Speed Regulation of Model Railway Controllers: A Comparison of Technologies

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***Abstract*—In this manuscript the relative performance of a variety of model railway controllers is tested in real-world conditions. Model railway locomotives use permanent-magnet, brushed, dc motors. Series resistance in armature windings, brushes and the rail, and magnetic losses in the armature all contribute to non-ideal operation. This manifests most annoyingly as moment by moment variation in locomotive speed. The effect is more noticeable in smaller scales. It is more noticeable on vintage models. Speed regulation performance is compared for a number different controllers using different technologies. Some interesting conclusions are drawn.**

***Index Terms*—Brushed dc motors, speed regulation, control, vintage models.**

I. INTRODUCTION

Vintage model trains sell for relatively large sums. Many of them are charming historical pieces. In particular the relatively unrealistic models originally made in the middle of the 20th century have a surrealist warmth.

Vintage trains have a strange habit of slowing down on curves and speeding up on straights to a much greater extent than modern models. When filmed, they are usually captured travelling at enormous scale speeds, because the speed-variation effect is more jarring at lower speeds, plus many old models will simply not travel reliably at low speed.

The problem is not confined to vintage models. The smaller scales preferred in many countries in the 21^{st} century for their compact format also have difficulty holding the constant modest speed observed on many modern railroads. At 160 to 1, N-scale models running on nominal 12-volt systems present a challenge.

II. THE CONTROLLERS

In this manuscript, we will compare the performance of 8 controllers. Four of these are commercial products, and four are constructed to exemplify various technologies.

One controller is a “Safety Minor” manufactured circa the 1960s by Hammant & Morgan. This particular model was selected because it is an example of an autotransformer design that attempts to produce a fixed average voltage with minimum series resistance, and because the Hammant & Morgan models were perhaps the best of their age. The output resistance is not as small as one might imagine, because the rectifiers at the time were selenium-based. Nevertheless, this represents a “good” vintage controller that is well remembered. [1]

Also included is an “HM 2000”. This is an electronic controller that was sold by Hornby after it had taken over H&M. It is a thyristor (silicon controller rectifier) design that operates by phase control. The half cycles of a rectified ac waveform are turned on at varying times during the half cycle to achieve variable voltage/power delivery, after the fashion of a classic triac-based light dimmer. This technique offers the possibility of sensing locomotive back EMF (the voltage visible on the motor when current is not flowing), allowing for feedback to adjust phase in response to sensed speed. The HM 2000 has transistor circuitry to do exactly this.

The third commercial controller is a Gaugemaster-style circuit.[1] This is also a phase-control type, with a thyristor-UJT topology. [2] This particular controller has an excellent reputation for low-speed operation.

From the American stable we include an MRC260 from Model Rectifier Corporation. MRC started making controllers after the second world war, and still exists today. [3] This controller delivers a complicated waveform but appears to have no feedback.

The intention was to include a Hornby HM3000, despite their rarity and weak reputation. One was purchased, but it has got stuck overseas owing to Covid-based border closures. This may be fixed in an update in the future.

Next a simple opamp square-wave controller circuit with feedback is included. It is designed to provide locomotive speed control by sensing EMF in the off part of the duty cycle. Able to operate on ac, rectified dc, or filtered dc, it is referred to as a universal Feedback Controller, UFC. The circuit is shown in figure 1.

Next a microcontroller-based pulse-width modulation is presented. It does essentially the same job as the UFC, but has programmable gain and various other control options. [4]

Next a version of negative-resistance controller is tested. It uses the ideas in [5], but absent the automatic resistance adjustment, because that does not operate reliably in the case of toys relying on contact through wheels on irregular and

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[1] Not having one of the 1980s-vintage units available at the time this work was carried out, an identical copy was constructed in house.

