Simulation Methods for Mixed Legacy-Autonomous Mainline Train Operations

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Abstract

We introduce and demonstrate a simple and efficient method for simulating mixtures of legacy and autonomous trains. The method generalises an earlier simulation that we developed for legacy-only operations, in which trains run according to fixed-block signalling rules. Autonomous trains, which use moving-block signalling rules, are incorporated into this framework by employing an overlapping set of short virtual fixed-blocks. Safe occupancy is then maintained by using shadowing rules that link the two sets of blocks. The paper gives relevant rail background, details of the proposed simulation rules, and demonstrates exemplar solution trajectories. The simulation technique is validated both in terms of (i) maintaining safe occupancy and (ii) providing a close approximation of the true continuous-space dynamics of autonomous leader-follower pairs. At the Dresden meeting, a variety of interesting mixed-fleet capacity results will also be presented.

**Keywords:** mainline rail capacity; fixed-block signalling rules; modelling and simulation

1 Introduction

This paper forms the latest part of a body of work [Mor22a; Mor22b] in which (i) we have taken ideas from traffic flow theory to modelling the capacity of mainline train operations, and (ii) we have examined the potential gains that might arise from more digitalised, connected, and autonomous systems.

In [Mor22a], we proposed a simplified analysis of legacy fixed-block rail operations, which resulted in fundamental diagrams that relate the speed, density, and flow rates in terms of pertinent system parameters such as signal aspects and block lengths. This theory
was then modified [Mor22b] to demonstrate the increased capacity that might be achieved in a moving-block set-up, that, for example, might be achieved with level 3 of the European Train Control System (ETCS) [Sta11]. See Section 2 for a brief account of these ideas.

Unfortunately, the full gains of moving blocks might only be achieved when connected and/or autonomous trains (CATs) follow each other in sequence – because legacy driver operated and/or guided trains (DOGs) will continue to observe fixed-block rules and will not share continuous position information with their neighbours. Therefore DOG-DOG, CAT-DOG, and DOG-CAT leader-follower pairs cannot achieve the reduced headways of CAT-CAT pairs. Thus there is a pressing need to simulate mixed traffic systems and to understand both their equilibrium (smooth running) capacity and potential undesirable dynamics (stop-and-go waves etc).

In [Mor22a] we proposed and demonstrated a simple time-step simulator for legacy fixed-block mainline operations. However, the difficulty in simulating mixed running is that for CAT-CAT pairs, the follower is governed by a continuous space train-following model (TFM), analogous to a car-following model (CFM) – for example, we have shown [Mor22b] that an appropriately parameterised Gipps’s model [Gip81] might be suitable. Unfortunately, the resulting mix of discrete-space and continuous-space interactions becomes quite awkward to simulate.

Therefore in this paper, we propose (Section 3) a mixed-traffic simulation method which is built upon our legacy simulation, using fixed blocks only. The basic trick is to suppose that the CATs are modelled to run on a virtual track of short fixed blocks, with two-way “shadowing” rules that link these and the (longer) fixed blocks of the legacy system. We show (Section 4) that this method allows the rules for all four leader-follower pair combinations to be represented correctly, and for the continuous-space interactions of CAT-CAT pairs to be closely approximated.

2 Fixed-block and Moving-block Operations

In [Mor22a], we investigated the line capacity of mainline rail operations that use legacy fixed-blocked signalling rules, summarised by [Pac20] and the multi-author volume edited by [The20]. In summary, the safety-critical principles are that (i) track is partitioned into fixed blocks; (ii) each block should only be occupied by at most one train at any time; (iii) each train must be able to come to a stop safely within the blocks ahead (known as the “aspects”) whose occupancy the signals report, see Figure 1(a); and (iv) each train must be able to come to a stop safely ahead of any block that the signals report to be occupied by another train, see Figure 1(b).

Simple constant acceleration rules were then applied to derive the maximum safe speed for a follower train in terms of the integer-valued aspect parameter $\alpha$, block length $L_B$, safety margin $L_M$, and the train’s braking rate $b$ and net-spacing $s$. Via density $\rho := 1/(s + L_T)$, where $L_T$ is the train length, we may thus derive fundamental diagrams (FDs) that relate the
Figure 1: Safety limit cases [Mor22a]: here $\alpha = 3$ (four-aspect) fixed-block signalling is shown. (a) Each train must be able to stop safely within the blocks that the signals report upon. (b) The net spacing, $s$, must be sufficient for the follower train to come to a stop before the leader’s block.

speed, density, and flow of mainline operations. See [Mor22a] for mathematical formulae and Figure 2 for plots of the resulting FDs.

In contrast to legacy operations, it is assumed that CATs will use a moving-block system. Thus in a pure-CAT system, the trains have continuous-space knowledge of each other’s displacement. As we showed in [Mor22b], this is equivalent to a fixed-block system with an infinitesimal block size $L_B \rightarrow 0$, but infinite spatial foresight $\alpha L_B \rightarrow \infty$. This analysis gives rise to a new set of FDs indicated by the blue lines in Figure 2, quantifying the capacity gains – suggesting that a doubling of capacity might be possible in pure moving-block operations [Mor22a]. Furthermore, we showed that these moving-block capacity calculations match an analysis based on Gipps’s car-following model, where we assume that the leader train is capable of a brick-wall instantaneous stop – this is a pessimistic but appropriate assumption given the safety tradition of rail.

3 Simulation Methodology

In [Mor22a], we described and demonstrated a simple time-step simulator for legacy fixed-block operations. This is because we found commercial simulators, such as [Ope21], are not sufficiently adaptable for our purposes – for example, they do not allow one to perform “ring-road” experiments as are standard in the traffic flow theory literature.

