average, every section of lane is being fed by two entrances and so the provision can be twice the rate of entry.

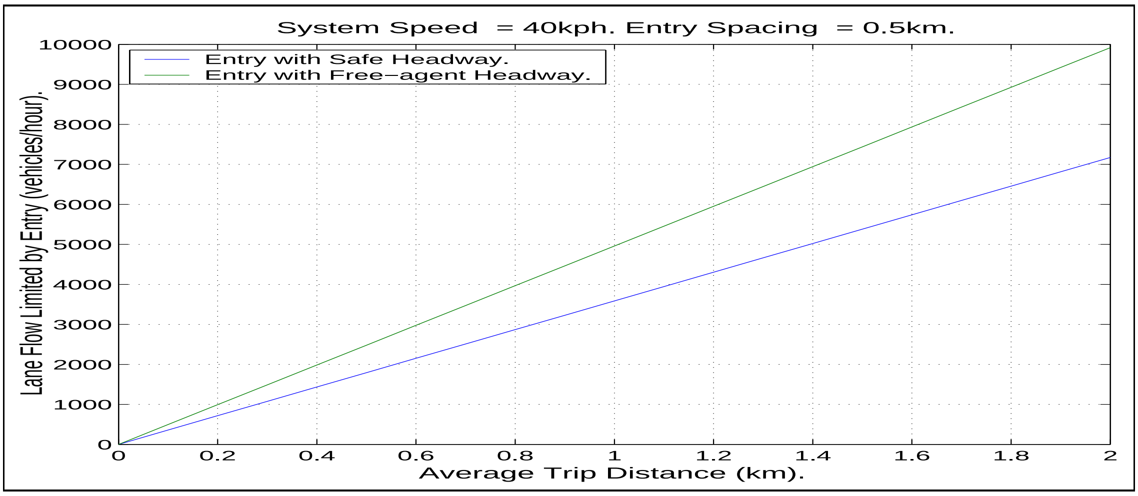

Figure 3.3: System Capacity Limited by Entry Flow Rate.

Figure 3.3 shows the effects of this. Ultimately, many factors will influence the possible rate of entry flow. In the case shown, singe-lane entry is assumed (as is most probable in a single-lane PRT system) and two alternative rates are shown, one if vehicles enter on average at brickwall spacing intervals, and the other if they enter at the closer free-agent intervals. Theoretically, and especially in PRT where most entry points are directly from stations, vehicles could enter either singly or platooned, but it is assumed that the exit rate from stations will still be designed for vehicles to leave individually.

Another factor with the potential to limit PRT system flow-rate in this way is therefore station capacity and throughput - a consideration of Lowson [16]. Vuchic [25] also highlights station capacity as a potential limit on system throughput. For PRT systems (where the vehicle carried a maximum of four passengers) sub ten-second time are suggested for station turn-round. Once necessary acceleration, deceleration and vehicle manoeuvres are taken into account this may more than double. The flow rate leaving the station may therefore be limited by these rates.

Although somewhat beyond the bounds of this study, this highlights both the obvious necessity of off-line stations and of stations having multiple berths, especially for systems with frequent stations and relatively short trip lengths. For example, if a complete station turn-round time is ten-seconds, and expected capacity demand on a station requires vehicles entering the lane at a rate of one every two-seconds then it is a simple deduction that at least five parallel berths would be necessary. Whilst the reality is likely to be more complex, this once again points toward the potential for investigations of this nature to play a useful role in the design of such systems.

3.5.3 Capacity and Utilisation.

The expected utilisation and capacity for a single-lane system can now be found. System 2 is used as an example. This 40kph PRT lane has 3.5m length vehicles running at a spacing of 0.05-seconds. Stations (pairs of exit and entry ramps) are spaced at 0.5km and the average trip length is predicted to be 1.5km.

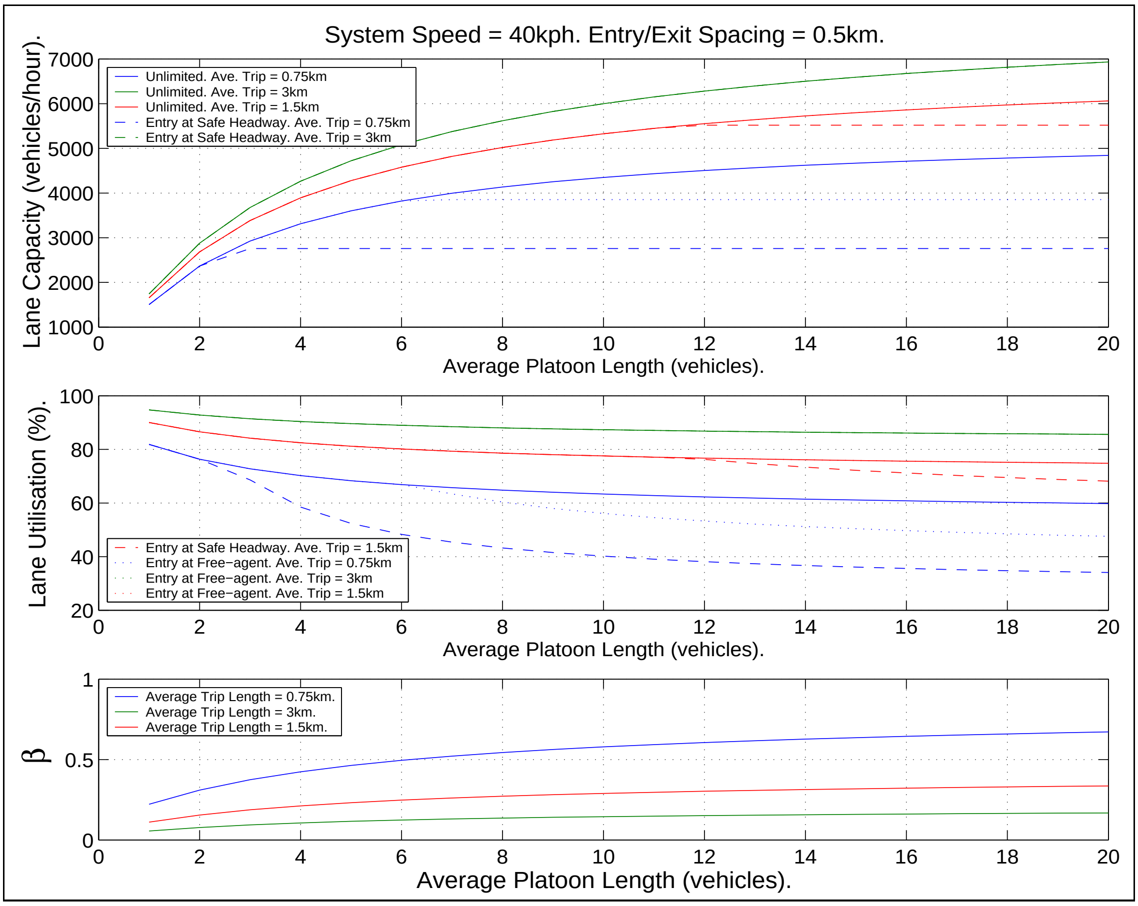

Figure 3.4: System Capacity and Utilisation for 40kph PRT System.

Figure 3.4 shows the capacity, utilisation (percent of maximum theoretical capacity and β values for the system at the predicted trip length and also at half (0.75km) and double (3.0km) this trip length. The dashed lines show the capacity and utilisation if limited by entry flow at normal brickwall spacing and the dotted lines if limited by entry flow at free-agent spacing.

Considering first the predicted average trip length (red plots) it is clear that even at single-vehicle operation there is up to a ten-percent drop in utilisation. Utilisation drops to only 80% when the platoon length is six vehicles. Despite this, the corresponding rise in theoretical capacity far outwieghs any drop in utilisation and so the calculated actual capacity increases by over 250%.

A further doubling of the platoon length to twelve vehicles has a much less significant effect on the utilisation and as the potential benefits of platooning are also reduced the overall capacity rise is only a further 20%. For this system characteristic it will be seen that the safety case shows a tolerable risk with platoons of four to six vehicles and this combined with the relatively small benefits of longer platoons once again shows the potential benefit to design of such calculations.

Above a platoon length of twelve-vehicles the increase in capacity is relatively small. However, the system throughput also becomes limited by the flow from stations. With the station spacing one-third of the average trip length this naturally occurs at three times the single-vehicle capacity. The flow rate from stations would be one vehicle every 1.95-seconds or 1839 vehicles per hour. If vehicles were allowed to leave the stations at an average of the free-agent spacing then the total system flow would not be limited even with twenty-vehicle platoons. Whilst a station throughput at 1.95-seconds per vehicle may be possible with five or so berths, the free-agent flow of one vehicle in around one second would require stations with up to ten berths and significantly more space.

Halving the average trip distance makes the flow limits from stations significantly more important. Working on the brickwall entry flow criteria still allows capacity to rise by 80% but there is no advantage of platooning more than three vehicles together. In reality it is likley that a system designed for such short trips would have closer stations and therefore these limits would be raised. In terms purely of the non-limited capacity section 3.5.1 shows why the β values, and hence drop in utilisation is reduced as trip times are shorter. Benefits of platooning are smaller, and any gains above six to ten vehicle platoons are low.

An average trip length of twice the expected has a positive effect and predictably by having a trip length six-times the station spacing causes there to be no capacity limits (even if platoon lengths are longer than twenty-vehicles). Once again it is likely, but not necessarily mandatory, that a system built for such trip lengths would have less frequently space stations and hence begin to the limit the flow.

A previously stated, in all these cases it may be that the station capacity cannot meet the ideal entry flow due to lack of vehicle berths. If a typical station only has three berths than the output flow may be reduced to around one in four seconds. The system flow would then be limited to 2700 vehicles per hour (based on the expected (1.5km) trip length), regardless of the lane entry safety criteria. This, in turn would render all platoon lengths above three-vehicles unnecessary, save to possibly marginally reduce the strain on the system by deliberately designing to run at less than the known maximum practical capacity.

3.6 Multi-lane Systems.

The workload equations also allow the consideration of multi-lane systems. A typical application of this is most likely in an AHS and so the System 3 characteristic is used with a speed of 113kph. To exaggerate the effects of platooning a relatively short journey distance of 10km is used with a station spacing of 5km. The equations can be used to investigate the proportion of flow in each lane, and the overall utilisation and capacity of the system.

3.6.1 Lane-flow Distribution.

As equation 3.2 in section 3.2 showed, if multi-lane systems are considered, the equations have to be iterated. Starting with the assumption of equal lane distribution (and remembering that it is assumed that the average trip distance for vehicles in each lane is the same) the workload for each lane must be calculated. These will not be equal however, and so the proportions of these to the total system workload must be then used as the initial p_i values and the process repeated until the two values converge.

The result of this is that the distribution of traffic within any multi-lane system will depend on the β and γ values, and hence, in this study, the platoon length. Figure 3.5 shows how this occurs in a three-lane and a five-lane system.

In all cases Lane 1 is the "inside" lane onto which all entering vehicles arrive. Both systems show similar trends. In the case of zero β values (the theoretical case of zero-platoon lengths) the flow is still evenly distributed. As the platoon lengths increase a higher proportion of the traffic moves to the outer lanes and flow decreases on the inner lanes. For the higher platoon lengths the first lane contains a minimal proportion of the flow - only 2.5% in the case of the five-lane system with twenty-vehicle platoons whilst, in both cases, nearly 60% of the total traffic is in the most outer lane.

This is easy to explain both practically and mathematically. The outer lane behaves very much like a single lane system. Vehicles will only enter this lane to use it for the major part of the trip and then only leave it when they are due to leave the system. Therefore the workload will remain relatively low as each vehicle will only perform one full manoeuvre. In the next lane to this one some vehicles will enter to undertake the journey, while others will enter and then leave to move into the outer lane and subsequently repeat the procedure in the opposite direction. More space is required for manoeuvres, and so less is available for purely longitudinal travel.

In the first lane a great proportion of vehicles will only be passing through the lane.

