Simulation of Mixtures of Legacy and Autonomous Mainline Rail Operations

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Short summary

This paper describes the analysis and development of a prototype (and first of its kind) simulator which models mixtures of legacy and autonomous mainline rail operations. This is achieved by using linked blocks to virtually superimpose occupancy information on two identical length tracks, one operating purely legacy trains and the other purely autonomous trains. These combine to form a single track running mixed operations. There are some surprising findings: the introduction of autonomous trains is not beneficial to system operations at all parameter settings, and moreover, there is a question of fairness to legacy train operations that may be adversely affected.

Keywords: Autonomous, Legacy, Modelling & Simulation, Railway.

1 Introduction & Background

This paper explores how to simulate the introduction of Connected and/or Autonomous Trains (CATs) with existing Driver Operated and/or Guided trains (DOGs). Within the rail industry, there are a variety of software packages which simulate rail operations, such as OpenTrack (Huerlimann & Nash, 2017). However, although OpenTrack and others are able to model various levels of European Train Control Systems (ETCS) and moving blocks, they cannot model mixtures of different levels of ETCS on the same section of track. Hence, we have built a new train simulator from the ground up, to address this gap in extant capability.

In current rail operations, track is divided into sections known as *blocks*. To ensure safe separation, only one train is allowed in any one block at any given time. Therefore, block occupancy information needs to be conveyed to train drivers. This is achieved through trackside signalling or cab signalling, which provide movement authorisations (Pachl, 2020). Trackside signalling uses *aspects* to convey occupancy information at discrete points along the track, and depending on the number of aspects, governs the number of blocks the driver can (in effect) see ahead (Theeg & Vlasenko, 2020). Cab signalling delivers occupancy information directly to the driver, continuously in time. In effect, whether a train is a DOG or a CAT determines how much occupancy information is conveyed and the frequency at which it is delivered. This point is further explained in Section 2, which gives further detail on how we model CATs.

To ensure safe separation, any block-based simulator has to consider how a train reserves blocks on its braking path. In our simulator, this is achieved through a *watch-point* (see Fig. 1). When the watch-point progresses into a new block, it receives the new block's occupancy information, hence mimicking trackside signals (receiving information at discrete points). If the block is free, it is reserved and the train proceeds, whereas it must begin braking if the block is already occupied or reserved by another train. The key trick in this paper is to generalise this principle to model mixed DOG and CAT operations.

The paper is organised as follows. Firstly, Section 2 explains how virtual and linked blocks are employed to develop our mixed legacy-autonomous rail simulator. Section 3 then describes a highly simplified track simulation setup which we use for an initial inspection of mixed running performance. Section 4 presents and analyses the simulation results. Lastly, Section 5 provides

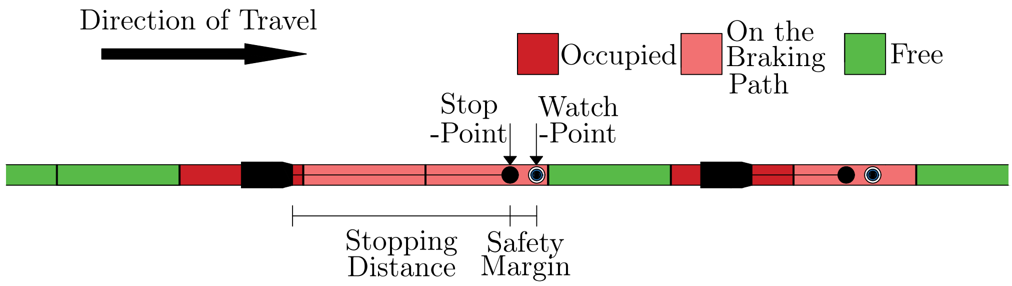

Figure 1: Simulation concepts. The train's watch-point (eye symbol), stop-point (black circle), stopping distance (horizontal black line), and the block states differentiated by colour. Blocks on the braking path are reserved so that other trains may not enter them.

