Exploring the Complex Relationship Between Railroad Infrastructure, Operating Constraints, Maximum Speeds, and Public Schedules

A. Lu*, J. Kozlowski, S. Fahey, and S. Whitman

* Corresponding Author

Alex Lu**
ADD-Strategic Operating Initiatives and Field Administration, Metro-North Railroad
P.O. Box 684, Ossining, N.Y. 10562-0684
Tel: (978) 387-1475 Email: me@lexciestuff.net
** formerly Train Scheduling Manager, ScotRail Railways Ltd., Glasgow, Scotland.

Janek Kozlowski
DD-Operating Capital Projects—New York State, Metro-North Railroad
420 Lexington Ave., Floor 10, New York, N.Y. 10170-1099
Tel: (212) 499-4470 Email: Kozlowski@mnr.org

Sean Fahey
ADD-Operations Analysis & Logistics, Metro-North Railroad
420 Lexington Ave., Floor 10, New York, N.Y. 10170-1099
Tel: (212) 499-4397 Email: Fahey@mnr.org

Shaun Whitman
Rules Examiner, Metro-North Railroad
420 Lexington Ave., Floor 10, New York, N.Y. 10170-1099
Tel: (212) 499-6770 Email: Whitman@mnr.org

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ABSTRACT

Outside the railroad industry, tremendous temptations exist to treat passenger trip times as performance measures or the industry’s health yardstick. However, many factors not known or well-understood by casual observers affect trip times—indeed, some are recognized techniques utilized by infrastructure owners to deliver journey time reductions. Factors triggering running time modifications include: track design, maintenance, layout, special work; infrastructure (structures, signal, power, grade crossings); cant deficiency, tractive effort, braking rates; rules, operating practices, ongoing projects; timetable speeds, and finally schedulers’ decisions on train performance modelling, en-route adjustments, and dwell times. Historical operating documents issued by railroads can be used to reconstruct more specific understanding of what events are associated with which trip time changes, but perishable nature of these ephemeral documents make it difficult. Because some information was never written down, rationale for certain modifications maybe unknowable. At best public timetables offer a general sense of where service offerings were trending; from them it is impossible to know what was really happening. Some opposing industry trends actually give rise to similar schedule impacts, e.g. deferred track maintenance and track rehabilitation both lead to lengthened journey times. Applying forensic analysis methodology to Penn Central’s Mohawk/Buffalo divisions revealed some time degradations can be correlated to specific events associated with downgraded infrastructure and vehicle issues, but overall long-term changes were balanced. Case study of Metro-North’s New Haven Line revealed new stations, necessary safety modifications, increasing congestion, and temporary construction delays all contributed to recent timing changes. To maximize system performance, operators must balance trip-time, capacity, and reliability subject to an overarching constraint of safe operations.
INTRODUCTION

This paper serves three basic purposes:

1. Explains for non-rail-industry audiences many factors behind determination of published public timetable trip times between station pairs on conventional railroad networks.
2. Show that changes in public timetable running times alone is insufficient evidence or information to infer or explain happenings in rail industry investment, maintenance management, infrastructure stewardship, etc.
3. Provide ideas on how operating documents (where available) are utilized to reconstruct reasons for advertised journey time changes and feel the industry’s pulse, while also demonstrating that it might not tell the entire story.

It is divided into four major sections:

1. Technical and operational factors that affect running times
2. Operating documents that describe these factors
3. Methods for constructing a schedule that properly accounts for them
4. Case studies in forensic schedule analysis:
   (a) Penn Central’s Mohawk-Buffalo Divisions (1956~2010): utilizing only operating documents and modelling methodologies
   (b) Metro-North’s New Haven Line (2009~2016): utilizing institutional knowledge of section schedulers and published sources

MOTIVATION

Standard methodologies for rail transit planners and schedulers to create service specifications, establish public timetables, create vehicle assignments, traincrew diagrams (pairings), routing plans, and terminal docking plans are well-understood and documented (e.g. (1-3)). However, running times between stations are sometimes seen as empirical observations obtained from operational experience, running time checks, or track occupancy records. Although specialized software is available (e.g. (4,5)) to estimate impacts of numerous factors on runtimes, delays, and network congestion (e.g. (6)), considerations affecting published runtimes are less familiar to outsider stakeholders. Indeed, recent work (7) attempted to infer what was generally happening in the rail industry through retrospective inspection of public timetables. Some outside pressure groups (8), trade press articles (9), and even industry strategy documents (10) cite trip times as a performance measure or goal.