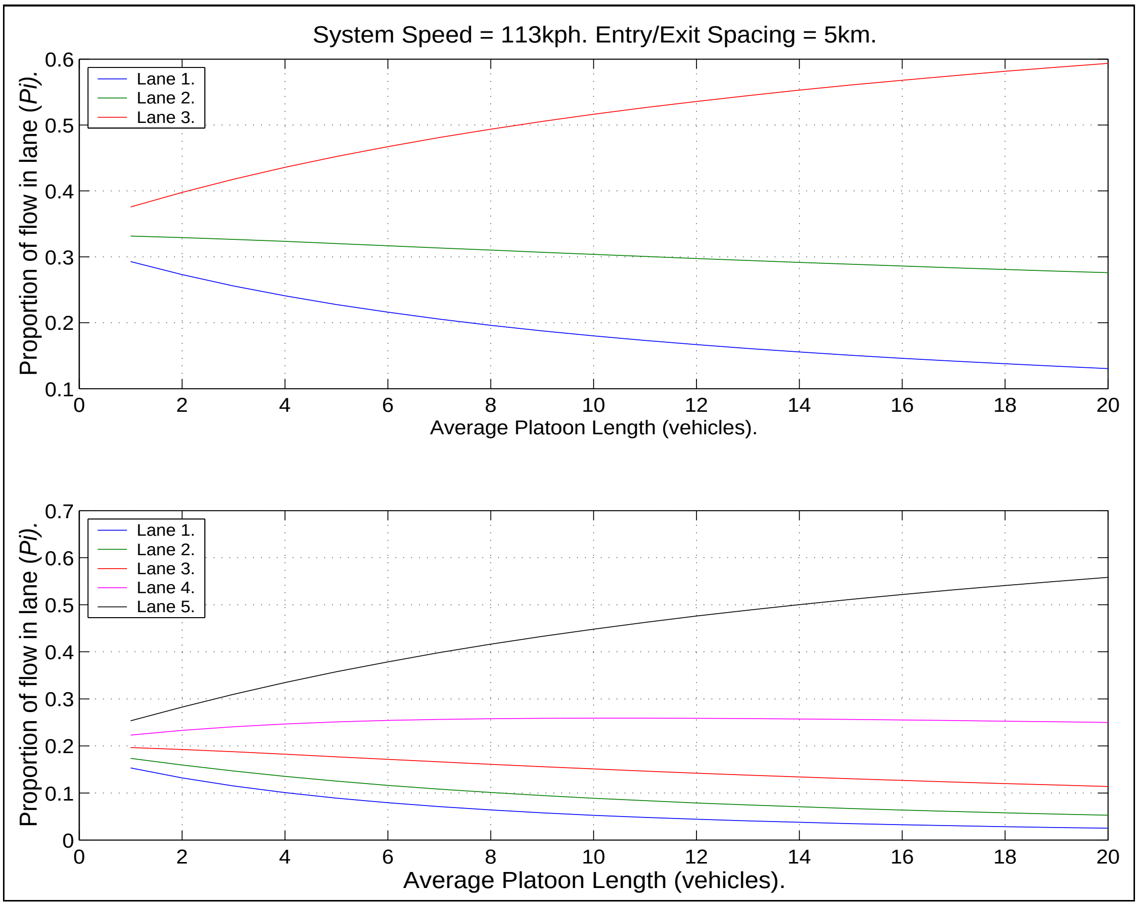

Figure 3.5: Distribution of Flow in Three and Five-lane Systems.

Much of the space will be occupied only on a temporary basis by vehicles traveling between the entry/exit point and the desired lane and so there will be little space left for vehicles purely traveling along the lane. In equation 3.2 β is most significantly scaled by the proportion of the flow in the lane being calculated plus all higher lanes and hence the workload is higher if there are a larger number of lanes outside the lane in question. Ultimately, if the value of β, or the number of lanes, is sufficiently large, there will come a point where there is virtually no space in the first lane for any vehicles purely traveling along the lane.

The system modeled here works on the assumption of no lane assignment for vehicles (I.e. the average trip length for all vehicles in each lane is equally: $r_i = 1$). In some studies, the workload equations are used to optimize the lane distribution [26, 28]. It seems reasonable to place vehicles on longer journeys in the outer lanes, so that the relative time spend crossing lanes is reduced and so this may provide some increases in utilisation.

3.6.2 Capacity and Utilisation.

Figure 3.6 shows the capacity and utilisation for the system with a single lane, three-lanes and five-lanes. Limits due to possible entry flow are also shown, entry ramps are assumed to be two-lane with the exception of the single-lane system (the calculation assumes that the number of entry lanes cannot exceed the number of running lanes). These limits are interesting but more constricting than in the previous example as the ratio of trip length to junction spacing is only 2:1. This is mainly because the trip length has been shortened to demonstrate the effects of higher β values.

The single-lane system behaves in a very similar way to that previously seen. Generally the system characteristics appear to allow higher utilisation than the 40kph system and platooning benefits appear still to significantly increase up to the highest platoon length shown. What is more interesting is the effect of adding more lanes. Even with single vehicles there is a significant drop in system utilisation from 95% (single-lane) to 86% for three-lane and just 77% for a five-lane system. The reductions tend to diverge as platoon length (and hence β) increase, especially between one and three-lane systems.

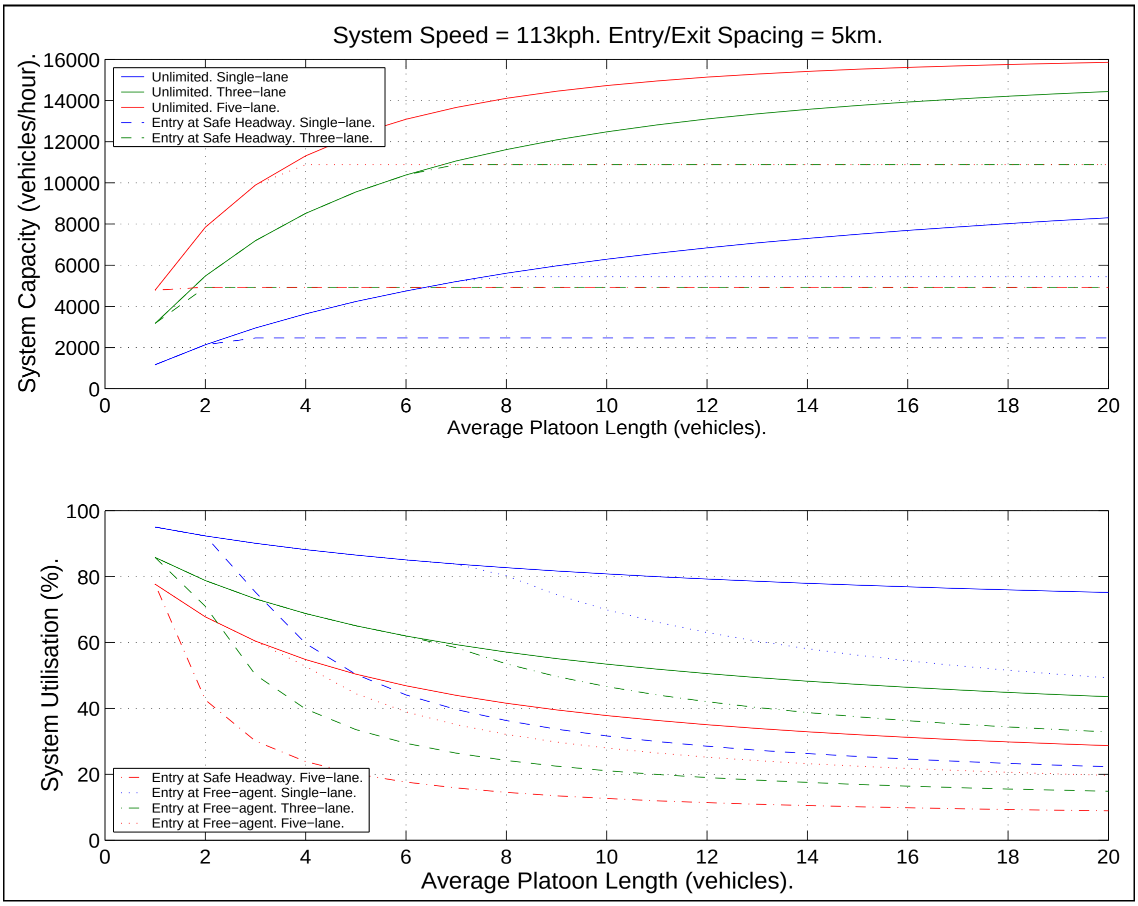

Figure 3.6: System Capacity and Utilisation for One, Three and Five-lane Systems.

As with the lane distribution, this is not hard to explain. The more lanes the vehicles have to move across, the more space is taken up on each lane by those manoeuvring vehicles. Added to the fact that as platoon lengths increase a higher proportion of vehicles move toward the outer lanes leads to multi-lane systems having inherently lower utilisation than single-lane system, and more so as β increases.

What is particularly interesting is the consideration of the benefits of moving from three-lanes to a higher number of lanes. With single vehicles the capacity increase between three and five lanes is 51%. If the increase in land required to accommodate the extra two lanes is 66% (2/3) then the relative capacity to land increase is 76%. If platoon lengths of ten-vehicles are used, then the capacity increase is only 18% and relative to land increase 27%. This drops to only 15% at twenty-vehicle platoons. A similar trend would be found even if moving from three to four lanes allowing a useful consideration during AHS design of the best way of increasing capacity whilst maintaining minimum infrastructure size and cost.

Whether the limits imposed by junction flow are realistic or not (a ratio of 2:1 trip length to junction spacing is not too inaccurate, as will be shown later) the plots as shown further illustrate the point concerning AHS design and the benefits of adding further lanes. Considering the highest limit (two-lane entry ramps running under the free-agent criteria) it is clear that the same capacity is obtainable with five-lanes running with four-vehicle platoons as with a three-lane system running with seven-vehicle platoons.

Depending on a more exacting safety analysis comparing the risks of increasing the platoon length this appears a significantly more efficient way, in term of cost and infrastructure to provide this capacity. Of course, if two-lane, brickwall headway entries are required then an alternative process is to conclude that a five-lane system has no cause to use platooning at all, a three-lane system needs only pair vehicles to meet the capacity (a two lane system could meet it with three-vehicle platoons) and a single lane could do the job with six-vehicle platoons.

3.7 Conclusions.

By the use and modification of Hall's workload equations a general set of calculations has been produced to allow the effectiveness of platooning to be examined at a practical level, considering both vehicle longitudinal running and manoeuvres on and off the lane. It has been shown that the strategy used when platooning is important to the utilisation and must be carefully defined in the equations.

Whilst the platoon length has an important effect on the utilisation and capacity of the system, it has also been shown the the ratio of average trip length to the speed (the average trip time) has a significant influence on the system's effectiveness and that capacity and utilisation can be improved with correct choice of speed given the expected use of the system. Some consideration has also been made on the possible effects of other limitations on the system, such as entry flow onto the system, junction and station spacing and the capacity of the stations themselves.

The equations have also demonstrated the effects of increasing the number of lanes in a system and the potential benefits and restrictions of multi-lane systems. For any system there are potential advantages of increasing the lane number but, as before, these can be significantly limited by a drop in the utilisation, due to increased manoeuvre complexity and number, and junction restrictions.

The equations allow investigation and design to be carried out into the potential characteristics, benefits and problems that may be involved when aiming to maximise the capacity of any PRT or AHS network. They can be used to indicate the best, or most effective methods of increasing system throughput, whether it be through platooning, longer platoons, better station throughput, additional lanes or increased entry flow.

Chapter 4

Example Systems.

Having considered and demonstrated the methods and overall effects of platooning in terms of both safety, capacity and utilisation, it is now possible to consider any specific system. In chapter 2 the high-speed AHS (System 3) was used to consider safety whilst capacity was investigated for System 2 (40kph PRT system) in chapter 3. In this section the safety of System 2 and capacity of System 3 will be demonstrated and then the low-speed PRT system (System 1) will be studied in full.

4.1 System 2 Safety.

As previously described, this system is based on the proposed ULTra system [16] with four-person automatic vehicles running at 40kph on a single dedicated lane. The vehicle length is set at 3.5m and emergency deceleration is limited to $5m/s^2$. Studies suggest that this is an acceptable maximum level for a public transport system with all passengers sitting but not restrained [29]. Failure deceleration is set at $10m/s^2$. As with all these studies, the actuation time delay for pure-feedback control is set at 0.2-seconds, but for this case (and the lower speed), the minimum delay for the more overall platoon control systems is set at 0.05-second, suggesting a slightly lower-grade system.