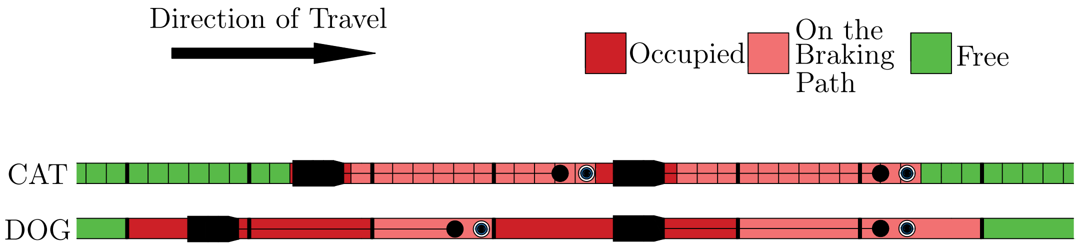

Figure 2: DOGs and CATs simulation setup. Both use fixed blocks, but CATs operate on shorter blocks than DOGs. Here six CAT blocks fit into a single DOG block. CATs can thus operate at reduced headway.

a wider discussion of linked-block principles and the simulation findings, and Section 6 describes conclusions and future work plans.

2 Simulation Principles For Mixed Operations

This section explains the method we use to model mixed legacy-autonomous operations. As explained above, DOGs operate using fixed blocks, where occupancy information is conveyed at discrete points along the track via trackside signals.

In contrast, it is assumed that CATs can directly and continuously relay their speeds and positions to each other and this data is used to establish a buffer zone ahead of each CAT (the *moving block*) whose length equals the stopping distance plus a safety margin. The buffer zone moves along the track with the CAT and if it comes up against an obstacle, the CAT brakes to ensure safe separation (Pachl, 2020).

In our simulator, we model the CAT's buffer zone as a union of *virtual* fixed blocks, of shorter lengths than used for the DOGs' blocks. Due to the shorter block lengths, the CAT receives new occupancy information at a high temporal frequency and high spatial precision which approximates an update which is continuous in space and time. See Fig. 2. CATs can thus operate at reduced headway when following other CATs.

To model mixed running, we use two tracks of identical lengths, where one track operates purely DOGs and the other operates purely CATs with shorter virtual blocks. These tracks are *linked* through a *lookup* process, where one track's occupancy information is virtually superimposed onto the other and vice versa. See Figs. 3& 4.

Fig. 3 shows a CAT following a DOG. Each virtual block on the CAT's track performs a lookup on the corresponding block of the DOG's track. The DOG occupies / reserves three blocks (Fig. 3(a)). Each of these DOG blocks is inspected by six virtual blocks on the CAT track (Fig. 3(b)), which are thus effectively considered reserved (Fig. 3(c)). The CAT will commence braking when its watch-point reaches the first of these reserved virtual blocks. See Fig. 3(d). Here the CAT may continue for another seven virtual blocks before it commences braking. Note that the minimum