Advertised times, even in aggregate, should not be seen as performance yardsticks to measure general state of passenger rail. Relationship between system performance capability and published journey times is many-to-one where different confluences of multiple events (some good, some bad) could all result in similar runtime improvements or degradations. Just as it is widely acknowledged that many factors independently cause reduction in on-time performance or line capacity (trains per hour, tph), multiple reasons cause scheduled time modifications; indeed, some factors trade-off with one another. Maximizing on-time performance (11,12) or line capacity is not a reasonable long-term strategy—and good express train running times is only one of multiple factors indicating healthy and well-managed railway systems. The Railway Races on Anglo-Scottish grouse trains is one early such example (14), which ultimately ended tragically at Salisbury in 1906 when London & South Western Railway wrecked its premier overnight express with relentless emphasis on journey time.
Planners performing commuter rail feasibility studies (e.g. (15, 16)) are familiar with assumptions and existing conditions that must be defined prior to generating journey time estimates. Beyond infrastructure capabilities and specifications, medium-term operational considerations like track maintenance, train stopping patterns, and rostered equipment all impact advertised trip times. Short-term temporary speed restrictions (TSR), capacity-related delays, or dispatching considerations also add extra minutes, communicated to customers via supplemental schedules or special timetables.

**RAILROAD TRACK FACTORS**

Track geometry and technologies are fundamental to passenger train operations, ensuring safety at speed. Right-of-way curvature constraints and track design and maintenance parameters are translated to maximum authorized speeds (MAS)—highest speed at which one given train may operate on the given track segment at that specific time—which in turn directly affect published journey times.

*Track Geometry*

Figure 1(a) shows a typical Track Chart & Maintenance Program (17) excerpt from a major Northeastern railroad, showing constraints affecting passenger train runtimes. Diamonds above the track are mileposts (MPs). Design track geometry is shown at the bottom. Curve at MP 225 is ~0.3 miles long (horizontal scale measurement) and has degree of curvature 1°50”. Design superelevation on Tracks 2&1 is 4”. Assuming track geometry is properly maintained within design limits, allowable speeds are given by formulae in 49 CFR 213.329 (Appendix A).

When contemplating new track construction, track geometry is rarely known before right-of-way design. However, constraining curve radius can be approximated by inspecting aerial photographs or maps. Best-case curve could be sketched out (Figure 1(b)), curve radius measured, then converted to best-possible geometry assumption. (curve radius ≈ 5,730 feet ÷ degrees.) A common misconception is that if track geometry is legal at certain speeds, services could operate at that speed. Track speed is the first step in figuring out MAS; many other factors can result in MAS being revised downwards (rarely, upwards). Track speeds provide a lower bound for runtime.

*Track Maintenance*

Economic factors like intended traffic, and labor/material costs drive railroad choices of track maintenance levels. FRA’s “class of track” designation describes maximum permissible deviation from design geometry in parameters like gauge, alinement, and crosslevel. Whenever track inspectors discover deviations approaching FRA limits, maintenance gangs must be called to restore track profile.

Track class is an additional constraint over-and-above design geometry. Although a curve geometry might be designed for 75 mph, if track is maintained only to FRA Class 3 standards, passenger trains would be limited to 60 mph. Maintaining to Class 3 standards means, amongst other items, track gauge must be kept between 4’8” and 4’9¾” (18). To understand if track maintenance constraints are contributory to lengthening journey times, we can check if FRA track class was downgraded. Some railroads’ track charts report this information (Figure 1(a)).

*Special Trackwork*

Taking diverging routes through switches and crossings usually requires lower speeds. In North America this is typically shown as a signal speed. Once designed, switch sizes are not normally changed, e.g. No.20 turnouts have a 45 mph MAS.
Three situations arise where turnout speeds do change: (1) in track rationalization or normal switch
replacement, if space constraints or parts availability dictates, turnouts might be replaced with smaller
ones, e.g. No.20 replaced with No.15, with MAS reducing to 30 mph; (2) for speed improvements,
straight points may be replaced with curved points, e.g. “curved” No.20 are good for 60 mph while
occupying the same footprint; (3) turnouts improperly adjusted, worn, or having incorrect geometry
results in TSRs. Advertized running times are affected in each case.

Special trackwork layouts affect timing in less obvious ways. Removal of critical switches or wyes
result in trains making reverse moves to access platform areas or major terminals, adding several
minutes. Some railroads eliminated maintenance-heavy switch diamond by replacing standard junctions
with single-leads (Figure 1(c)), preserving mainline MAS but requiring diverging moves at lower
speeds. Single-lead junctions effectively introduce short single-track segments, additional delays occur
when two opposing branch trains need to access the mainline simultaneously.

**INFRASTRUCTURE CONSIDERATIONS OTHER THAN TRACK**

Non-track infrastructure components impact MAS (and triptime capabilities.) Normally, designs
maximize latent achievable right-of-way speeds (limited by curvature and terrain). As railroads move
through rebuild cycles, components become MAS constraints in some situations.

**Structures**

Dynamic forces exerted by moving trains on structures are related to equipment axle weights and train
speeds. When installed, designs generally support intended maximum load (based on Cooper rating—
representation of two typical locomotives and its train) at prevailing line speeds. Situations resulting in
structural MAS constraints include: (1) over time, degraded structures are ‘de-rated,’ having their
dynamic loads reduced to maintain safety due to compromised members; (2) vehicle weights may
increase, resulting in higher loads, thus permissible speeds are reduced to compensate; (3) area linespeed
increased due to civil improvements, but a bridge remained qualified only for original speed. Industry
references (19,20) on relationships between bridge ratings and speeds are available.