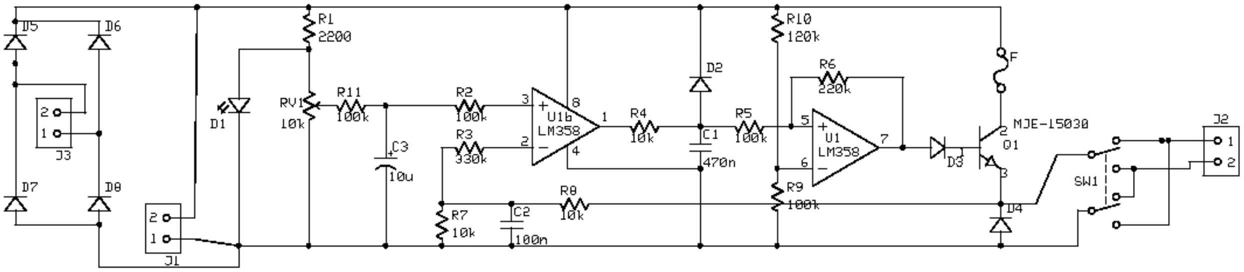

Fig. 1. Circuit of the UFC feedback controller.

dirty track, such as model trains. This design has a fixed small negative resistance, the idea being that it acts as closely as possible to a "perfect voltage source" at the track.

The last controller is a radical design using a flyback converter in a pulse-width modulation design. This controller uses the flyback design to address contact issues, in a similar fashion to the Gaugemaster HF1 electronic track cleaner. However, this strategy then demands that it apply proportional-integral feedback control to produce a connection between loco speed and throttle knob position. [6]

III. The Test Setup

Figure 2 shows an oval of N-scale track on a wooden base 80cm long. The oval is constructed using Japanese origin track with 10-inch nominal radius and 11-inch nominal straight sections inserted in the sides. This gives a total length of 2.15 metres, equivalent to a length of 345m at a scale of 160:1. The wooden base is inclined at an angle of three degrees. A locomotive running on the track sees an incline on one side, and a descent on the other. This arrangement has been chosen because it is possible to time a train climbing on one side and descending on the other, and to calculate the discrepancy in speed on each side. This can be expressed as an error percentage using

$$\epsilon = 100 \times \frac{t_{up} - t_{down}}{(t_{up} + t_{down})/2} \tag{1}$$

where t_{up} is the duration of the climb, and t_{down} that of the descent. The error percentage ϵ represents the discrepancy between the two speeds that might in reality be nearly equal.[2]

Two locomotives were tested. Both were deliberately chosen as examples of "difficult" locomotives. The first is an Italian-made, plastic-body, Lima brand diesel, two of whose four axles are dummies, that is they are neither driven nor do they pick up power. The locomotive is essentially an 0-4-0 configuration, not a 4-4. This locomotive weighs 47 grams and is tested carrying a weighted wagon adding 20 grams. It has a 3-pole motor with straight poles. The second locomotive is a Graham Farish 0-6-0 diesel. It has a cast metal body, so that it weighs 57.8 grams, and is also tested carrying a 20g wagon. It also has a 3-pole motor with straight poles. The additional weight and more recent construction ought to make this locomotive slightly better, but it lacks the 5-pole motor of more recent designs.

The track sensors were adjusted to respond to a white patch pained on the underneath of both locomotives, not other parts of the trains.

The track was initially tested while flat, to check for any bias arising from track irregularities, lack of precise level, block sensor positioning, etc. On the level, both trains registered an average of 0.6% discrepancy, travelling in either direction around the loop. This is considered small enough to ignore.

Trials were carried out at various speeds. Discrepancy results appeared similar, except where the train was moving so slowly that the controller experienced difficulty keeping the train moving at all. Thus all tests were carried out with a top-to-bottom transit time small enough to avoid such issues. More will be said about speed capability later.

IV. Results

Figure 3 shows the speed errors for both locomotives with each controller. The NRTC controller shows what would ideally be expected by the manufacturer of a locomotive, that is the "constant voltage response". This is about 35% for both of these locomotives. Anything more than about 20% is visible quickly to an observer as "not prototypical".

The UFC, P684, and Plasma controllers represent the "aggressive" feedback school. These all bring the error down to a low value in both locomotives, well below what is usually visible. Surprisingly, performance with the Lima is superior to that of the Farish in these controllers. This may be a function of a larger back EMF, a consequence of the motor design.

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[2] The ascent and descent times in a real world situation will be close to equal because the train has considerable mass, and because the driver tends to correct the throttle, which is practical in the timescale of a full-size train but not on a scale model.