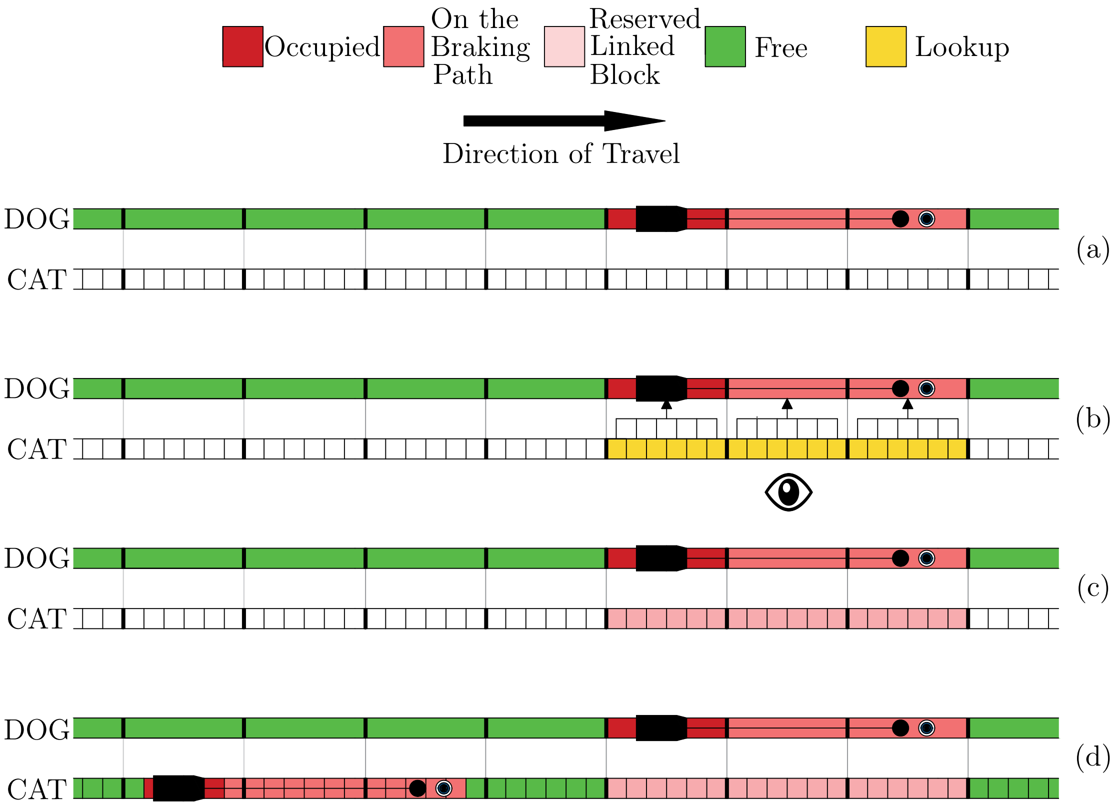

Figure 3: CAT follows DOG. Through the use of linked blocks and a lookup process (eye symbol, yellow blocks, and arrows) the occupancy of the corresponding blocks on the DOG's track are virtually superimposed onto the CAT's track.

headway is greater than if a CAT were following a CAT, because of the way that DOG blocks coarsely reserve corresponding virtual blocks irrespective of the continuous position of the DOG (which is not communicated and is thus unknown).

Fig. 4 shows a DOG following a CAT. Each DOG block performs a lookup on the six corresponding virtual blocks of the CAT track, and is marked occupied or reserved if any of those virtual blocks are occupied or reserved. As for CAT following DOG, the minimum headway is greater than for CAT following CAT, now because the following DOG is not able to receive the fine-scale position information communicated by the CAT.

3 Simulator Setup

Using the virtual and linked block principles introduced above and the architectural framework described by Morey et al. (2023), a simple time-stepping simulation has been developed to examine the dynamics of mixed legacy-autonomous operations at a converging track section.

The simulation follows many of the classical theoretical studies in car-following modelling (e.g., Bando et al. (1995)) where a set of identical trains repeatedly circulates around a *ring track*, which consists of identical blocks. Here the track setup consists of two ring track sections of equal length, which have an overlapping joint section, see Fig. 5. Each ring operates purely DOGs (section S1) or purely CATs (section S2), and their joint section (section S3) operates mixed running through the addition of linked virtual blocks (section S4). This simple layout induces the mixing, reordering, and self-organising of different train types, and therefore enables a first examination of some of the possible complex dynamics that might result from mixed operations.

In each simulation, the number of trains is prescribed and conserved over time — so (in effect) we prescribe the train density as an input parameter, and we examine the traffic patterns and