**Signal Braking Distances**

Standard signalling textbooks (21) or railroad documentation (22) show braking curves for computing
minimum signal spacing from design variables like entry speed, vehicle characteristics, number of signal
system aspects, and required capacity (minimum permissible headway, tph). Lines are initially equipped
with track circuits and signal blocks at correct distances such that all trains (with train-type-specific
speed restrictions) can come to a safe stop prior to encountering STOP signal. The system provides
sufficient sighting distances and appropriate aspects for anticipated traffic patterns. For given aspects,
an inverse relationship exists between capacity and signal design speed. Once installed, track circuit,
interlocking, and signal locations are normally fixed. Design speeds are normally higher than civil
speeds and therefore do not require restrictions.

Situations where signal systems requires permanent speed restrictions (PSR) below civil speeds include:
(1) traffic pattern changes after signal installation, resulting in inappropriate signal spacing; (2) vehicle
characteristics assumptions (e.g. braking rates) in initial design rendered obsolete by vehicle changes
(e.g. additional weight), resulting in speed restrictions to match new braking curves to existing signal
spacing; (3) track reconfigurations (e.g. siding extension, interlocking expansion) require signal
relocations, but desired locations do not work well with existing blocks (expensive to relocate), resulting
in lower MAS to provide sufficient braking distance.
Signal modifications can also require operating speed changes. Removal/addition of automatic intermediate signals result in block length changes, thus changing distance travelled at lower speeds when signal indication is not the most favourable aspect possible. Changes in capability to display aspects results in signals displaying the next most restrictive aspect, changing the speed at which moves could legally be made.

Systems maintained per original design generally have no impact on operating speeds. However, when signals are modified or simplified to reduce maintenance costs or support different traffic patterns, they could reduce capacity or inadvertently lengthen trip times. References (21, 23) in signal design’s speed implications are available.

**Cab Signal Systems (CSS)**

Cab signals are normally designed as overlays to conventional multi-aspect signals. CSS may merely repeat & enforce wayside aspects, provide additional aspects allowing higher speeds, or replace automatic wayside signals with code change points, providing cost savings. Suitably equipped trains can generally access higher MASes through additional aspects or improved safety from aspect enforcement. CSS does not usually affect trip times once installed, however, where CSS was removed or had capabilities modified (e.g. aspects removed/added), changes to operating speeds can occur after initial introduction.

U.S. passenger railroads once relied on CSS modifications to enforce curve speeds prior to full Positive Train Control (PTC) implementation, at high-risk locations like Frankford Jct. and Spuyten Duyvil. CSS aspects are enforced at speeds (e.g. 15/30/45 mph) that may not exactly match civil restriction (specified to nearest five mph). Signal engineers use next-most-restrictive aspect at nearest-code-change-point, resulting in e.g. 30mph enforced for 2,200 ft for a 40mph restriction requiring 1,400 ft braking distance. This has measurable impact on triptimes compared to locomotive engineers manually managing deceleration.

**Level Crossings**

Where roads and railways cross at grade, speed restrictions may be required in high-speed territory (>79mph in U.S.). FRA issued guidelines (24) recommending different protection levels based on train speeds, although it is not clear if this applies to existing crossings or generates new PSRs if crossing protection was not upgraded. In the U.K., enhanced level-crossing protection are required where trains operate at >100mph.

**Electrical Supply Infrastructure**

On electrified railroads, short-term substation power ratings can limit locomotive power demand (e.g. maximum throttle, or ‘dial down’ requirements), tonnage, train length, headway, and acceleration, although they do not normally generate speed restrictions. However, resultant achievable speeds could affect runtimes.

Catenary system designs can have subtle and complex impacts on maximum speeds: catenary pole spacing in central N.J. limits speeds to 140mph even with new constant tension designs (25). Railroads impose TSRs relating to pantograph-catenary contact instability in windy, hot, or cold conditions (typically in variable-tension territory.) Third rail systems are normally limited to 100mph maximum speed; difficulties exist in designing nosepieces to accept shoes at higher speeds.
**VEHICLE FACTORS**

Many speed constraints are vehicle-dependent and relate specifically to vehicle performance.

**Cant Deficiency (Underbalance)**

Limiting speeds (when derailments occur) on continuously welded rail (CWR) with modern fasteners can be much higher than the speed at which passengers feel nauseous or unsteady from curving forces (26). Since passenger comfort constrains MAS, vehicle-based tilting systems were developed to improve comfort, thereby increasing speeds.

Conventional U.S. passenger equipment normally operate at 3” (76mm) of underbalance; active-tilt equipment operates at 7” (178mm). Each imbalance level gives rise to different MASes on the same physical curve. Higher underbalances results in faster rail wear. If railroads qualify equipment at a different underbalance level, MAS is changed on most curves, and affects advertised trip times. Figure 2(d) shows differential MASes (27) for United Aircraft’s TurboTrain on the Shore Line.