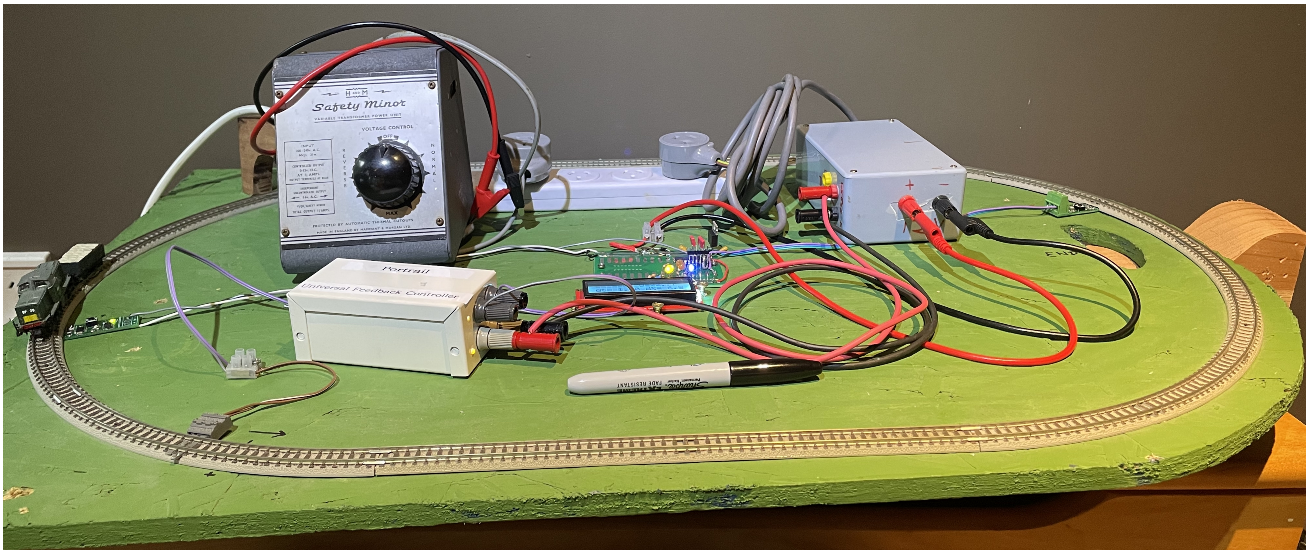

Fig. 2. Photograph of the inclined test track. Electronics with small liquid crystal display in the middle takes signals from two infrared block detectors and computes locomotive speed. One of the detectors is visible just to the right of the locomotive.

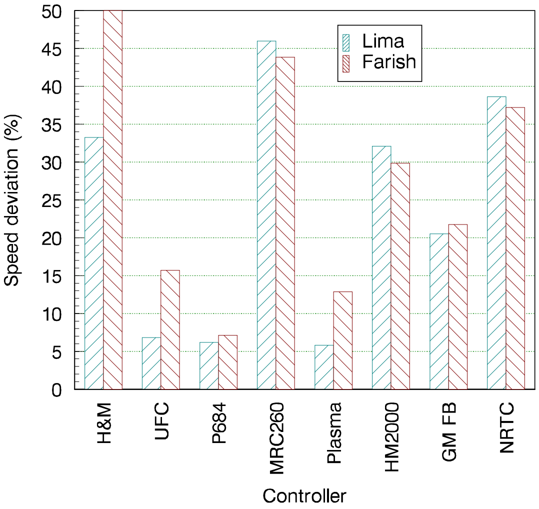

Fig. 3. Discrepancy in speed of a locomotive climbing and descending opposite sides of an oval of track tilted at 3 degrees.

The HM2000 has disappointing performance. We assume it has relatively low loop gain.[3] There is no obvious reason for this choice. The feedback-type Gaugemaster brings the error down to around what is really an acceptable level.

The difference between the H&M and the NRTC is surprising. Neither performed well. The H&M performed better with one locomotive and significantly worse with the other, compared with the NRTC, which was relatively consistent. The Safety Minor has a measured output resistance of around 3Ω, and the NRTC a value of -1Ω, both measured at the enclosure terminals. Interconnection resistance is less than an Ohm. Locomotives have varying apparent series resistance, a result of brush contact resistance, pickup-and-wheel contact resistance, and winding series resistance. N-scale locomotives typically have series resistance in operation of a few tens of Ohms on average. However, the H&M and the NRTC differ in that the type of dc current they supply. The H&M is unfiltered, so it has a pulsing waveform. The difference is suspected to be an interaction between the locomotive and supply impedances, but no clear explanation presents itself.