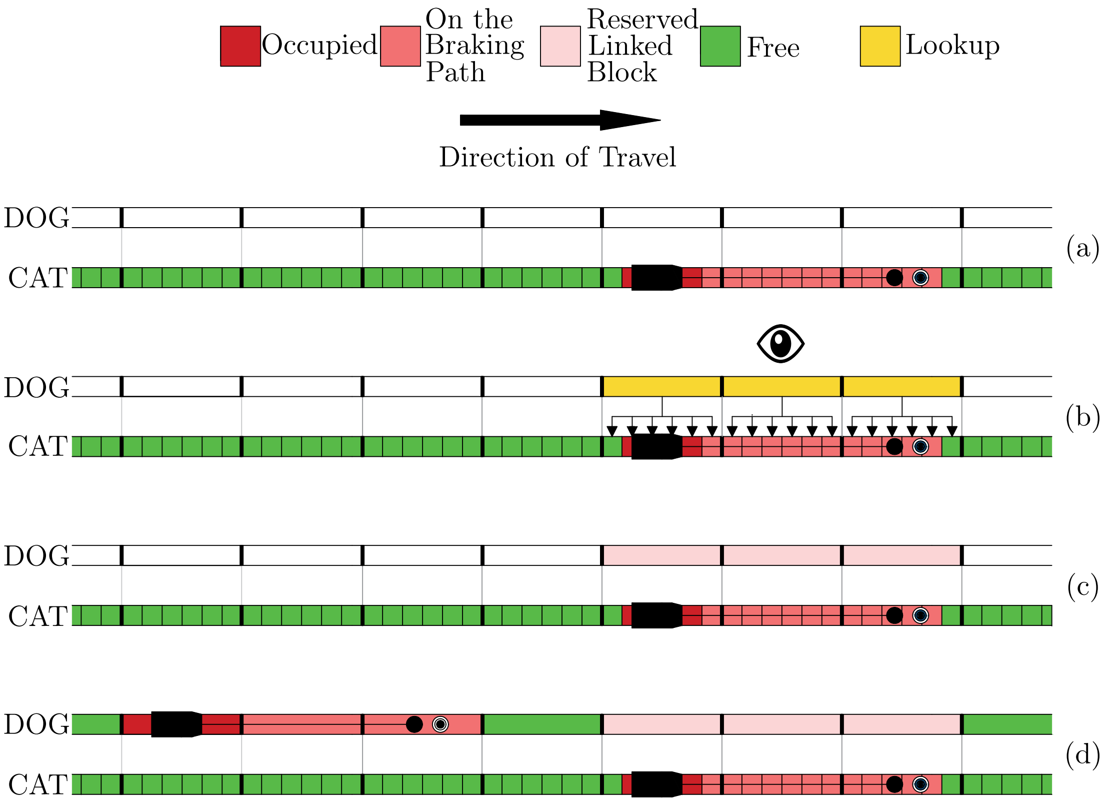

Figure 4: DOG follows CAT. Compare Fig. 3, where CAT follows DOG. The lookup process is now used to superimpose the occupancy of the blocks on the CAT's track onto the DOG's track.

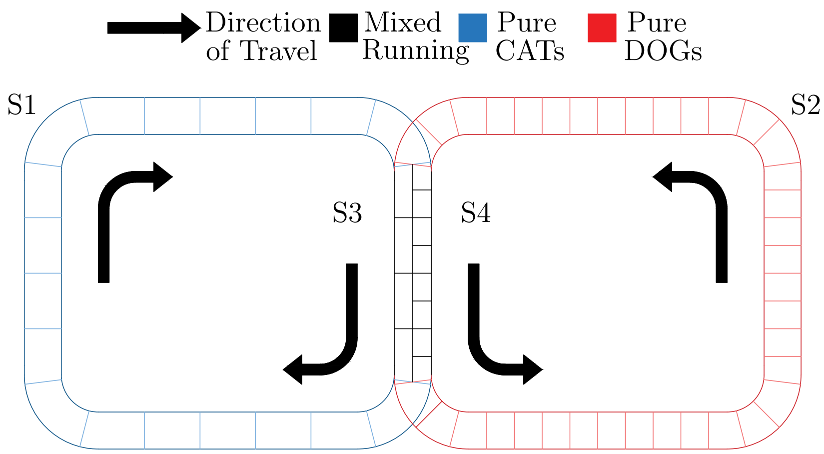

Figure 5: Simulator track layout. Two ring tracks overlap to form a joint section (S3 & S4, black) which operates mixed running. Sections S1 (blue) and S3 have pure DOG operations, whereas S2 (red) and S4 have pure CAT operations. Schematic only — lengths of sections not to proportion shown here, and we employ virtual blocks that are ten times shorter than DOG blocks.