U.K.’s vehicle size, weight, and suspension design allows conventional equipment to operate at 150mm (5.9”) of cant deficiency; at one time Railtrack was exploring operating non-tilt passenger equipment at 165mm (6.5”) of “exceptional” cant deficiency. Tilting equipment in Europe can operate at between 225mm and 300mm of underbalance (28).

**Installed Power**

On diesel-powered trains, engine horsepower/power-to-weight ratio directly impacts acceleration rates, and maximum achievable speed. Acceleration rates and loading times make tremendous differences to journey times, particularly on curvaceous routes peppered with PSRs or local service with many stops. If railroads improved locomotive horsepower or assigned fewer cars per train, published runtimes are affected. Indeed, British Rail had timing profiles for each consist type down to whether HSTs had seven, eight, or nine coaches, each class of electric locomotives, and trailing tons hauled (Figure 2(j)). When Britain’s InterCity 125 HST trainsets were introduced on regional lines with 75~90mph maximum speeds, 10%~15% triptime reductions were nevertheless achieved (compared to previous coaches and locomotives), due to improved acceleration and braking capabilities.

**Braking Rates**

Vehicle technology advancements gave rise to differential braking rates. Most modern U.S. passenger coaching stock utilizes two disc and two tread brakes per axle; Amtrak’s Acela utilizes three disc brakes per axle to achieve 26% better braking rates (29).

On HSTs, disc-and-tread combinations delivered 9%g (0.88 m/s², 2.0 mphps) of service brake, enabling operations at 125mph on legacy lines equipped with signal systems designed for 100mph (30). This allowed for tremendous time reductions, not only from the 125mph capability but also reduced deceleration time upon approach to every PSR and station stop. Hydrostatic brakes designed to deliver 12%g (12% of acceleration due to gravity, 1.17 m/s² or 2.6 mphps) braking rates on British Rail’s Advanced Passenger Train was not commercially successful, but electro-pneumatic brakes (EPBs) delivered more predictable and responsive braking performance in suburban multiple-units and heavy freight trains.
**OPERATIONAL PRACTICES**

Operating practices also impact published journey times.

**Rules or Staffing-based Delays**

Changed operating rules or staffing requiring existing infrastructure to be operated differently (typically for increased safety margin) can lengthen trip times. Examples: (1) some railroads require trains to hold outside station if another train is already platformed (especially at low platforms), resulting in runtime degradation for trains in the opposing direction; (2) reduction in yard personnel leads to more through trains stopping to operate hand-throw switches; (3) reduction in trainman or station positions lead to lengthened intermediate station dwell times; (4) reduction in towerman positions or hours lead to reduced en-route flexibility, making it difficult to pass slower trains or require routing via slower tracks.

**Work Zone Delays**

Track conditions affect speeds, but so do track maintenance activities. As train volumes increase due to growth or traffic consolidation from duplicate lines, maintenance windows became narrower, making it difficult to perform work effectively and clear up prior to each train’s arrival. It is now common for express trains to stop on the mainline while track gangs clear up, and then pass the work site at reduced speeds. Delays from “slow zones” can be so severe that railroads issue special construction timetables (Figure 1(d)) reflecting extended timings.

**Single Tracking Delays**

On double-track lines, major projects require trains to be single-tracked past the work site when one track is out-of-service. Schedules are written such that opposing trains do not meet near single-tracked sections, so trains do not have to wait to clear. However, moves through interlockings (at either end) are made at reduced speeds; in densely trafficked areas several minutes’ wait for opposing trains to clear is inevitable. If track rehabilitation projects are planned in advance, these delays are written into published schedules.

**Approach Control Delays**

When remotely-controlled switches are thrown from high speed routes to slower routes, most signal systems display restrictive aspects to approaching traffic, to enforce speeds through junctions, even though blocks ahead may be unoccupied (31,32). In congested locales, this can add minutes (colloquially, “burn time”) to runtimes. When routing plans are modified, scheduled times can change substantially.

**Train Slot Delays**

At junctions or single track territory, trains are planned to operate within designated timetable slots to avoid occupying key interlockings simultaneously. Slots do not always line up with unconstrained running time between them, thus extra time waiting for slots is written into timetables (see “Circle Time” discussion later.)

**MAXIMUM AUTHORIZED SPEEDS**

Operationally speaking, railroad MAS is generally given by Employee Timetable. The Timetable is a living document issued to operating employees, periodically updated by proper authority. It is not the only document that governs MAS for a given location at a given time. It is said that “MAS is a long
Math problem where the answer is a single number.” Although speeds are shown on other sources like track charts, diagrams, etc., speeds shown therein are necessarily simplified, and not authoritative. For simplicity, typical practice in Northeastern U.S. is discussed here.

Hierarchy of Documents

Employees in charge of trains (or trackcars) must be familiar with all operating documents. In descending order of generality:

1. Operating Rule Book
2. Employee Timetable: Schedules & Special Instructions
3. General Orders
4. Bulletin Orders
5. Train Orders (issued by Dispatchers)

Some railroads also utilize General Notices and Operating Notices, of informational nature.