Figure 4.1 shows the injury risk for an eight-vehicle platoon following lead-vehicle failure for the system using pure feedback control system. Inevitably the fatality risk, in particular, is lower than for the 113kph system as collision speeds are limited by the line speed. In this case, the risk actually reduces with increased spacing and for this example a spacing of 0.3-seconds is chosen to be reasonably safe (around a 1% chance of fatality) whilst maintaining still feasible "platooned" conditions (actually the spacing between vehicles is almost equal to vehicle length but this is inevitable with relatively large time delays at low speeds).

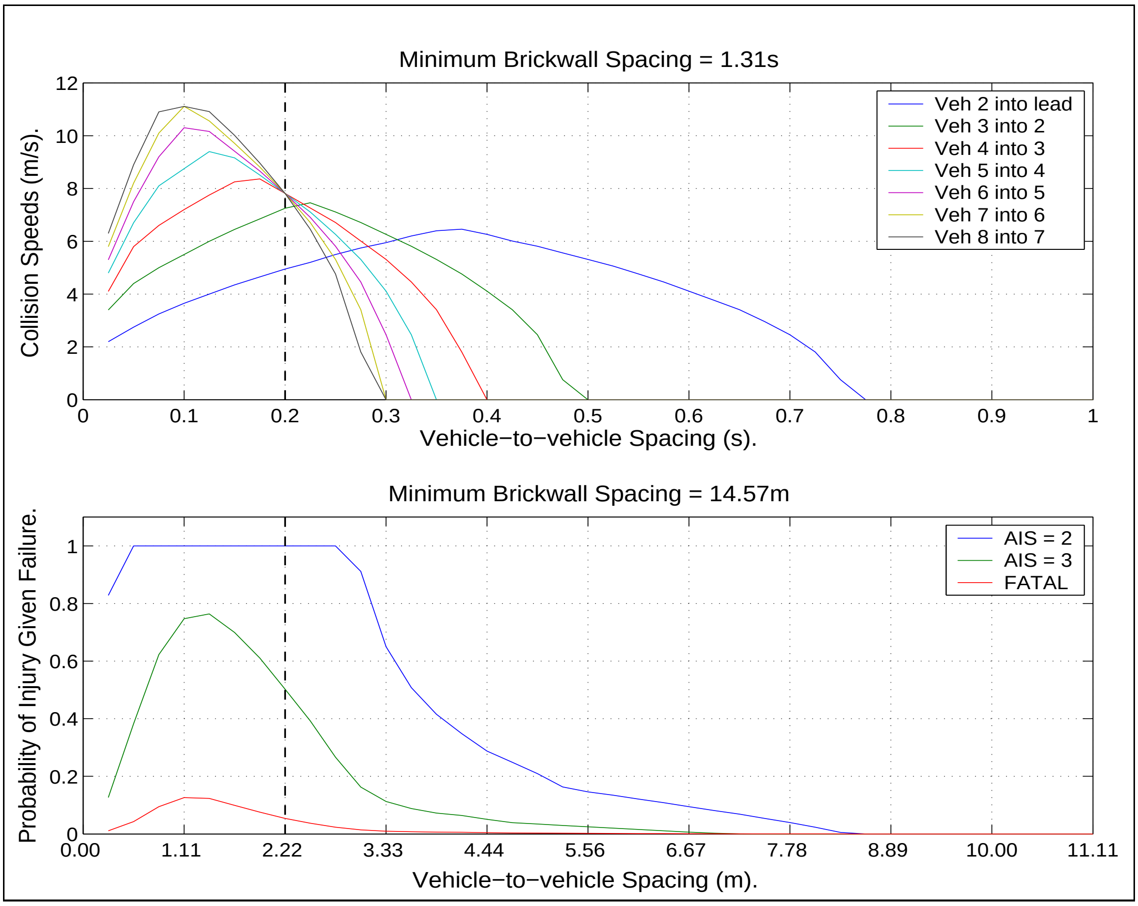

Figure 4.1: Injury Risk in 8-vehicle Platoon Failure for 40kph System.

For the operation at free-agent criteria the spacing of 0.7-seconds is chosen. At this, only one collision would take place after a vehicle failure, and that below $3m/s^2$. This is not quite as beneficial as in the faster system, giving a vehicle-to-vehicle spacing around half of the brickwall spacing. In a similar way the best spacing for the other platoon control methods are found to be equal to the minimum spacing requirement for both (the faster delay of 0.05-seconds). These values can then be used to create the design charts which consider overall risk and tolerable lengths of platoons and number of operations (figure 4.2).

Once again it is the free-agent operation which has the least risk but the least capacity benefit. If it is assumed that the capacity is equal to the number of trips in an hour then again the tolerable risk for a fatality once in ten years is approximately the region of tolerable safety is between 10^8 and 10^9 journeys per fatality.

Whilst the most basic form of platoon control has higher risk and lower benefits than the more complex systems, the charts imply that running three-vehicle platoons would be tolerable and this would provide as equivalent capacity compared to the system operating with the free-agent spacings. For the faster platoon control systems the reasonable limit appears to be between five and six-vehicle platoons. Five-vehicle platoons would enable a potential capacity over 5500 vehicles per hour.

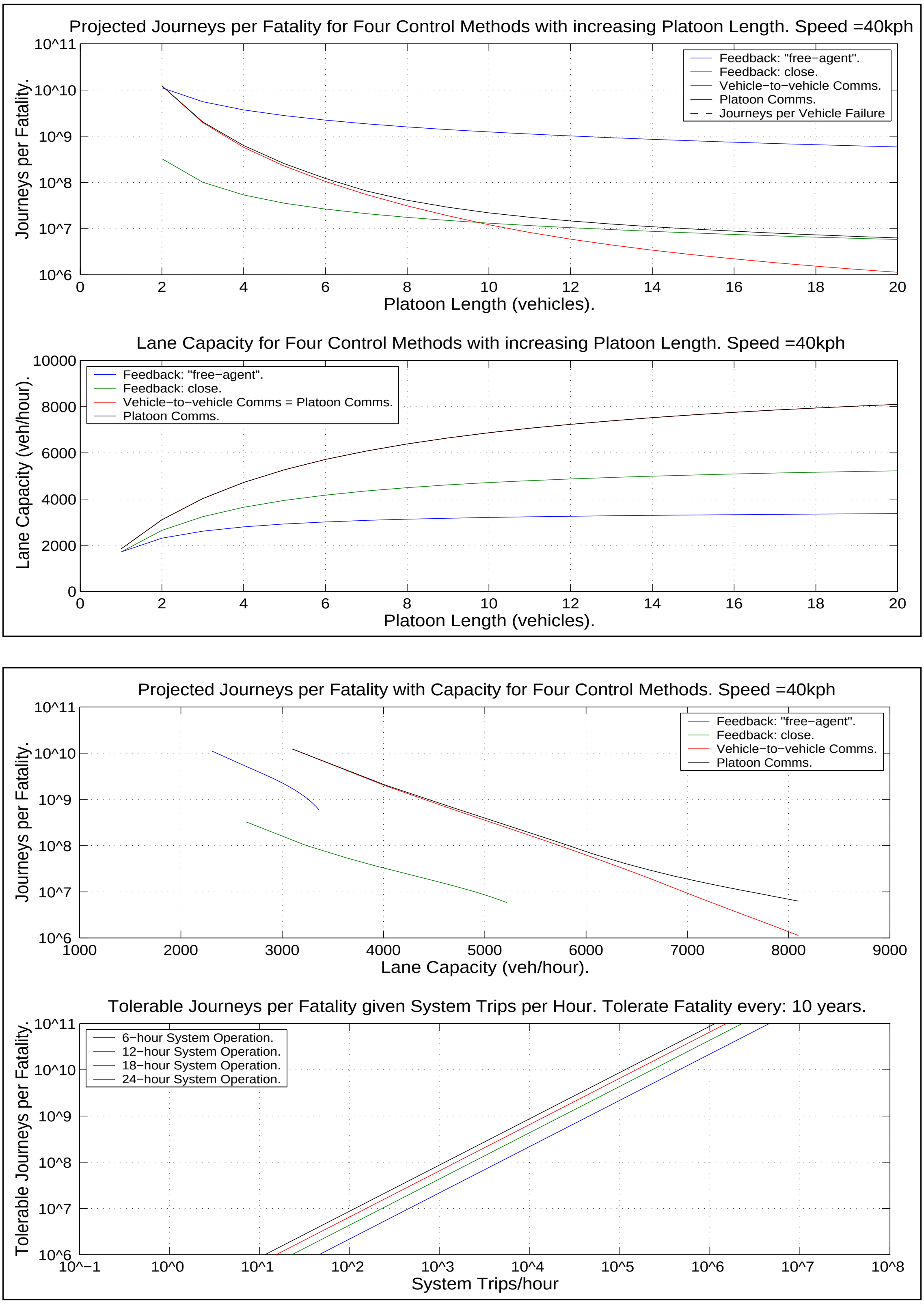

Figure 4.2: Safety and Risk Design Charts for System 2 Example.

Despite it almost certainly failing the safety requirements for tolerable risk, it is interesting to consider the three platoon modes above platoon lengths of six-vehicles. It is above this length that the two safer modes (that with a 0.05-second delay between all consecutive vehicles and that where there is only the delay between the failed and first-follower) start to significantly diverge. For platoon lengths of ten-vehicles or longer the third mode actually shows a higher risk of fatality than even the simplest platoon mode (although the safety/capacity trade-off is still significantly better).

This is almost certainly due to the fact that the spacing for the simplest control mode is greater than the actuation delay (0.3-seconds compared to a delay of 0.2-seconds) for the very reason that a lower risk is found at this spacing. This can be demonstrated if a lead vehicle failure is assumed for a twenty-vehicle platoon and the collision speeds of each following vehicle is calculated. Figure 4.3 shows this.

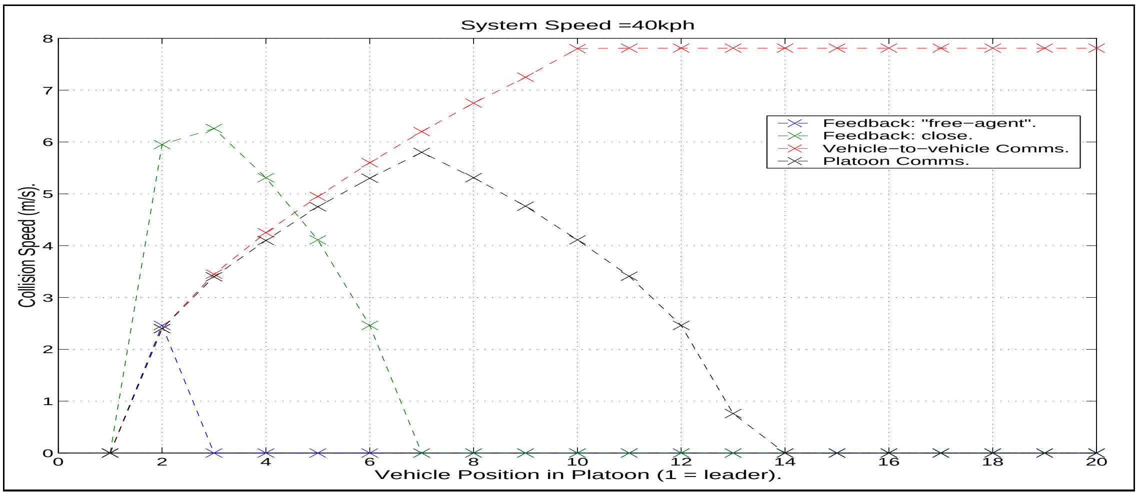

Figure 4.3: Collision Speeds Down the Platoon for Four Control Methods.

With the free-agent spacing only the first follower collides, and then at relatively slow speed. The increase in risk with a greater platoon length comes purely from the higher risk of failure in the platoon as it lengthen. In reality this is slightly mis-leading. If for free-agent operation, each vehicle is treated as an individual, then platooning is no longer a realistic way of considering the system. In effect, the platoon is of infinite length but the overall chance of vehicle failure which may cause fatality in any journey is only the chance of a single vehicle failure. This shows that the free-agent operation has potential to near double a system capacity purely by accepting platooning style safety criteria but without implementation of actual platoon control systems or operations.