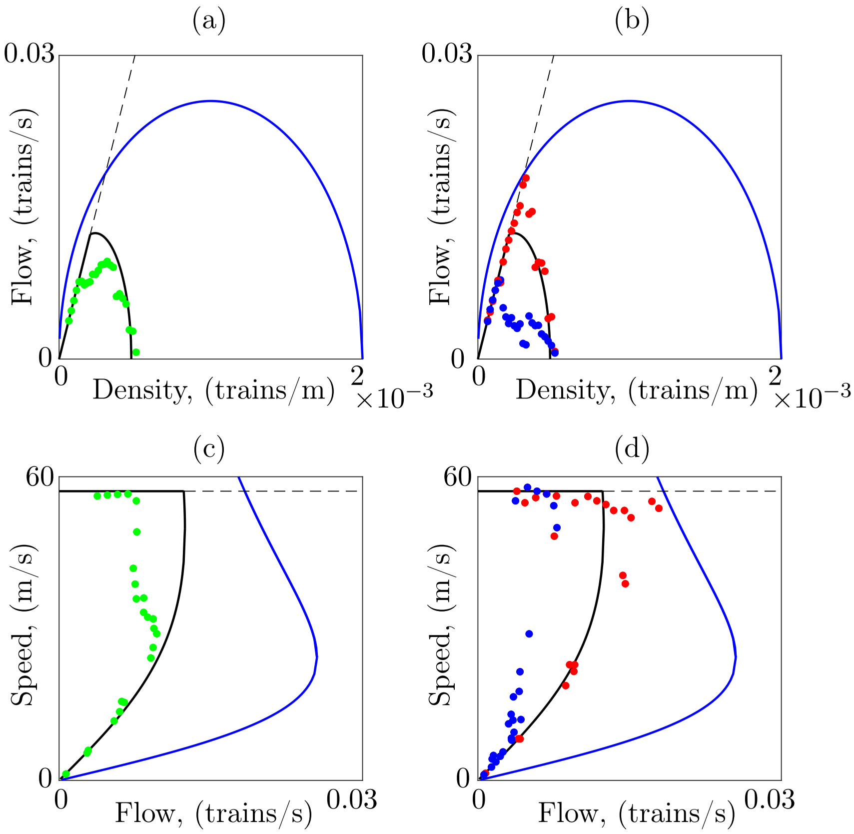

Figure 6: Fundamental Diagrams (FDs) for mixed mainline rail traffic. The black and blue lines show theoretical predictions for pure DOG and CAT operations respectively. Dots show mixed running simulation results: green (mixed population average), blue (DOG population average), and red (CAT population average). (a & b) flow-density graphs and (c & d) speed-flow graphs.

performance metrics (e.g., the time-average speed and the flow) that result. Our simulations begin with all trains at rest randomly spaced around their respective rings. For the simulations shown here, for simplicity, we prescribe an equal number of CATs and DOGs, however, of course, the penetration rate of CATs may also be varied as an input parameter.

The parameters used in the simulations are, see Morey et al. (2022a): trains' acceleration $0.4\,\mathrm{ms}^{-2}$; braking rate $0.65\,\mathrm{ms}^{-2}$; maximum speed $60\,\mathrm{ms}^{-1}$; train length 400 m; number of blocks in sections, S1 & S3 20; S2 & S4 200; DOG block length 1600 m; virtual (CAT) block length 160 m. Thus each ring track is 64km long and the joint section is 32km long. We varied the number of trains from 4 to 27 of each type, yielding densities from 1.60×10^{-5} trains/m to 5.32×10^{-4} trains/m.

4 Simulation Results

From simulator output, we derived fundamental diagrams (FDs) that relate density, flow, and speed averaged over the entire network. See Fig. 6. Results are compared with theoretical bounds derived by Morey et al. (2022a) and Morey et al. (2022b), which suggest that pure CAT operations might potentially have double the capacity (maximum flow) of pure DOG operations.