Operating Rule Book

Rule Books provide instructions governing all aspects of operations and define how other documentation are interpreted. All rules therein apply unless superseded explicitly by more specific instructions. MASes are not discussed here, because speeds are necessarily specific to one location. Geographically specific information is given in the Timetable.

Employee Timetable—Schedules

Employee Timetable contains the authority for train movements under “timetable and train order operation”. Station pages define station locations. Schedule pages (Figure 2(a)) show authority to occupy track by each train at each location at specific times, subject to superiority of trains. Although timetables have more timing points (e.g. interlockings, employee stops) than shown in public schedules, they do not typically provide rationales for timing, thus it is only a little better than public schedules for understanding why running times changed. City-to-city running times divided by rail mileage are not good indicators of MAS, or even average speeds while underway.

Employee Timetable—Special Instructions

Special Instructions are where MASes are defined. MASes are defined under three headings (27):

- Maximum Speeds Unless Otherwise Specified (i.e. “Line Speeds”, Figure 2(b)),
- Permanent Speed Restrictions—Curves & Bridges (also “Civil Restrictions”, Figure 2(c)), and
- Special Maximum Speeds (more specifically, “Equipment Restrictions”, relating to train equipment operated, Figure 2(d)).

To figure MAS for specific locations, first look up Line Speed, then check Civil Restrictions and lower MAS if necessary, and finally determine Equipment Restrictions—including blanket and location-specific restrictions. MAS thus determined is the base under normal operations, to which time-specific conditions may be applied.

General Orders

General Orders (GO) are periodically issued documents that make permanent changes to the Rule Book, Employee Timetable, or Timetable Special Instructions under the authority of the Superintendent of
Operations. GO (Figure 2(e)) may be issued in sticker form; employees are expected to moisten and paste over relevant timetable pages (like stamps), such that new data covers over superseded information. GOs may also be issued in loose-leaf format, replacing superseded pages.

When the Engineering Dept. makes permanent changes to infrastructure, resulting in MAS changes or new infrastructure being put “in service”, they are described in GOs (33). If TSRs are in effect for prolonged periods, the Superintendent may elect to print TSRs in GOs.

GOs could help track general state of railroad maintenance, because it contains a partial history of TSRs. When analyzing GOs, each and every single one must be obtained. They are issued with sequence number and effective date, so completeness of data records are easily determined. Each GO is issued with a summary page describing changes made; thus a reasonably complete history (and corresponding journey time impacts) is usually readily reconstructable.

**Bulletin Orders**

Bulletin Orders (BOs, e.g. Figure 2(f)) are frequently issued documents making temporary changes to operating documents. Most railroads have a daily BO issued under different names, e.g. Daily Train Operations BO, TSR Bulletin, etc. This document is where most TSR information could be found.

However, a TSR by definition occurs due to temporary conditions, and thus should not appear as permanent changes to operating documents. Certain TSRs, e.g. allowing tracks to settle for 72 hours after tamping, are lifted in three days. Others, like “mud spot” conditions, might persist for several weeks until track gangs could effect repairs. Other TSRs could be associated with poor tie conditions being unable to hold gauge, leading to downgraded track class, which might not be repairable until rotted ties are replaced by travelling production gangs and could persist for months. These might stay in the BO and never makes it into GOs, as long as authorities intend to capitably rebuild track when scheduled.

BOs carry information on Working Limits, requiring trains to contact Track Foremen to obtain permission through work sites. This generates delays and prescribes an MAS past the work site, although it is technically a signal speed, and not a TSR (Working Limit Stop Sign is considered a “signal.”)

BO data is perhaps the best resource to understand state of maintenance relating to MAS and consequently published speeds. The challenge is, BOs are temporary changes and therefore never pasted into timetable books. Although operating employees are required to have all BOs in effect on their person while on duty, when they are superseded by Summary BOs, GOs, or Timetable Reprints, all superseded BOs are typically discarded to avoid confusion. Therefore, railroad state of maintenance is perishable information: unless you were there at the time, it is highly unlikely that a reliable, accurate, and complete account of factors affecting travel speeds can be reconstructed.

Despite computerization, records that change daily are oftentimes not retained electronically for long periods, because business justification for their retention usually is not there. It is said, “in Operations, you’re only as good as your last rush hour; nobody remembers great work you did last Thanksgiving.”

BOs also promulgate train schedules revisions, typically for special movements—when necessary to convey to all operating employees one-day-only schedule e.g. for Circus Trains. Normally, schedules (and consequently advertised times) are not modified in response to TSRs, even for ones lasting several months. It is therefore difficult to infer state of maintenance using public running times.
BOs identify general speed restrictions in effect for one-day only, e.g. Heat Restriction, or Reduced Rail Adhesion. Most railroads utilizing CWR issue speed restrictions on exceptionally hot days to guard against track buckling risks (e.g. 20mph MAS reduction when highest forecast temperature is >85°F or a 25°F change in temperature (34), although cut-off and restriction severity varies by railroad and region).