From the second to the fourth vehicle, the most basic platooning control system returns the highest collision speeds and thus results in the higher risks shown in figure 4.2. The key change is for the seventh vehicle onwards. Because the spacing is greater than the minimum spacing requirement, this vehicle, and all others under the feedback control system stop without colliding. For the most complex full platoon control system the collision speed is highest for this vehicle but subsequent vehicles collide with ever reducing speed because all followers have begun decelerating at the same rate. In this case the fourteenth vehicle and onwards no longer collide.

Conversely, vehicles running at the minimum spacing requirement with vehicle-to-vehicle communication, all combine at a higher speed up to the tenth vehicle, beyond which the collision speed is maintained for all followers. As with the free-agent operation, once the platoon length exceeds the number of vehicles which will ever collide, the increase in risk is only due to the raised chance of vehicle failure in a platoon. Therefore the risk for the most basic system steadily converges with that operating with full platoon communication and both have significantly lower risk (by almost a factor of ten) by the time that twenty-vehicle platoon lengths are considered.

In contrast to the results in figure 2.6 and the conclusions drawn for the high-speed system in section 2.7.3, at this speed it appears that operating with vehicle-to-vehicle communication or full platoon control can make a significant difference to the safety of the system if high platoon lengths are utilised. That said, it should be noted that platoon lengths of this magnitude involve running at risk far higher than is tolerable and so this may remain only an interesting theoretical consideration. For all practical purposes, where platoon lengths are unlikely to exceed five vehicles, either system returns a similar level of risk.

4.2 System 3 Capacity.

In section 2.7.3 the safety of platooning in the Automated Highway System was considered. This system has a speed of 113kph and is designed to represent a lane with more orthodox private vehicles possibly running with an advanced version of an active cruise control system. The vehicles are deemed capable of a higher emergency deceleration of $7m/s^2$ and the safest control systems give a time delay (and spacing) between consecutive vehicles of 0.03-seconds.

To consider the possible capacity and utilisation of the system the same platoon operation rules are used as set out in section 3.3.1. Average trip distance is somewhat harder to defined in this case. An AHS with these speeds may have several applications. For urban commuting data from the USA suggests that trip lengths may average around 17-miles (27km) [30] while UK National Travel Data finds average car journeys to be around 15km [31] - although this may well be lowered by shorter local journeys. In the same data, non-local bus and rail journeys, which may better parallel motorway journeys, average 40km. However, for higher populated areas, such as the M25 London Orbital Motorway, the journeys may be shorter.

The expected average trip length is set at 20km. This appears to be a reasonable compromise of these lengths and is used in other studies including that of Hall [26]. As before, trip lengths of half this (10km) and double this (40km) are also considered, which covers the possible spread. A study of motorways in the UK (primarily the M5, M6 and M25) showed the spacings of junctions, not including motorway merges and service stations, to average 4.5-miles (7.2km) which gives a typical trip length to junction spacing ratio of around 3:1, very similar to that for the 40kph PRT system.

As with figure 3.4 figure 4.4 shows the capacity, utility and β values for the system if unlimited and also if flow at junctions (single-lane entry ramps) is limited to brickwall or free-agent headways.

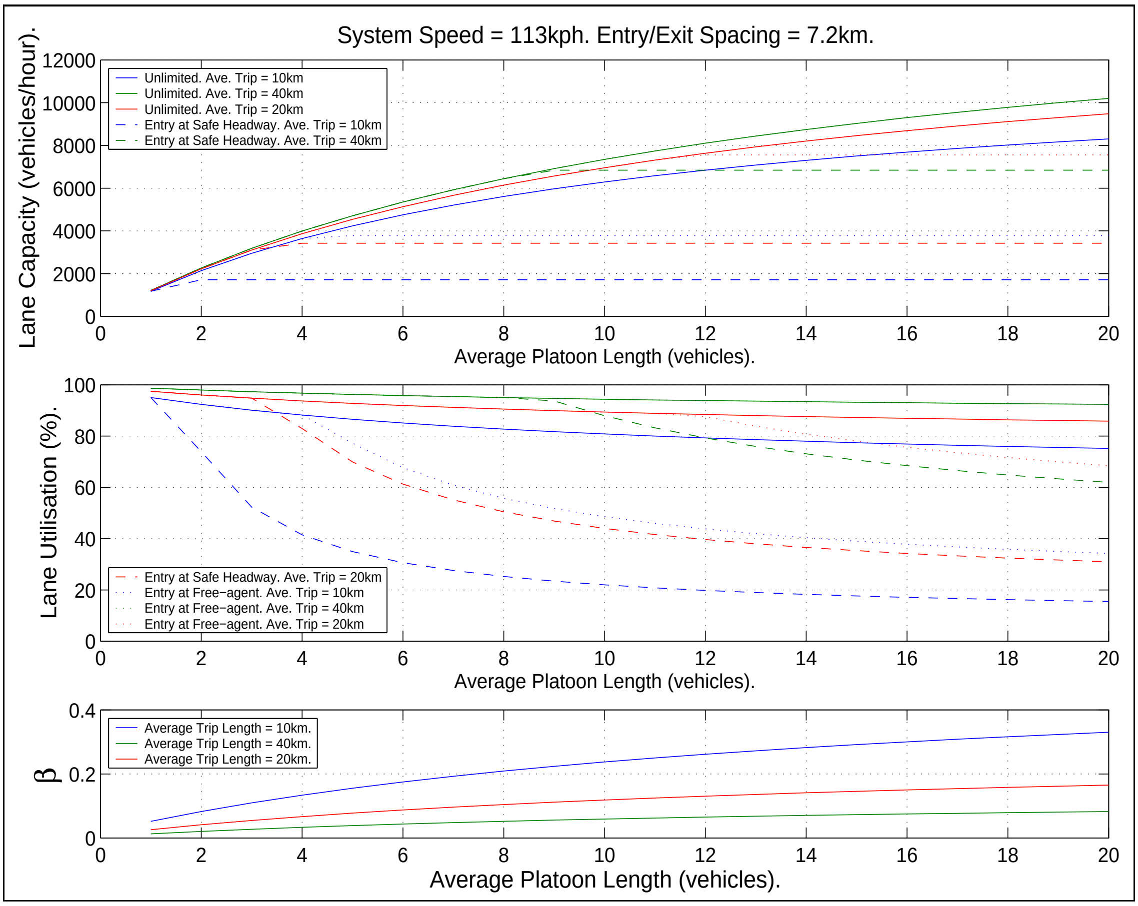

Figure 4.4: System Capacity and Utilisation for 113kph AHS.

In general terms the utilisation is significantly higher in all cases compared to that for the 40kph system. This is primarily because the journey times are longer. For the 40kph system the journey times ranged from around one to five minutes whilst for this system they are between five and twenty-one minutes. As seen in figure 3.2 this has a major effect on the value of β and the utilisation as a much great proportion of each journey will be spent in pure travel along the lane, rather than in manoeuvres.

Due to the nature of the inverse relationship between β and trip time the effect on utilisation for the extremes of trip length in this case is significantly less marked than in the other system. A general conclusion from this might be to aim to design systems for journeys of at least five-minutes, although this only accounts for utilisation, rather than any station or lane capacity considerations.

The average trip length has a greater impact when the limits due to the entry flows are considered. For the 10km journey the trip length to entry spacing ratio is only just above unity, while for a 40km journey it is just less than six. Figure 4.4 shows that for the shorter trip length restricting entry flows to that for the brickwall criteria is extremely limiting to the point of platooning giving negligible capacity increase. Entering at free-agent spacings is a little better, but platoon lengths would still only be beneficial up to four vehicles.

It is useful to note that the safety study in section 2.7.3 suggested platoon lengths of five or six were viable. Even with the expected trip length of 20km, platoon lengths of only half this number would increase the capacity before the brickwall entry criteria would limit the system flow. Therefore it would be necessary to enter vehicles at the free-agent spacings to make full use of six-vehicle platoons. With this operation a utilisation of 92% is calculated, with a capacity of upto 5134 vehicles per hour. This rises to 5350 vehicles an hour if the average trip length is doubled and with 20km trips the free-agent entry flow would only start to limit system flow if platoon lengths could be twelve vehicles or more.

In reality it seems likely that a combination of safety considerations and entry flow limitations would not render this viable. The benefits of platooning are still significant for systems of this nature, especially considering that figure 1.1 showed single-vehicle flow to be considerably lower at this speed than at the speeds of the two PRT example systems. Whilst it can be shown that free-agent flow in this case would yield a very high (96%) utilisation and capacity of 3352 vehicles an hour, with five-vehicle platoons and sufficient entry flow rates at junctions, this AHS lane still could maintain tolerable safety whilst exceeding this capacity, resulting in average headways of well under one second.

4.3 Low Speed System.

The proposed "System 1" mode is again based on the ULTra concept, utilising a dedicated guideway network with small four-person vehicles. The only major difference is the speed, which is reduced to 6m/s or 21.6kph. Based on single vehicle running (figure 1.1) this has the potential for the maximum capacity of any system operating in this way.

Whilst the speed seems slow, it is still above most inner-city public transport speeds (suggested at around 14kph [32]). It may be an ideal application for town and city centre environments, shopping malls or airports where there is a desire to move a large volume of passengers relatively short distances. Once again the safety and potential capacity can be considered using the same methods as previously developed.

4.3.1 Safety.

Considering figure 4.5 it is immediately clear the the inherent advantage of this system is the low speed, and the obvious reduction of risk that causes. For the simple feedback control system the necessary time delay of 0.2-seconds is both a much closer physical spacing, whilst at the same time being a greater proportion of vehicle length and safe headway. The result is that at all spacings above the minimum required the risk of

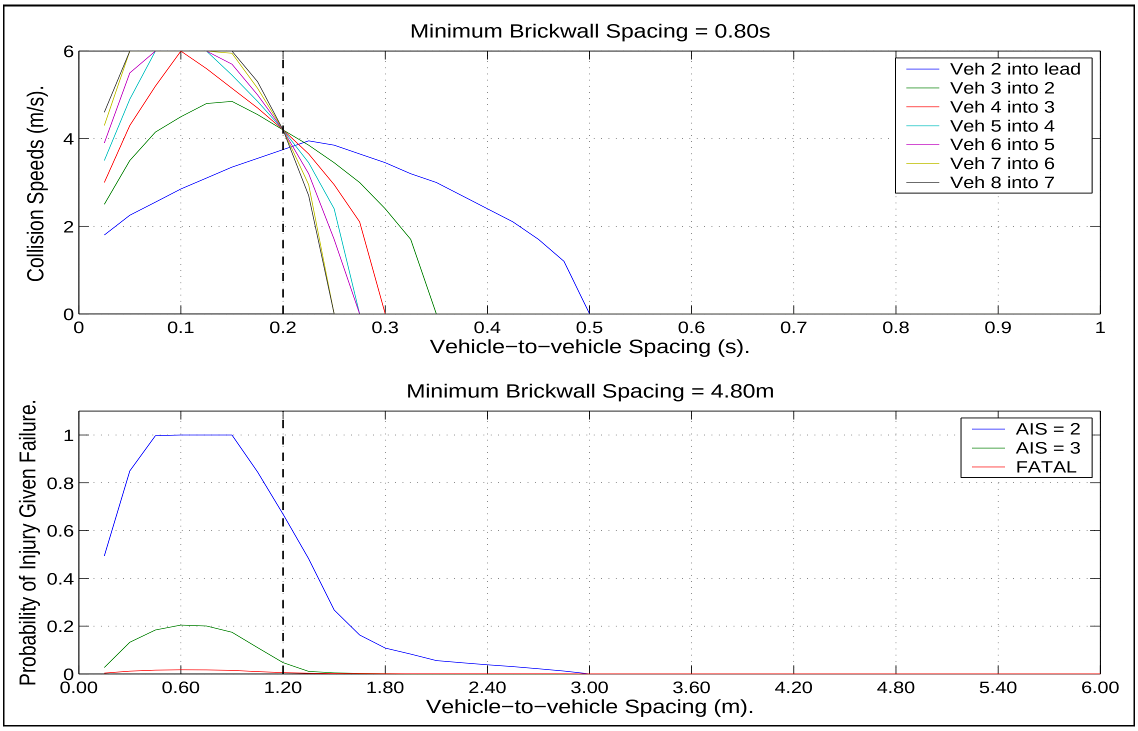

Figure 4.5: Injury Risk in 8-vehicle Platoon Failure for Low-speed PRT System.

fatality, and indeed any injury, drops significantly. Even at this spacing, the risk is well below that at either of the two higher speed systems. For this, the platoon separation is set at 0.2-seconds and the free-agent spacing at 0.42-seconds (this value brings the total free-agent headway to one-second).