In our simulator, at any instant, each train is assumed to be in one of four discrete states, namely (i) at maximum (goal) speed, (ii) accelerating to goal speed, (iii) halted, waiting for the block ahead to become free, and (iv) braking to come to a stop ahead of a block that is not known to be safe for the train to enter. Each train then advances down the track according to standard 1D kinematics, registering its presence with the block(s) that it occupies, and updating its state as appropriate – for example, switching to the braking state at the instant that a “watch point” which precedes the train by its instantaneous stopping
distance first enters a block which is not known to be free. It is important to note that legacy trains do not interact with each other directly, but only via their occupancy of the discrete fixed-block infrastructure.

In contrast, CATs should ideally follow each other with (e.g.) Gipps’s CFM, in which consecutive trains use continuous-position knowledge of each other (and employ a continuous range of ac/decelerations rather than just the four states described above). The mixed-traffic simulation is thus challenging to code up, since each train must maintain a pointer to its leader to determine the appropriate following behaviour, discrete or continuous. In track layouts with merges and diverges, the relative ordering of trains might change and the pointer syntax will become particularly complicated.

We have developed a rather simple solution to these problems, illustrated in Figure 3. The idea is that all trains, both CATs and DOGs, drive on fixed blocks according to the four-state rules of our legacy simulator. However, the CATs drive on a virtual set of blocks which are
Figure 3: Block shadowing rules for mixed operations. DOGs run on the original coarse fixed blocks, whereas CATs run on shorter virtual fixed blocks. Occupancies signalled by (a) DOG leader; (b) CAT leader, where red blocks are signalled as occupied and grey blocks are signalled as free.

much shorter than the legacy blocks, to capture the idea that moving blocks are equivalent to block length $L_B \rightarrow 0$.

To ensure the correct following behaviour for all four possible leader-follower combinations, the virtual and legacy blocks shadow each other in the following ways. Firstly, see Figure 3(a), a DOG leader blocks out all of the virtual blocks that overlap with it, so that a CAT follower must act conservatively (as the legacy DOG train does not broadcast continuous-position information). In contrast, see Figure 3(b), a CAT leader blocks out only a short sequence of virtual blocks (enabling close-following by a CAT follower), but also blocks out any legacy block with which its virtual blocks overlap – thus a DOG follower must act conservatively as it only has access to the legacy signalling system, and not to the continuous-position information that the CAT broadcasts.

4 Demonstration

Using the new simulation framework, we have performed a range of experiments with different mixtures of DOGs and CATs, using a variety of different track topologies. The aim is to examine how realised capacities of mixed running compare to the theory in Figure 2. For more complex track topologies, we have also made comparisons with the emerging Macroscopic Fundamental Diagram (MFD) ideas for rail [Far17]. Full details will be given at the Dresden meeting.

Here we focus, very briefly, on displaying some of the dynamics via trajectory plots, see Figures 4 and 5. The basic set-up is a “ring-road” into which we inject DOGs and CATs via two distinct input tracks, in such a way to randomise the resulting order, with density controlled by the length of the “ring-road”.

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Figure 4: Trajectory plot showing mixed running of CATs and DOGs on a ring with a resulting stop-and-go wave. The legacy block infrastructure is denoted by the overlaid horizontal black lines and red lines which denote the associated safe stopping points. Each train’s state is represented by colour: green (at goal speed); magenta (braking); red (halted); blue (accelerating). The black boxes highlight regions with consecutive CATs, where the close following is particularly clear when the trains come to a halt.

Figure 5: Zoomed-in trajectories. (a) Sub-sequence of legacy trains in a stop-and-go pattern. The additional black lines denote the stopping point of each train and the “watch point” that is a safety margin $L_M$ beyond that. (b) Sub-sequence of CATs at an apparently uniform speed. The fine virtual block infrastructure is overlaid (thin horizontal black and red lines). The CATs cannot achieve smooth running at their goal speed, and thus approximate the desired continuous TFM behaviour by a rapid jittering between accelerating (blue) and braking (magenta) states, as their watch points roll over the virtual block infrastructure.
Figure 4 gives a large-scale view of 25 minutes of running over 32 km of track into which 10 trains are injected (5 DOGs and 5 CATs). A stop-and-go wave results. The close-following behaviour of consecutive CATs is particularly apparent as they come to a halt, since in that setting, the net spacing may be as short as the safety margin parameter $L_M := 100$ m.

In contrast, Figure 5(a) gives a zoomed view of consecutive DOGs coming to a halt, and shows the fine detail of how safe occupancy is maintained, by initiating a train’s braking when its watch point first reaches the rear of an occupied block. At halt, the net spacing of consecutive DOGs is $L_M + L_B - L_T = 1,300$ m.

Finally, Figure 5(b) gives a zoomed view of consecutive CATs in apparently constant-speed running. In fact, constant-speed running below the goal speed is not compatible with the four-state simulation, nor can CATs choose their acceleration continuously in this framework. Rather, each CAT approximates the correct continuous-space TFM behaviour by jittering between accelerating and braking states as its watch point rolls over the fine-scale virtual blocks. Potentially, the jittering may be reduced in scale by shortening the virtual blocks. However, to maintain provable safety, blocks must be at least as long as the safety margin $L_M$, and our simulation method requires $L_M > v_{\max} \Delta t$, i.e. the maximum distance that a train can move in one time step – so shortening the blocks requires that the time step $\Delta t$ is reduced, with the associated computational cost. However, it can be in any case shown that the resulting undesirable oscillations in velocity are rather small, and a modest low-pass filtering of the trajectory recovers a very close approximation to the dynamics of Gipps’s CFM.

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References


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