Figures 4 and 5 show the ranges of readings used to derive the average values shown in the first figure. The error bars give a visual impression of the standard deviation inherent in each measurement. There is visible a weak trend for superior speed regulation to have reduced uncertainty, as one would expect; the feedback is not only compensating for grade, but equally for other disturbances. Such disturbances probably include mechanically-mediated and particle-induced drops in electrical conductivity and friction between moving parts.

A. Low Speed Capability

During these tests it became clear that the tilted track gave an excellent test of a controller's ability to achieve low-speed running. If the controller resulted in fragile control at low speed, the locomotive would stall on the uphill grade, race on the down, or momentarily stall. For each controller, the above measurements of speed discrepancy were made at the low end of the speeds each controller could support for each locomotive.

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[3] It should be acknowledged that the HM2000 is designed for use with OO-scale (1:76, quaintly referred to as "4mm to the foot") or HO-scale (1:87) models. These scales present fewer issues than N-scale (1:160) because they can afford larger motors.

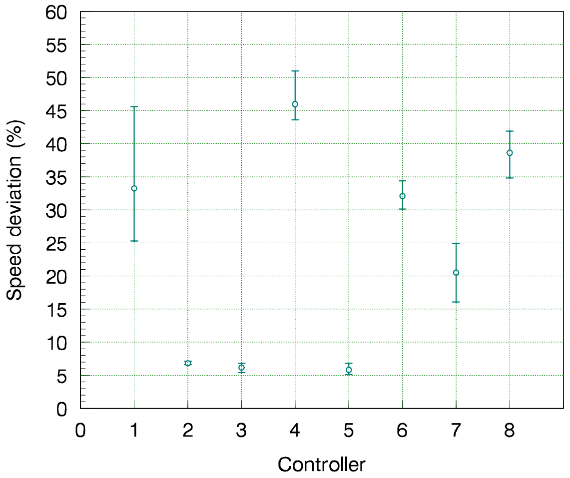


Fig. 4. Mean and error range in speed discrepancy measurements for the Lima locomotive.

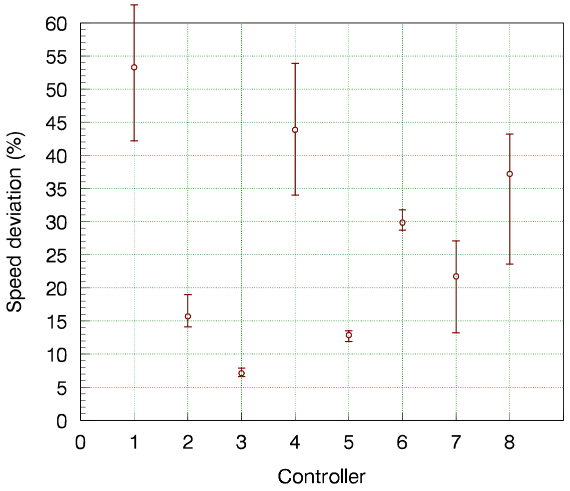


Fig. 5. Mean and error range in speed discrepancy measurements for the Farish locomotive.

The NRTC could achieve transits of about 15s with the Farish, and the same with the H&M Safety Minor and Gaugemaster. Any slower, and running became erratic or the locomotive stalled. To put this in perspective, the up and down transits add up to a round-trip time of 30 seconds representing a scale speed of just over 40 kilometres per hour, which is *not* slow running at all.

The UFC had no difficulty getting to 25s, and the P684 could manage about 32s, the Plasma made 36s easily and could manage 50 seconds (each way!) with careful adjustment. At the disappointing end, the HM2000 could barely make 25s although the performance was reduced, and with the Lima