**Train Orders**

Train Orders (TO), e.g. “Form D,” “Form M”, or “Form 19,” (Figure 2(g)) are issued to specific trains and may contain instructions superseding anything discussed above. Typical uses include:

- **As Track Warrants** to convey movement authority, e.g. when a superior train is running so late that the Dispatcher allows an opposing inferior train to make progress down the line and meet it at a different siding. Dispatcher issues TOs to both trains superseding timetable authority, instructing superior train to hold at a non-scheduled location, and inferior train to meet it there.

- **To Remove Track or Signal System from Service**, e.g. when Maintenance Foremen require exclusive use of blocks to effect repairs.

- **To Issue Emergency Speed Restrictions** (ESRs), e.g. when routine track patrols find defects like broken joint bars, heat kinks, or pull-aparts such that, to reduce derailment risk, trains must travel at lower than MAS. Engineering documents like the MW-4 (Figure 2(h)) normally prescribe train speeds over each defect type.

Unfortunately, TOs containing ESR records are also perishable, most railroads requiring retention for only one to seven days. TO is also not the only way to communicate ESRs to train crews. Northeastern railroads allow daily BOs to be amended via radio with additional speed restrictions. Even if historical TOs were available, at best it represents an incomplete record of speed restrictions.

Computerized records seldom deliver sufficient detail for useful forensics. Centralized Traffic Control (CTC) playback “tapes” or recorded radio voice records are typically expunged after 2~4 weeks, and systems are normally designed for specific known-time event investigation access, rather than extensive data trending analysis.

Track defect prevalence can correlate with state of maintenance (but it is not an absolute indicator, because maintenance strategy can also drive this number). Broken joint bars rarely occur if track structure is properly supported. Heat kinks are unusual with correctly adjusted CWR, properly ballasted shoulders, and functioning fastening systems. Pull-aparts can occur during extremely cold weather particularly at spots with internal rail defects, head cracks, engine burns, or defective welds; they are minimized by frequent rail grinding and prompt rail repair. Although track inspection records must be kept pursuant to 49 CFR 213.241 and are subject to inspection by the FRA, they are generally unavailable to researchers.

**DEFINING PUBLIC TIMETABLE RUNNING TIMES**

To understand published journey times, it is worth pondering how train schedulers arrive at trip times from constraints discussed above. For clarity, British practice is discussed here. North American passenger schedulers utilize similar concepts (e.g. (6)), but no industry standard exists.
Train Performance Calculator (TPC)

TPC models locomotive performance over specified terrain with defined speed restrictions. Basic inputs are physical characteristics (speed restrictions, gradients, curvature, station locations), traction characteristics (wheel adhesion, horsepower, braking rate), and load characteristics (tonnage, load, rolling resistance, wind resistance, etc.). The output is unconstrained running time—before considering station dwell times, congestion, signal checks, TSRs, etc. (i.e. theoretical minimum under ideal conditions.) Normally, four Sectional Running Times (SRT) types are given for each station-to-station segment: stop-to-stop, stop-to-pass, pass-to-stop, and pass-to-pass. “Stop-to-pass” means train stops at first station but by-passes second station; acceleration from standing stop at first station is included, required braking to stop when arriving at second station is excluded (but required braking to comply with any PSRs in second station’s limits is included.)

TPC models are provided by industry vendors (35) and typically validated by running time checks requiring operations of special test trains. To build speed profiles, schedulers traditionally utilize onboard speedometers and record mph readings every few seconds. To understand traction output, another scheduler records throttle and brake positions and times actuated. (Today, this work is performed with computerized dataloggers.) Schedulers also note any signal checks or unusual conditions. Speed profiles and control manipulations are compared to TPC outputs and internal parameters tweaked until it reproduces recorded traction performance under various conditions.

Square, Circle, and Triangle Times

Building a public schedule from raw running times necessitates addition of extra allowances to ensure train operations reliability and achievability under field conditions (i.e. to make schedules “robust”.) The three types of en-route time adjustments are:

- **Engineering Adjustment [Square Time]** or “Recovery Time”: Extra minutes or fractional minutes inserted wherever major track engineering work or TSRs are in effect. They are location-specific and typically derived by comparing TPC runs under unconstrained condition with TPC runs with TSRs in force.

- **Routing Time (Circle Time)** or “Pathing Time”: Extra time inserted upon approach to major junctions, to absorb delays resulting from signal checks, waiting for conflicting movements to clear, or as insurance against missing critical slots at busy junctions. They are junction-and-time specific and derived from inspection of stringline charts and junction utilization/clearing times. They are also inserted for trains running on close headways where a following train may operate for long stretches at less than MAS due to adverse signal indications (called “running on double yellows.”) Accuracy and adequacy is critical, as trains missing assigned slots on busy lines can have knock-on effects far beyond the immediate locale.

- **Performance Allowance <Triangle Time>** or “Pad”: Time inserted upon approach to major stations whose purpose is to absorb unanticipated en-route delays not explicitly allowed for in Square and Circle times, like individual variations in driver performance (i.e. operating techniques and skills of different locomotive engineers), e.g. experienced operators typically shut off power and coast at an earlier point if approaching major terminals with allowance to spare.