For the tighter control systems (with a delay of 0.05-seconds) matching the delay with the minimum required would result in a 0.3m space. Whilst, at this speed it may be possible to control with sufficient accuracy to maintain this, it has been suggested that 0.6m is a useful minimum in all platooning control [5] and, as the possible benefits of having the space larger than the minimum for slow-speed systems have also been shown, a space of 0.1-seconds is set for these operations.

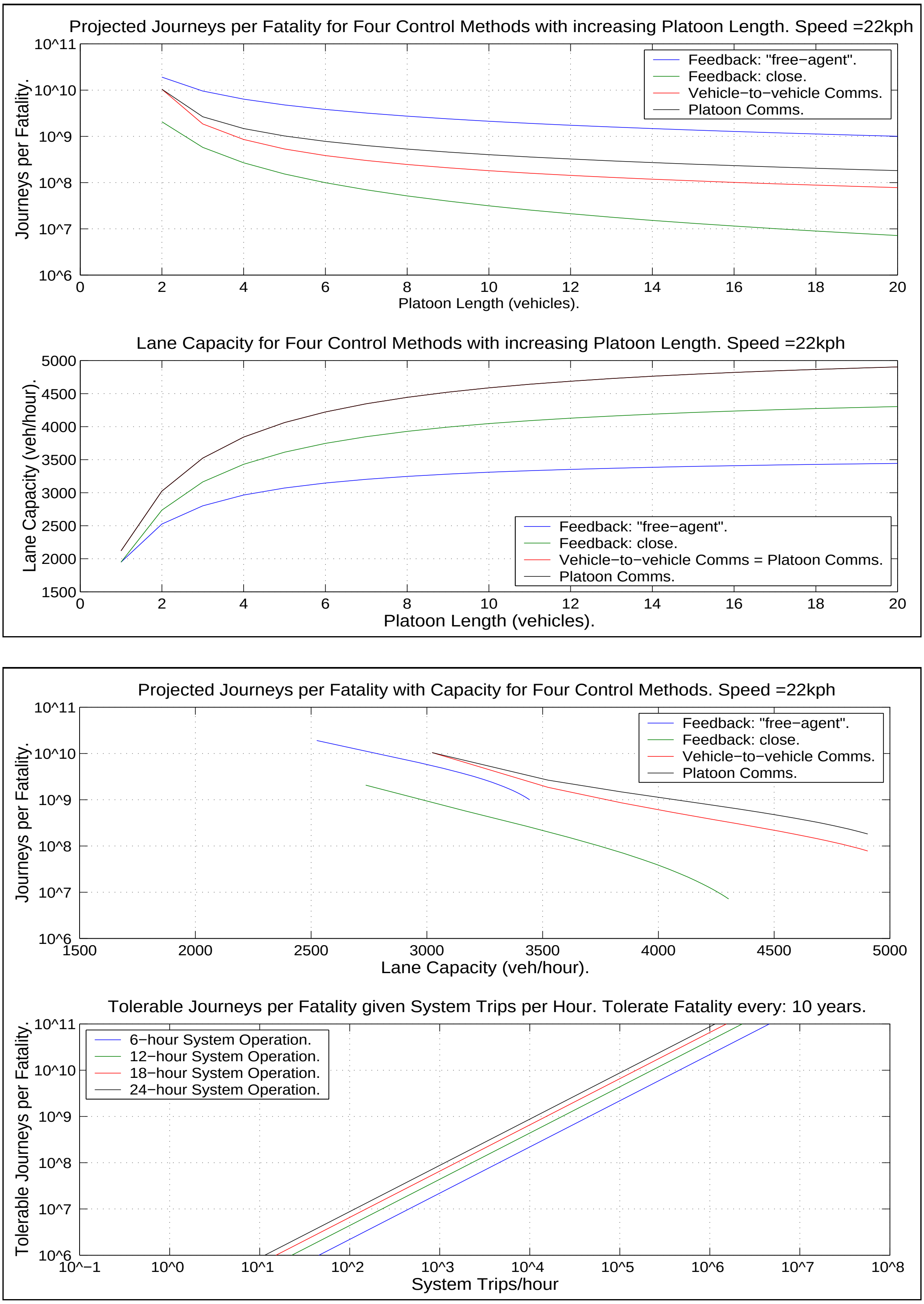

Figure 4.6: Safety and Risk Design Charts for System 1 Example.

Figure 4.6 shows the resulting safety charts for this system. The different control methods have similar effects as previously but the overall risk is generally lower and of similar magnitude for each. The slightly lower possible capacities also theoretically reduce the potential number of daily and yearly trips and so the tolerable number of journeys per failure. In this case 10^8 looks a reasonable lower limit of risk.

This would allow platoons of up to six-vehicles under even the most basic control method, up to sixteen-vehicles with the introduction of vehicle-to-vehicle communication and over twenty-vehicle platoons if full platoon control was utilised. The journeys per fatality for free-agent operation is above 10^9 in all cases. Again, in reality it is unlikely that the risk is that high, and that the mode is the safest by some margin, whist maximum theoretical capacity could never exceed 3600 vehicles per hour.

4.3.2 Capacity.

Figure 4.7 shows the capacity and utilisation for this system. The average trip length is set at 1km, although 0.5km (which is shown) may be more likely given the potential uses. 2km is also shown, but a system designed for such journeys would possibly demand higher speeds. Station spacings are set at 350m, which seems a sensible minimum spacing in a dense, inner-city area.

Utilisation with 1km trip lengths is reasonably high, generally around 90%, while halving the trip length reduces this significant (again the effect of the β / trip time relationship) to below 80% for four-vehicle and longer platoons. Other than with the very short trip lengths there is no restriction imposed by station flow rates, as extending platoon lengths does not increase capacity as significantly as in the other example systems. However, because much longer platoon lengths can be accommodated, the overall capacity can be made to equal that possible with the 40kph system whilst maintaining tolerable safety.

The question that is worth most consideration for a system of this nature is how long it is worth making the platoons given that the benefits from ten-vehicles onwards are not particularly great. As an interesting comparison, a similar set of occupancy and workload equations show that the utilisation of a pure free-agent system would be 88% for 1km and 78% for 0.5km trip lengths, resulting in practical capacities of 3149 and 2807 vehicles per hour respectively.

In both cases this would be equivalent to running an average of three-vehicle platoons, but with considerably lower risk, and a capacity increase from brickwall spacings of around 62%. By increasing to sixteen-vehicle platoons, the risk goes up by more

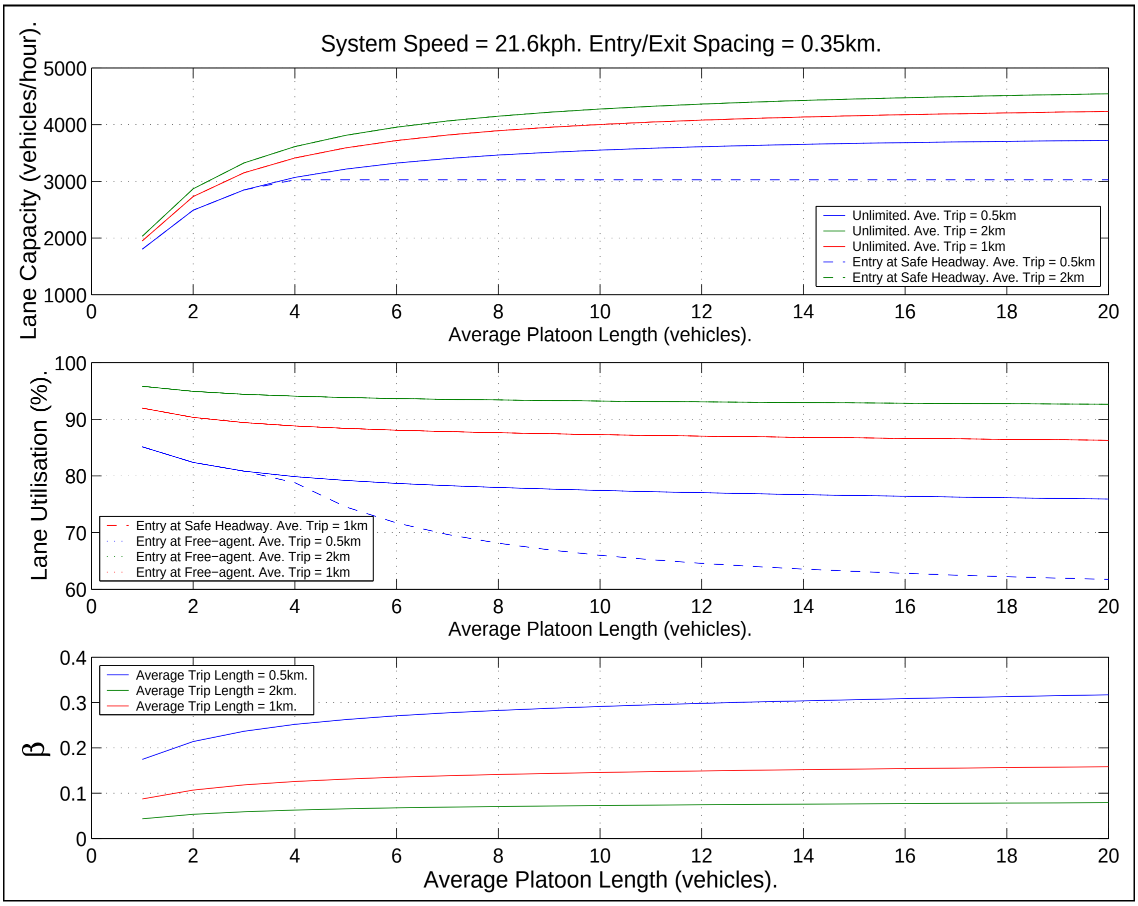

Figure 4.7: System Capacity and Utilisation for 6m/s PRT System.

than an order of magnitude, while capacity only increases by approximately the amount gained from changing from single to three-vehicle platoons. Whilst this still seems beneficial when the system calls for particularly high capacities, if safety considerations are required to be more stringent, this system speed appears to favour free-agent operation more than the other examples.

One possible option not previously considered is to change the mode of the system to suit the capacity demand, using brickwall criterion for low-capacity operation, free-agent running as a normal mode and platooning when peak capacity is required. The example guidelines for platooning control set out in section 3.3.1 may make the switch between these systems relatively simple, although it would require further study to consider this fully.

4.3.3 Vehicle Availability.

The possible limitations of entry flow capacity and station throughput have been detailed elsewhere. One remaining, and possibly prohibitive, consideration for a low-speed system may be the actual number of vehicles available. This can be demonstrated by a simple example.

For simplicity, a simple two-station loop is considered with the stations at opposing ends a distance of 1km apart. Journeys are assumed to all be one-way and 1km in length. Purely considering the use of single vehicles operating at safe brickwall headway the maximum capacities ($CapLim_{lane}$) for a 21.6kph and 40kph PRT lane are 2119 and 1839 vehicles an hour respectively. Because all vehicles will pass through and stop at both stations (there is no need for bypassing the stations if all journeys are one-way) these are the maximum capacities and full utilisation is assumed to be possible.