Note in our network that capacity is constrained by the mixed running section which is in essence a bottleneck and generally, flow falls short of even the pure-DOG bound, because there is interrupted flow induced by the point where sections S1 and S2 merge, which becomes quite acute at intermediate density ranges.

However, Figs. 6(b&d) show that the DOG and CAT populations have quite different experiences. Whereas the CAT population develops flow rates that exceed the pure-DOG bound, and even

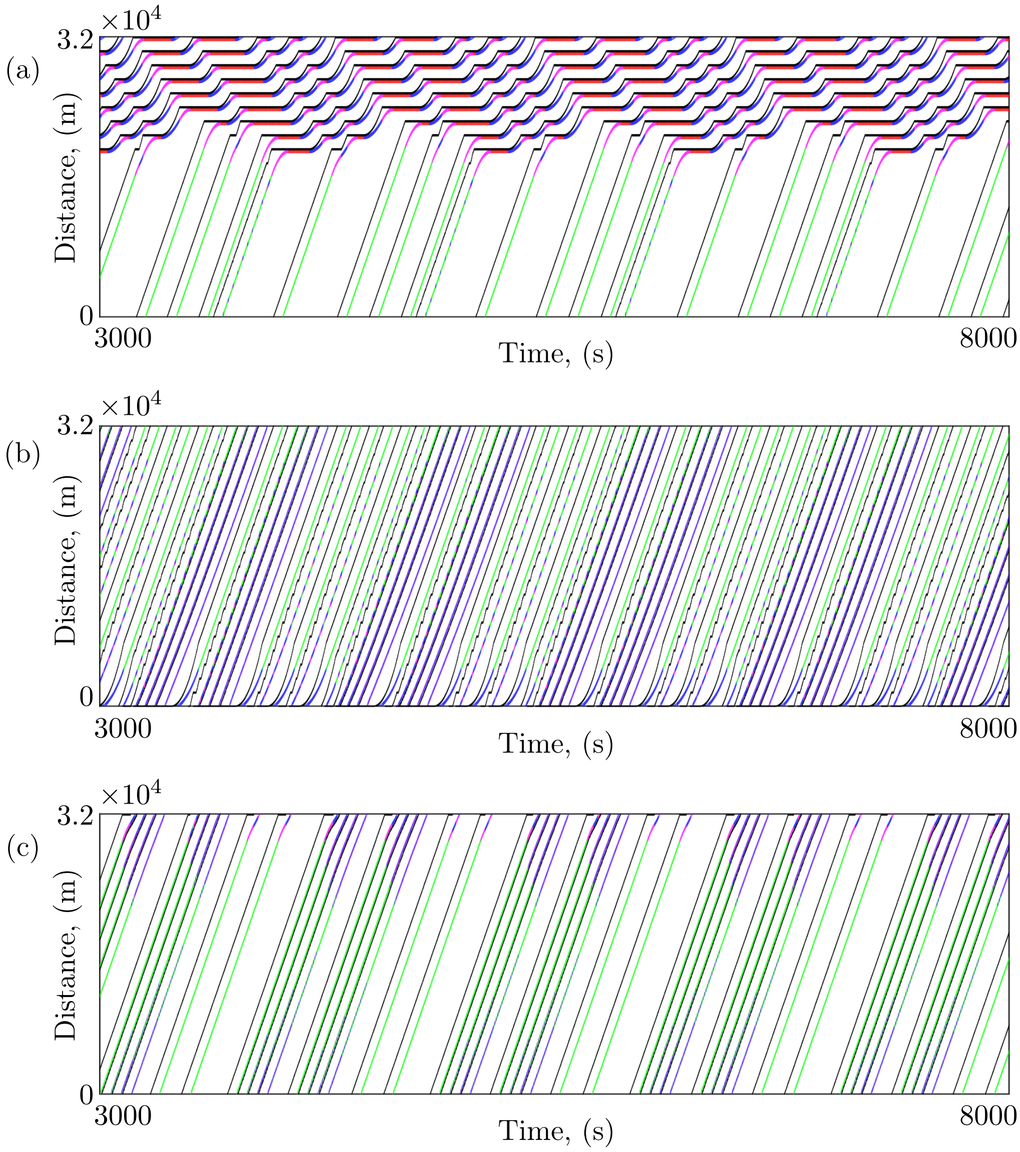

Figure 7: Trajectory plots showing mixed running of 10 DOGs and 10 CATs. Colour represents each train's state: green (at goal speed), magenta (braking), red (halted), and blue (accelerating). Sections (a) S1, (b) S3 & S4, (c) S2.

approach the pure-CAT bound at lower density ranges, the DOG population suffers a dramatic reduction in speed and flow, which may be explained by the exemplar trajectory plots shown in Fig. 7).

Over time, the CATs tend to self-organise into platoons, see Fig. 7(c) which are never subsequently broken up by the DOGs. This is because the gaps between consecutive CATs are so short that a DOG approaching the end of section S1 must wait for the CAT platoon pass before it can join the mixed running section. In consequence, DOGs tend to form queues at the end of section S1, see Fig. 7(a), which can only be discharged in the gaps between the CAT platoons. Therefore DOGs also tend to form platoons over time, which fit into the gaps between the CAT platoons on the mixed running section.

The overall effect is unfair. Without additional control policies, the CATs achieve their enhanced throughput entirely at the expense of the DOGs.

5 Discussion

The use of virtual and linked blocks that we have demonstrated here seems to be quite an elegant solution to extend existing fixed-block simulators to deal with mixed running scenarios. In fact, the trick can also be used as a simple device to help simulate other network features, e.g.: 1. Two-way single-track sections (by a union of two parallel one-way sections where each block in one direction watches all of the blocks in the opposing direction — thus a train is prevented from entering the section if any block on it is occupied or reserved by a train travelling in the opposite direction); 2. More complicated mixtures of future train types, perhaps with different communication rates/latencies and/or braking capabilities, and thus different types of moving zones; 3. Complex routing patterns where an individual train might choose different paths at a diverge depending on previous history (without that history needing to be stored as a property of the train in question).