Published departure-to-arrival times are the sum of all appropriate station-to-station times plus any Square, Circle, and Triangle times inserted en-route (Figure 2(j)). Taken together, en-route adjustments should account for all operational and infrastructure factors discussed in this paper’s first half. It is impossible to back-out en-route adjustments from public schedules without access to rail industry documentation. Fortunately, U.K. Network Rail’s Working Timetables (WTT) are published for all to
see (36). However, the U.S. passenger rail industry does not generally publish en-route adjustments in schedule documents, not even in Employee Timetables. Adjustments are typically domains of railroad scheduling departments and are known under names like “schedule skeleton.” In some cases, these bases for running times are carried in individual section scheduler’s heads and never written down.

Understanding scheduling rationale and reasoning behind each adjustment requires either interviewing the section scheduler when the timetable was written, or determining all contemporaneous constraints schedulers should have taken into consideration when determining the published running time.

**Station Dwell Times**

En-route adjustment do not cover time required for station work, typically defined as the period between time when a train is fully berthed in station (i.e. wheels stop moving), to time when doors are closed and “okay to go” is given.

Dwell times are open to debate even amongst train schedulers because they can include time required for passengers to make transfer connections, to service trains at major terminals (typically, food and baggage, more rarely, fuel, water, change of gauge, change of host railroad, etc.), required extra time for hand-off between incoming and relief crews, combining or separating a train’s different sections. On commuter lines it also accounts for platform congestion and passengers holding doors. On mixed freight-and-passenger trains it can include required time for switching freight cars. Frailey (37) discusses North American passenger train switching operations extensively, including W.E. Deming’s landmark study for the Burlington Northern.

Fortunately, station times are easier to understand; they are often published in public timetables for major terminals. However, suburban carriers do not typically publish dwell times at intermediate stops and may even have flag stops or situations (e.g. evening outbound drop-offs) where trains are permitted to operate ahead of published schedule. They can also be hidden, as mixed freight-and-passenger trains can make freight stops with unpublicized dwell times, and trains often have unadvertised operational stops requiring dwell times—even on commuter lines, employee stops or time required to receive train orders are omitted from public schedules.

**Forensics of Running Time Degradations**

Research has thus far established that modifications in public timetable running times result from changes taking place in these general categories:

- Track design geometry, maintenance, layout, and special work
- Infrastructure factors like structures, signal, power, and grade crossings
- Wheel-rail interaction issues like cant deficiency
- Vehicle factors like tractive effort and braking rates
- Operating rules, practices, and ongoing projects to rehabilitate infrastructure
- Maximum authorized speeds per Timetable (from above constraints)
- Scheduler’s decisions:
  1. Train performance modelling
  2. En-route adjustments
  3. Station dwell times
It follows, therefore, to fully understand *What Happened to Speed* (7), specifics of what changed in each category during the study period for the services in question should be examined. Although public timetables offer a general sense of where service offerings were trending, they cannot tell us whether these changes resulted from schedulers’ decisions (for either marketing or operational reasons), deterioration of physical infrastructure, ongoing projects to restore the plant, or permanent system upgrades. Indeed some factors counteract one another, or indicate completely opposite industry trends. For instance, deferred track maintenance and increases in track rehabilitation both lead to lengthened journey times, and passengers would be none the wiser.

It is possible for published journey times to remain static after substantial upgrades increasing MAS, if schedulers elect to utilize upgraded capabilities to improve reliability or provide additional dwell time for connections at intermediate stations. Triptimes capabilities could be improved even while physical plant is deteriorating by changing operating practices, or reduce congestion by reprioritizing and cancelling trains.

Although advertised trip times and the industry’s health may not be all that correlated, longitudinal analysis of journey times can be a high-level screening tool to identify corridors of interest where in-depth forensic analysis could reveal reasons behind runtime changes. Secondary sources written by contemporary observers (e.g. (38)) can sometimes provide helpful insight into management actions and decision rationales.

**THIS HAPPENED TO SPEED: CASE STUDY OF PENN CENTRAL’S MOHAWK AND BUFFALO DIVISIONS**

Exploring this hypothesis a little further, we examine a case study utilizing some sources discussed above. It provides a more specific (but still incomplete) explanation as to why public timetables were revised during the study timeframe. Limited to the former Penn Central (PC) Northeastern Region, this methodology can be applied to any corridor of interest.

When correlating passenger corridor performance with infrastructure investment, three dimensions should be considered: service speed, capacity (trains per day operated at design speed), and reliability (probability that planned timing is actually achieved). In service design of mixed traffic corridors, published service speeds often results from trade-offs along these dimensions. MAS and resulting SRTs are practically the only elements where infrastructure owners exercise complete control.

The *20th Century Limited* in 1966 ran 14% faster (16:00) than *Chicagoan* (18:30), chiefly because of shorter scheduled dwell times (0:35 versus 1:48) at intermediate stations. Today’s westbound *Lake Shore* (19:05) has less dwell time (1:22) built into its schedule, even when marshalling time at Albany is included, but nonetheless takes 3% longer than 1966’s *Chicagoan*.