If the total time lost in the station (including for passengers to leave and enter the vehicle) is ten seconds then the time for one complete loop and number of loops one vehicle can complete in an hour is:

$$T_{loop} = \frac{2000}{V} + 20 \tag{4.1}$$

$$Loop_{veh} = \frac{3600}{T_{loop}} \tag{4.2}$$

Which, if V is speed in m/s, can be found to be 10 loops an hour at 21.6kph and 18 at 40kph. The capacity limit in either lane is therefore:

$$CapLim_{vehicles} = Loop_{veh} \times N_{vehicles} \tag{4.3}$$

The maximum throughput for the stations, given a ten-second berth time, is simply:

$$CapLim_{station} = \frac{3600}{10} \times N_{berths} = 360 \times N_{berths} \tag{4.4}$$

Where N_{berths} and $N_{vehicles}$ represent the minimum number of berths at either of the stations and the total number of vehicles on the system. The actual capacity is therefore the minimum of any of these values:

$$Capacity = \min\left(CapLim_{vehicles}, CapLim_{berths}, CapLim_{lane}\right) \tag{4.5}$$

Figure 4.8 shows the result of this. Whilst the number of berths at the stations limit the number of trips due to station throughput restrictions, this is the same for both speeds. The effect of the number of available vehicles is, not surprisingly, proportional to the difference in speed.

For example, if stations have three berths, the potential capacity of the system is 1080 return trips an hour. If 40kph is utilised then to meet this capacity, sixty vehicles are required. If the system runs at 21.6kph then 106 vehicles are needed. If the stations

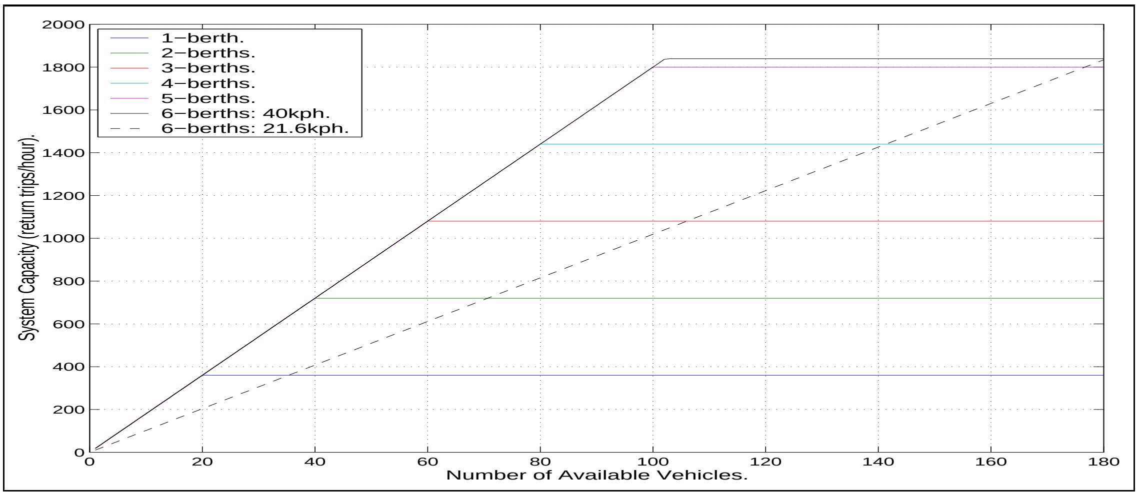

Figure 4.8: Capacity Limited by Available Berths and Vehicles.

have six berths then the lane capacity becomes the limit, but only assuming that the 40kph system has at least 103 vehicles. With the same number, the slower system has only 57% the capacity and requires only three berths. To achieve maximum lane capacity the slower system would need 208-vehicles.

In reality, the top capacities will probably not be possible in either case as it requires extremely tight control throughout the system (effectively all block lengths and berths are either all occupied or vehicles are entering and leaving them). Nevertheless, it is another important consideration when designing a system that the number of available vehicles may be a significant factor in determining the capacity.

Chapter 5

Demonstration.

To provide a visual aid to the platooning strategy proposed in section 3.3.1 and to investigate whether the predicted achievable capacities were in any way realistic, SIMULINK was used to construct a demonstration of a System 2 lane (40kph PRT). This was not a simulation where vehicle dynamics or system control was modeled but a combination of a few basic vehicle strategies and manually programmed control to provide a demonstration and a real-time animation of vehicle movements with a number of block-lengths in the lane over a fixed period.

The target platoon length was chosen to be four-vehicles. The average trip length was set at 1.5km with a 0.5km station spacing. The main effect of this was to determine the possible number of vehicles likely to enter and exit at any station. Station length was set to 80m (between start of exit ramp and end of entry ramp) which would allow full deceleration and acceleration of vehicles from and to lane speed and space in the station for a reasonable number of berths.

The exact station dynamics were not considered - the model only considers vehicle movements when fully on the lane. The target station exit rate is at the brickwall criterion. Vehicles cannot exit before their target time but can be held until an appropriate "slot" is free. If a vehicle is held for sufficient time it may be platooned in the station and enter the lane in a platoon if there is the correct space on the guideway to receive it.

5.1 Vehicle Model.

Each vehicle in the demonstration is represented by a sub-system (all are identical). Each vehicle receives just four variables. The status of the vehicle it is following on the lane and the position of the rear of that vehicle allow the speed control to be determined. The vehicle also receives route information (entry and exit points) and the "enter" command. This is a step input which requires setting manually. Simply this changes from zero to unity at the time at which the vehicle will arrive on the lane.

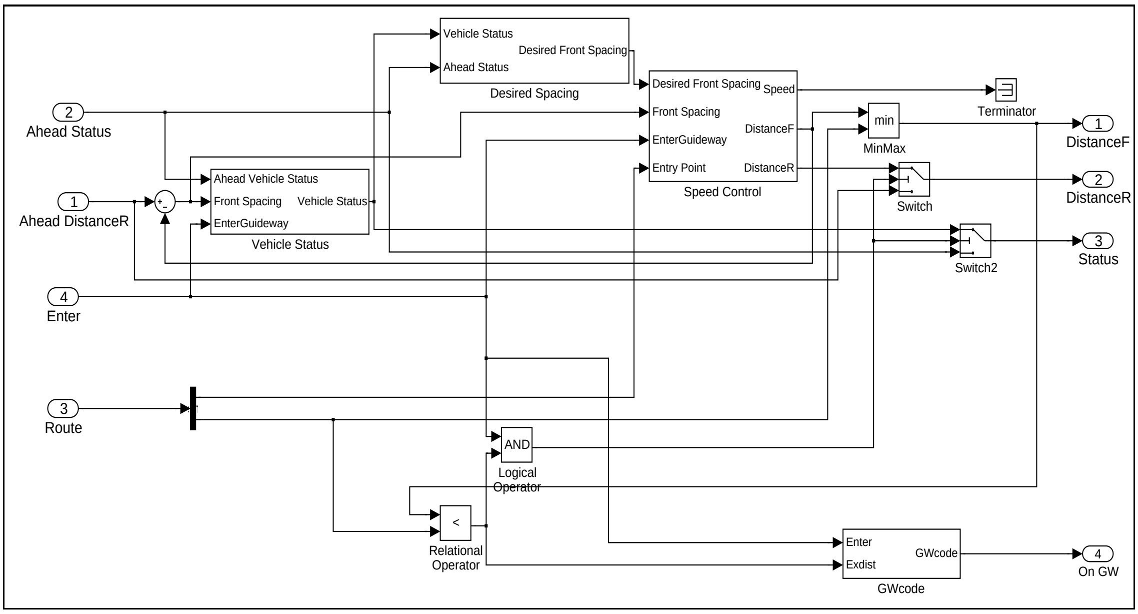

Figure 5.1: Demonstration Vehicle Model.

The status number allocates where the vehicle is in any platoon (1 at the lead to 4 at the rear). This is determined by the number of the vehicle in front and the spacing. For example, if the vehicle is within the block length of a already existing 2-vehicle platoon, the vehicle ahead will have status 2 and so the vehicle status will immediately change to status 3. If the vehicle enters into a clear block length or is too far behind the next vehicle, the status will be 1 (leader). To prevent vehicles entering at the front of platoons the status number can never increase but it can decrease (so that if a lead vehicle leaves the platoon the next follower moves up to the front of the block length and becomes the leader with status 1).

The desired spacing ahead of the vehicle is purely determined by a comparison of the vehicle status with the status of the vehicle directly ahead. For vehicle status of 2 or higher then the desired spacing will be one intra-platoon spacing. For lead vehicles the desired spacing will be the necessary inter-platoon spacing (no less than brickwall) to maintain the correct block-length.

Speed control is very basic. For the purposes of the demonstration the acceleration and jerk is neglected. If a vehicle is required to reduce the spacing ahead of it, it runs at the allowable overspeed (usually 110% of lane speed - although this is a parameter

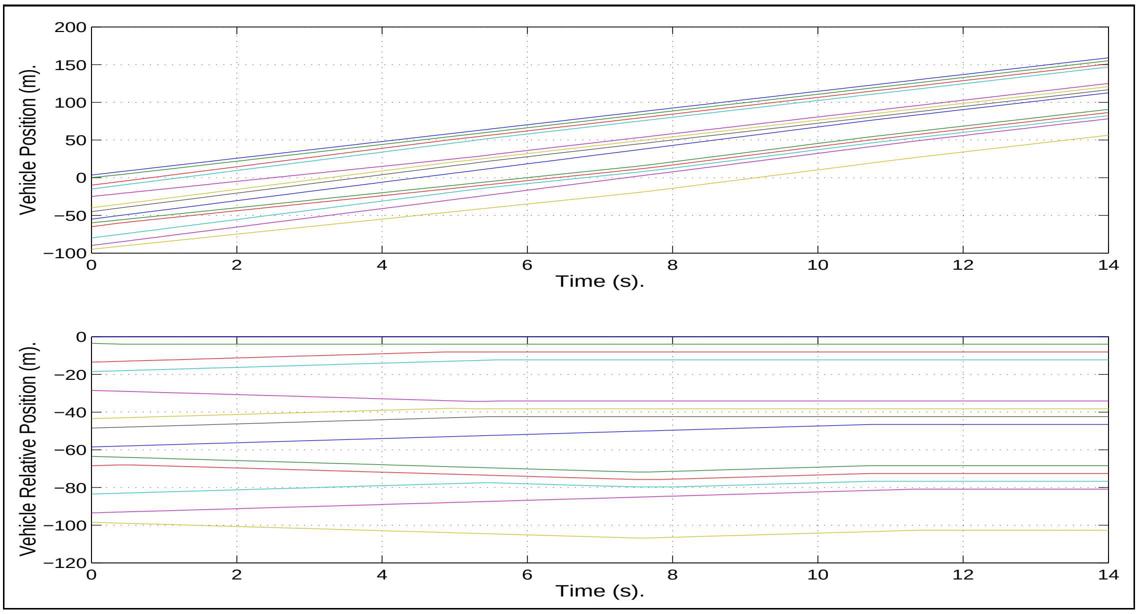

Figure 5.2: Example of Vehicle Assignment into Platoons.

which can be changed) and if it is required to increase the spacing ahead of it, it runs the equivalent below lane speed. There are various other functions in the model but they are concerned with the presentation of results and the animation, rather than the working of the demonstration.

Figure 5.2 shows how the vehicle works. Each line represents a vehicle and in this example the starting positions are random. By each vehicle switching speed accordingly, the set eventually sorts itself into correctly spaced four-vehicle platoons. In the demonstration a moving set of six block-lengths is shown with the possible leader of the next (seventh) block always remaining. The total capacity is therefore calculated by the number of vehicles in this set, adjusted for the variability of the total length of the set. This is because the leader of the seventh block will be seen to have to drop back from the normal position on occasion to make room for manoeuvres occurring ahead of it.

5.2 Results and Animation.

The system demonstrated has five main stations at 500m intervals. At the start there is just one vehicle per block length, each at the head. Through each station a certain number of vehicles leave and enter the guideway thus decreasing and then increasing the flow rate on any section of the lane. There are two further stations, the last of which is only 300m from the previous one. Typical high-demand operation occurs between the second and sixth stations, the sixth and seventh stations serving only to remove vehicles from the lane. Following the seventh station the number of vehicles has returned to the starting value.