Clearly, the results shown here are only an initial analysis of the simplest possible network which allows mixed running with the potential for the ordering of CATs and DOGs to change over time. Of course, in the traffic flow theory community, there has been much interest in macroscopic/network fundamental diagrams that describe urban road network dynamics, and some recent papers have begun to explore these concepts in rail networks, e.g., Corman et al. (2019), Farhi et al. (2017), and Cuniasse et al. (2015). We have designed a sequence of test networks of increasing complexity and the immediate goal is to determine whether they display similar results to those we found here: i.e., that potential capacity gains might be quite unfairly distributed between CATs and DOGs.

A further question concerns the pathway to autonomy and the network performance as the penetration rate (i.e., proportion) p of CATs is increased slowly from zero. The anticipated benefits result from CAT-CAT leader-follower pairs operating at reduced headway. Without platooning or self organisation, the proportion of such pairs scales like p^2 — so the benefits might initially be very modest, to say the least. However, how this plays out in more complex networks with many merges and diverges remains to be seen.

6 Conclusions and future work

In this paper, we have described an elegant approach to simulate mixed legacy-autonomous rail operations. We have achieved this through the use of virtual blocks and a lookup process to link occupancy information. This technique provides the basic mechanism to simulate a wide variety of future rail scenarios. We have demonstrated exemplar results from a simple stylised network. The findings are surprising: it seems that the introduction of Connected and/or Autonomous Trains (CATs) does not necessarily increase capacity, and potentially, the system self organises so that high flow rates for CATs are achieved at the expense of lower flow rates for legacy trains.

Future work should of course involve experimenting with a wider range of track setups, incorporating more realism (e.g., station stops, complex routing) and more advanced control rules (e.g., prioritisation at track merges), and investigating varying penetration rates of CATs.

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