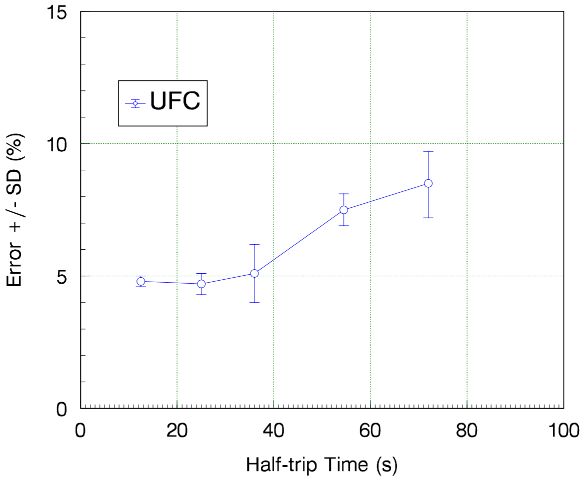


Fig. 6. Mean error and the error range in speed discrepancy measurements for the Lima locomotive for varying speeds measured as a function of the half-round-trip time, that is with slower speeds to the right.

locomotive it would not manage 10s transits without erratic performance. The MRC could not get much slower than 10s with the Lima, although it was fine at 15s on the Farish.

Roughly speaking, the feedback designs are vastly better at low-speed work. This is something afficianados have known for a long time.

B. Speed & Repeatability

The above suggests that the capacity of a controller to run a train slowly might be assessed by examining the variation in error as a function of trip time. The Lima locomotive was used with the UFC controller described in figure 1 to investigate this question. Results are shown in figure 6. All data represent the result of at least 20 measurements.

There is a general rise in the percentage error as the locomotive moves more slowly, but it does not show a clear increasing function with decreasing speed. There is a rise in the standard deviation of the measurements, but it is neither striking nor monotonic. The conclusion is that there is no obvious function, and statistical variation is not a sensitive way to measure controller performance. A given controller works as well as it works down to a minimum speed, below which stiction halts the locomotive.

C. Variation with Locomotive

It was asserted above that this investigation used locomotives selected to be more challenging to control. To demonstrate this, measurements were carried out using the H&M Safety Minor across a selection of locomotives of various types and brands. Five are of known provenance. A brand

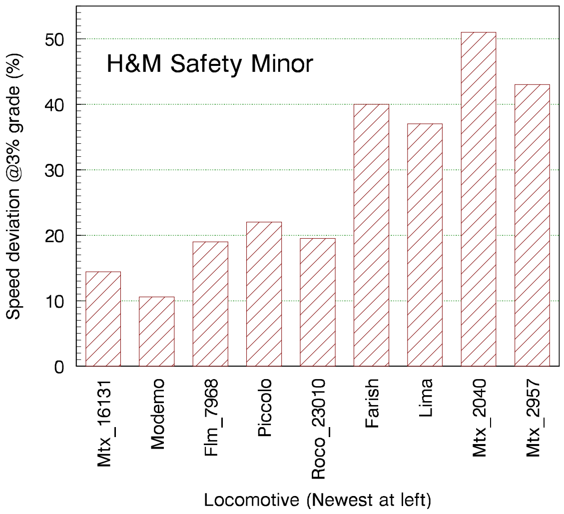


Fig. 7. Variation in error percentage for a variety of locomotives. The five locomotives at the left are in order of age, starting with a 2020 model. Older locomotives are of uncertain age, believed to be greater than 20 years, in no particular order on the right.

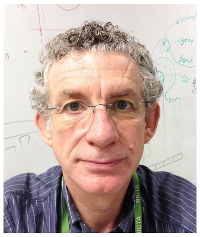
new Minitrix 16131 4-4 diesel fitted with DCC is the newest. Next is a Modemo NT147 Japanese tram of 4-4 configuration but with only one bogey driven. This is about 3 years old. It weighs much less than the other units tested, and comes without couplings so was tested without the wagon. Next a Fleischmann 7968 track cleaner about 6 years old, then a Fleischmann Piccolo 0-4-0 steam shunting locomotive about 16 years old. In the known group the last is a Roco 23010 tramcar, known to be at least 21 years old. The remaining locomotives were bought second-hand and are of unknown history, but are chosen because they seem decades old.

The improvement over time is clear from the data in figure 7. The Modemo Japanese tram, weighing only 32.4g, has an advantage and performs relatively well. The Farish and Lima locomotives used in the first part of this study are indeed amongst the worst performers.

V. CONCLUSION

The large variation between controllers and locomotives was frankly surprising. Also surprising was the relative weakness of flagship feedback controllers epitomised by the HM 2000.

The extent to which mainstream controller manufacturers have failed to harness feedback in their designs suggests that they do not take the design of railway controllers seriously. The advice would be to employ or contract a professional engineer with experience in feedback control.



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