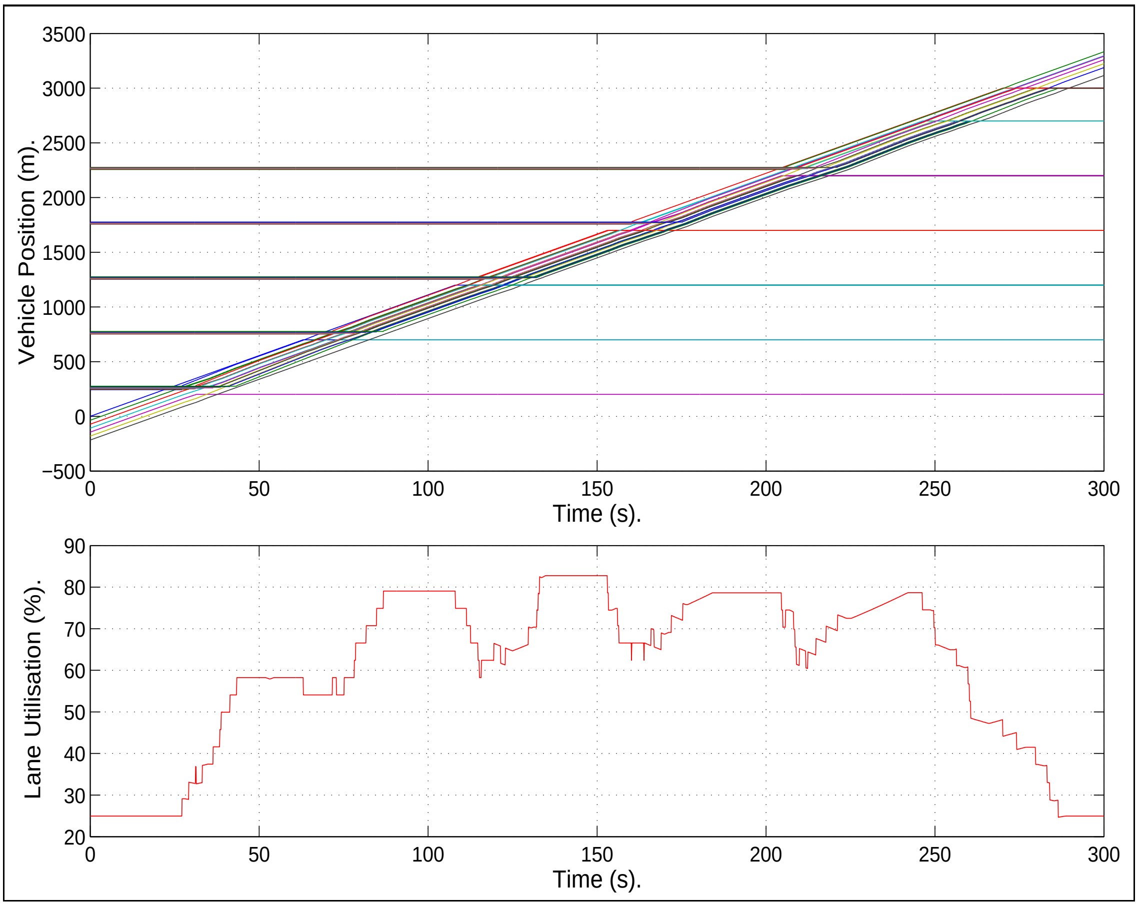

Figure 5.3: Time/Space Diagram and Utilisation.

Figure 5.3 shows the time/space diagram for every one of the 43 vehicles used in the demonstration. The clusters of horizontal lines show the station-exit/lane-entry points. The difference in longitudinal position is purely to enable a more realistic animation, vehicles all enter and leave the lane at the same longitudinal point for each station. The single horizontal lines to the right of the plot represent the station-entry/lane-exit points.

The second plot shows the utilisation of the system during the demonstration. Mostly, this changes in steps, as vehicles enter and leave the guideway. However, there are a few more gradual changes. This occurs when vehicles have entered the guideway but the leader of the seventh block-length has dropped back, effectively increasing the average block length and reducing the overall capacity of the lane. As the vehicles manoeuvre into correctly platooned positions all vehicles will close back up to the correct spacings, and the utilisation of the lane will increase.

To best describe the movements on the lane, it is useful to consider a set of selected stills from the animation. To aid the understanding of this some basic alterations and additions have been made to enhance the realism of the vehicle behaviour. These include a representation of the stations, the gradual entry of vehicles into the guideway and the stepped reduction of speed of the vehicle once off the lane. The vehicles and stations are also colour-coded to show from which station each vehicle joined the lane.

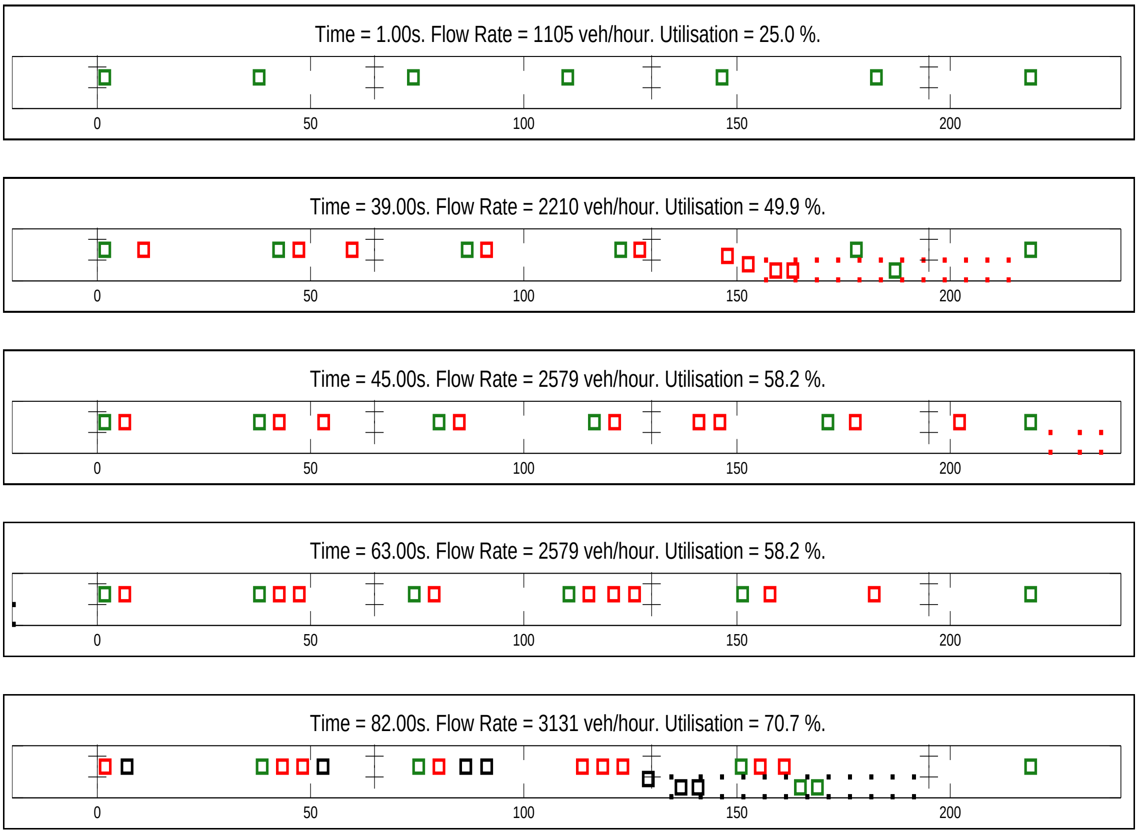

Figure 5.4: Demonstration Selected Stills 1.

Figure 5.4 shows the first five stills. Each is time stamped (from start of demonstration) and the flow rate and utilisation shown. At one second, each vehicle heads a block length and the utilisation is only 25%. The flow rate at this point is below that obtainable under brickwall headway criteria. At 39-seconds most of the set has passed by the first station (red). One vehicle has entered the station and five have joined the lane. At this point two further vehicles are joining, already platooned, and two more are preparing to join.

Once the set is clear of the station all red vehicles have joined the lane (45-seconds) but some manoeuvres must take place to ensure proper platoon operation. Although this takes a little time (the 63-second plot shows that substantial movement has occurred but all vehicles are not yet in set positions), the leader of the seventh block has only had to make a small and brief adjustment (at around 53-seconds) and so the flow rate has not dropped significantly to allow this. It is only with the approach to the second (black) station that the platoons are fully sorted and further input can begin.

At 82-seconds the second station has been past by most of the set. Two vehicles have entered the station, four more have joined, one is joining and two are waiting to join. Ultimately following this station the lane will be running at 79% capacity and four of the platoons will be at full length. Figure 5.3 shows that the total set length has not had to increase to account for the manoeuvres by the entering vehicles.

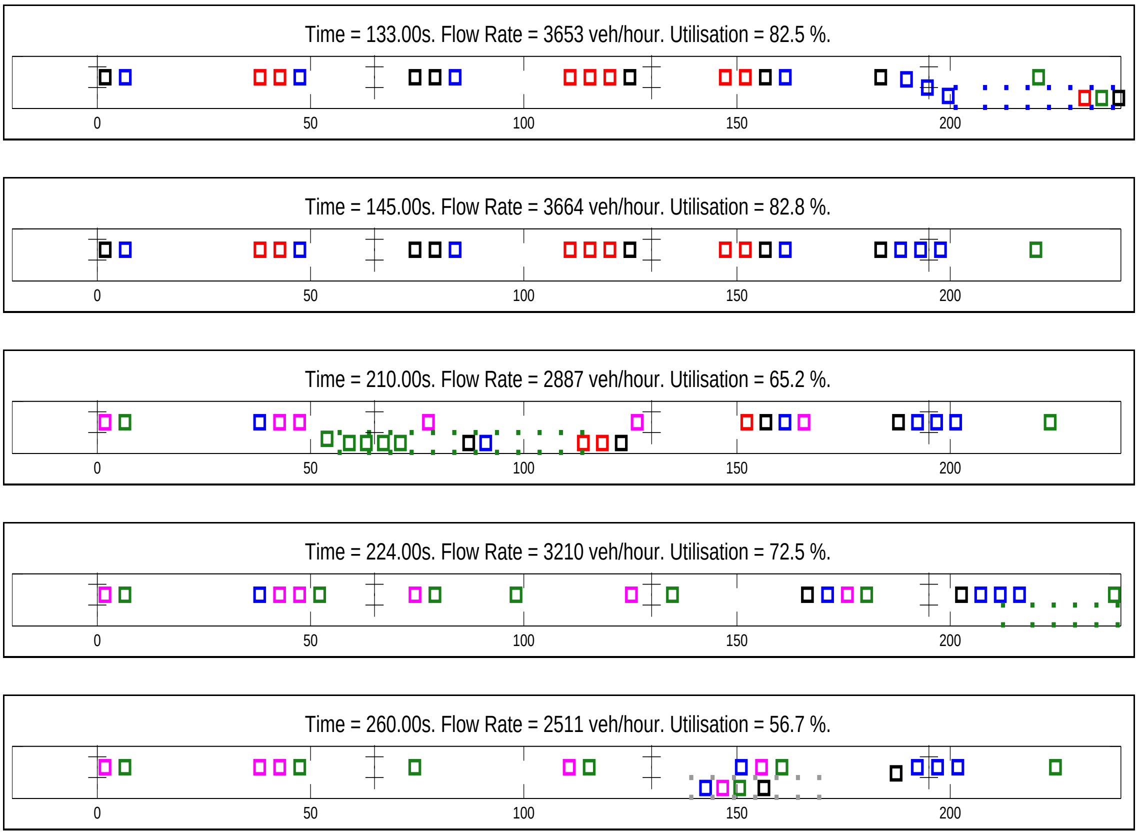

Figure 5.5: Demonstration Selected Stills 2.

Figure 5.5 shows the other five stills from the animation. As the third (blue) station is passed, six vehicles leave the lane but the addition of a further seven vehicles increases the flow rate further. The 133-second plot shows the addition of the last three vehicles as a platoon. This occurs because the position of vehicles already present in the lane has delayed the entry of two vehicles. By allowing platooned entry, a higher proportion of vehicles can leave the station and enter the guideway at near the correct time. The operation does, however, cause a slight lengthening in the total set-length.

Once running in the correct positions (this has occurred by the 145-second point) the set-length is correct and a the lane is running at 82.8% capacity. This is very close to the figure of 82.5% suggested by the workload equations and figure 3.4. It is at the fifth (green) station where the set-length increases the most. At 210-seconds half the set has passed the station. Six vehicles will leave and enter the lane here. It is at 224-seconds that the set-length is longest. All the vehicles have left or entered the lane but the leader of the seventh block has dropped back over 15-metres behind the usual position. This is because at the entry to the station the first three vehicles in the fourth block have left the lane as a platoon. The fourth vehicle immediately becomes a leader but is over three vehicle-lengths behind the required position in the block. Following vehicles see the vehicle as a leader and this creates a violation of the forward block, causing following vehicles to drop back to the correct spacing.

Only once the new leader of block four has regained the correct position do subsequent vehicles begin to regain their original places. This is an interesting feature but ultimately is due to an over-simplification of the vehicle control systems. As no safety margin is violated, the following vehicles should ideally wait until the new block-four leader regains it's position before making any adjustments. Whilst this would reduce the necessary lengthening of the set-length in this case, there will be other situations which will cause this lengthening and it useful to see perhaps an exaggerated example.

Another unnecessary process would, for example, take place if an entire block-length were to be empty after the station. Under this control system all following vehicles would move up to occupy the vacant block. Whilst in the short term this may seem like a beneficial process, ultimately it reduces the options for any vehicles entering at the next station and may result in a drop in utilisation. This may be worth further study.

The final still (260-seconds) shows the first of the exit-only stations and the flow-rate of the lane beginning to reduce. By the time the last station is passed, and the end of the 300-second demonstration, the set is running at just 25% capacity again, although there is one two-vehicle platoon and one empty block-length.

5.3 Conclusions.

By producing a relatively simple kinematically based model of a set of vehicles in an automated lane it has been possible to demonstrate some of the possible platooning concepts, operations and resulting benefits explained in this study.

Whilst the demonstration contains no vehicle dynamics, acceleration or jerk effects, or any overall control structure it has shown the the guidelines for platooning laid down, if implemented, could allow a system of this type to meet the levels of flow rate and lane utilisation suggested by the workload equations for this set of system characteristics.

It also has highlighted a few interesting control problems and effects which would assist in a more detailed development of both individual and system-wide controllers. These include problems which may increase disturbance in the lane flow and also cause vehicles to spend unnecessary lengths of time manoeuvring and in possible non-safe positions.

A demonstration such as this could also be used to consider the possible effects of trip length and station spacing on the flow of such lanes. It is interesting that between the first and second stations the number and length of vehicle manoeuvres in the lane, whilst not violating the set length, result in all the manouevres not being complete by the time that the next station is reached. In this case the effect is minimal, but if stations were closer together (350m for example) then it may prove more difficult to organise the entry of vehicles into the lane.

This is possibly the greatest simplification of the demonstration. Vehicles are entered into the lane by the manual setting of each vehicle's entry time. This includes having an overview of exactly where ever vehicle is at the exact time of entry of the entering vehicle. A system controller, whilst having this information in real time, would actually have to order vehicles to enter the lane well in advance of this point, so that the vehicle can reach correct speed and position at the correct time. This would then have to have the ability to predict the position of all near vehicles at the point of entry which becomes more difficult if vehicles are still manoeuvring.

Despite such considerations, the demonstration gives a very reasonable overview of how platooned operations could be made to work in such a system and goes some way to validate the previous calculations regarding utilisation and capacity of automated lanes.

Chapter 6

Conclusions and Future Work.

The aim of this study was to determine whether the operation of vehicles in platoons on an automated transport system was a viable and practical option. The potential benefits of such operation, in terms of the system capacity and throughput, are well known. This study set out to show whether or not platooning could be practically implemented to be both low-risk and effective in approaching the levels of traffic flow theoretically possible.

The two key areas of study were therefore the safety aspects of platooning, considering vehicle failure modes, collision speeds, control systems and risk of injury to passengers, and the effect of platooning on the utilisation and throughput of an automated lane or system. For this, use was made of equations of workload developed by Hall [26] and suitably modified to focus on a set of platooning laws designed to be realistic, achievable and efficient.

To consider the practical application and implications of these key points, three possible systems were used as examples to show how safety and system capacity can be effected by a number of factors including controller delays, platoon lengths, control strategies, average trip length and station/junction spacing. Whilst showing some system specific characteristics, they also were useful is drawing more general conclusions.

Finally, a simple kinematic demonstration was produced of a 40kph PRT lane to show the possible operation of an automated system using platoons and compare to the calculated predictions of the equations of utilisation and throughput.

6.1 Is Platooning Viable?

The justification for the safety of platoon operations relies on using a different set of assumptions compared to those for the "brickwall" safety criterion. Assuming that the lead, or failed vehicle, can only decelerate at some non-infinite rate (usually 10 - $20m/s^2$) means that if vehicle-to-vehicle spacings are small enough, any collisions which occur will be of small relative speed. The lower the spacing, the safer the collisions. Similarly, if failed and following decelerations are close, the system will be safer.

There is, however, a requirement which can be overlooked. This is the requirement for vehicles not to collide under any controlled conditions, including a full platoon stop where all vehicles decelerate at a high, but equal, rate. To ensure this is met, the spacing between consecutive vehicles must be equal to, or above, the distance covered at lane speed by a vehicle during the time between consecutive vehicles taking similar actions.

This Minimum Spacing Requirement can increase the necessary spacing between vehicles beyond that which allows sufficiently low collision speeds in the case of a vehicle failure. It is highly dependent on the control systems used for the platoon and it can be argued that a simple vehicle-to-vehicle look-ahead feedback system would not be sufficient to ensure safe platooning. The introduction of more complex control systems, which involve vehicle-to-vehicle communicated data and even some overall platoon commands, can significantly decrease the actuation delay times and allow safe operation.

An alternative to this is to run the vehicles with pure feedback control but increase the spacing significantly until collision speeds are again reduced. This mode of operating with vehicles at lower than the brickwall headways but not in close formation has been referred to as the "free-agent" operation. Whilst it offers potentially low risk at around one-second headways, it has not the potential to increase capacity beyond around 3000 vehicles an hour.

Based on typical values of vehicle failure rates, the Hazard Ranking Matrix, and measures of injury risk in collisions, the safety of the three systems considered (21.6kph, 40kph and 113kph) could be determined for different control methods in terms of the number of predicted journeys for every fatality due to platooning. Determining a tolerable level of risk is difficult as an overall level of one fatality in ten years is meaningless without a gauge of the number of trips undertaken in a year. It was reasoned, however, that for any system, the capacity may be used to indicate the expected number of journeys and the level of tolerable safety was usually found to be between 10^8 and 10^9 journeys per fatality.

Based on this the high-speed (113kph) system proved, as expected, to present the highest risk, mainly due to the high potential collision speeds. Platoon control with pure vehicle ahead sensing appeared to be too high a risk to be viable but increased communication and shared data, if it could reduce actuation delays sufficiently, could allow platoons of five, and possibly six vehicles, but no longer.

At 40kph there was a similar conclusion, but the more basic control system could allow platoon lengths of two or three vehicles. The lowest speed system was by far the lowest risk application. With a basic control system it appeared that six-vehicle platoons could be safe, whilst with closer spacing and tighter control platoons of sixteen-vehicles and more could be possible, although the overall capacity benefits are less substantial at a lower speed.

This work showed that platooning can be made practically viable and safe, although unless control methods are made sufficiently tight, this may only be by a limit of the number of vehicles in platoons to somewhat below the anticipated and suggested lengths in other studies.

6.2 Can Platooning be Effective?

The equations for workload allow any system characteristic to be entered as a mathematical representation to enable the determination of the utilisation and hence capacity of a lane or system. Critical to this is the nature of the platooning operations and manoeuvres, particularly at the points of entry and exit to the automated lane or system. These techniques vary from every vehicle entering and leaving from a brickwall spacing (fore and aft) to entries and exits occurring to and from platooned conditions (so called "virtual platooning").

Following a study of these methods, a set of platoon operation guidelines were constructed, with the aim of ensuring low risk, efficient and realistic platoon manoeuvres. These were then used to create the necessary parameters for the workload calculations. It was found that the nature of these manoeuvres had the potential to reduce the time and space occupied by vehicles entering and leaving the lane compared to single vehicle flow up to a certain platoon length. The overall effect of increasing platoon length was still ultimately to reduce the utilisation of the lane.

A key influence on the magnitude of this reduction was found to be the ratio of the average journey distance to the system speed (the average trip time). The shorter this was, the greater proportion of the journey each vehicle spent manoeuvring and occupying more than the ideal amount of space on the guideway and therefore the less efficient was the operation. For each of the three systems, the utilisation and capacity of a single lane was calculated using a predicted typical trip length and also a trip length half and twice this value.

On finding the potential capacity of the systems, there were other factors which were considered. This particularly included the capability of the system stations or junctions to provide the levels of flow that the equations suggested were possible. The two critical aspects of this were found to be the nature of the entry flow (which safety mode was used and the limit of station throughput) and the frequency of stations and junctions relative to the average trip length.

A multi-lane AHS was also considered briefly and it was found that the addition of lanes can also significantly reduce the overall utilisation of the system whilst still providing marginal increases in capacity. It was found that as platoons get longer and systems require more vehicle manoeuvring, a significant proportion of vehicles spend most of the journey in the outer lanes and few in the inner lanes. Whilst more investigation could take place it was generally concluded that the capacity benefits for systems of more than three lanes are negligible when compared to the extra space needed to create additional lanes.

The introduction of platooning, the additional vehicles, manoeuvres and operations, will inevitably lead to a reduction in the utilisation of a lane compared to the ideal values of capacity predicted. However, up to all reasonable platoon lengths, this reduction is not sufficient to outweigh the large gains in theoretical capacity from running batches of close-space vehicles. Therefore the overall effect of platooning is to increase the capacity of any system or lane, as long as the operations are designed carefully and well implemented.

In the example considered it was shown that, despite the decrease in utilisation it is possible, even with the relatively short platoons required for safe operations, for the lane to exceed the limits of capacity set by entry flow, station throughput and vehicle availability. The demonstration of the 40kph system showed that the workload equations could give a very reasonable indication of the possibilities of platooning at a practical level.

Even the use of the platoon safety concepts to run a non-platooned "free-agent" operation has the potential to double the capacity on a system and despite all the additional complexity of control systems and manoeuvres, the work shows that by platooning between four and six vehicles together, system capacities can be increased three-fold or more.

6.3 Future Work.

Whilst this work has taken significant steps toward establishing that platooned operations can be both safe and beneficial, there are several areas which may warrant further and more detailed investigation.

The model used for the determination of collision speeds and safety is based on a few simplifying assumptions which remove a certain amount of realism. Neither vehicle crush-zones or, perhaps more significantly, conservation of vehicle momentum are considered, both of which may reduce the collision speeds, especially for vehicles behind the first-follower. Onset jerk is not considered in the safety calculations and this may reduce safety, effectively slowing the onset of deceleration for following vehicles.

Similarly, no consideration has been made of the safety of passengers in the vehicles when they are hit by a following vehicle or those in the failed vehicle. More investigation is perhaps also required into the likely failure rates, and modes of the vehicles, and how the tolerable risk of one fatality every ten years may be translated into the tolerable risk for each journey.

As explained in the study, the equations of workload do not consider the influence of discrete entry points. Although the demonstration appeared to indicated the values suggested as reasonable (and so this to be of possible small significance) and the limitation of entry flow possibly demonstrated the influence of this factor, it would be interesting to attempt to include some parameter for this in the equations themselves.

Whilst the demonstration showed how such a system may work, the next inevitable step must be to produce a full simulation of such a lane. This has been partly achieved elsewhere [9] but it would be extremely beneficial to create a simulation in a media such as SIMULINK. This could then be used to develop control systems for both the vehicles, in terms of converting orders and positions into speed and acceleration demands, and the overall control system, which would synchronise vehicles and ensure the efficiency and safety of the platoon operations.

If the simulation could be made as generic as possible, systems of different speeds and characteristics, as described in this study, could be modeled and efficient strategies and operations developed. These could then be taken and demonstrated on possible real or experimental automated transport systems and the practical benefits of platoon operation proven.

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