**Scheduled Dwell Time**

Figure 3(a) shows dwell times in the Region of westbound New York-Chicago trains leaving Grand Central Terminal in late evening (*Chicagoan*, PC #63, *Lake Shore*), corralled from contemporary public and employee timetables (27,39-42). A few unpublished times were estimated. Beginning in 1961, dwell times mushroomed, especially during Penn Central’s era. Amtrak stopped this in 1971, “making trains worth riding again.” Dwell time growth began again at Albany in 1979; however, it was minimized at other locations.

Figure 3(b) shows that N.Y. Central assigned dwell times quite deliberately and methodically, with overnight trains having longer dwell times. In 1963, all trains had extra time at Buffalo, even important
trains like *20th Century Limited* were booked for eleven minutes. Significant dwell time was also included at intermediate points like Utica and Rochester.

Dwell times have critical impacts on train operations. When delays occur outside the operators’ control (e.g. weather, passenger action, etc.), extra dwell time can help absorb impacts. Typically, schedulers use average running time, but recovery time at major terminals can be derived from 95th-percentile time. Departing westbound, by maximizing the probability of leaving Buffalo on-time (95th-percentile ensures trains leaving Buffalo have only 5% chance of lateness), it minimizes downstream impacts by not having trains operate out of slot.

Amtrak added extra recovery time at stations where host railroad change is necessary (e.g. Cleveland), at crew change points (e.g. Toledo), to allow time required for coordination between different dispatching offices and relief paperwork.

### Sectional Running Times

Figure 3(c) presents a rather complex picture of those same trains’ SRTs. Relative periods of stability existed 1983~1997, but gentle upwards trends nonetheless existed, likely contributing to the perception that trains were getting slower. Marked deterioration occurred 1968~1971, adding 35 minutes (12%) of runtime. Another turbulent period arose 1999~2003, likely associated with the Conrail split when major operational changes occurred on the Chicago Line. As passenger train performance became political at the Federal level circa 2008, public timetables became more of a contractual commitment, rather than a reflection of infrastructure capabilities or a quantitative description of operational intent.

During 1976~1980 SRTs were abnormally long and likely not entirely due to deterioration of infrastructure. Relevant special instructions (40) states:

> “AMTRAK Engines, Class SDP-40F, in number series 540 to 649, are restricted as follows--trains with one SDP-40F Unit alone […] must not exceed 40 MPH on curves of 1 degree 30 minutes or greater.” (PCRR Rule 1157-G1b)

It then lists 45 and 22 such curves on Mohawk and Buffalo Divisions respectively. These 67 severe speed restrictions applying to passenger trains partly explain increased running times.

Interestingly, introduction of RoadRailers in 1993, and cancellation of Amtrak Mail in 2004 and ExpressTrak in 2006 did not have noticeable impacts on scheduled times—at least not in this Region. Since mid-2000s, Amtrak has utilized TPC to derive pure run time and produced standardized schedules. Different categories of scheduled time allowances are explicitly documented internally.

### Changes in Infrastructure

Figure 3(d) shows histograms of MASes for passenger trains. In October 1970, despite rail industry issues in the Northeast, significant portions of Main Line were available for 75-80 mph operations, with almost 40 miles qualified for 85 mph primarily west of Seneca River (27). However, infrastructure was degrading fast during the first years of Penn Central’s bankruptcy:

> “Applies in Buffalo Division: Passenger Trains--79 mph over the entire Division.” (PC GO 407 (aa), 1/1/71)
> “Intermittent inductive Automatic Train Stop [ATS] System on the entire region, out of service.” (PC GO 409 (a), 2/1/71)

ATS was deactivated as a maintenance cost-saving measure. By February 1971, numerous TSRs had noticeably increased slow orders in 30, 50, and 60 mph categories (33). ESRs may have been even more
numerous. By 1978, the de-facto speed limit over entire Region was 75 mph. As infrastructure slowly
returned to a state-of-good repair, speed profiles mostly returned to normal by February 1997, along
with substantial new segments of 90, 100, and 110 mph running. Higher-speed running, which requires
cab signals and higher superelevation on curves, occurred east of CP-169 where passenger traffic
dominates. West of CP-169, where heavy freight trains from Alfred E. Perlman Yard joins the Main
Line, the highest MAS was 79 mph.

Figure 3(e) shows simplified TPC runs using timetable MASes, indicating infrastructure speed
capabilities indeed did degrade beginning in 1971 and reached a low point in 1978, but recovered by
1997. This correlates nicely with the SRT findings. 110 mph running contributed 3 minutes’ savings
between Albany and Schenectady, but Figure 3(f) shows time was lost en-route to Utica due to new or
more severe restrictions.

Nothing Happened to Speed (at Least not Around Here)

This is not a definitive history of train speeds on the Mohawk and Buffalo Divisions, but it demonstrates
some factors already discussed. Passenger train scheduling is a complex discipline and a multitude of
issues are at work, all of which affect public timetable end-to-end trip times. Financial ramifications and
difficult public sentiments are consequences of inappropriate advertised running times.

Over a 50+ year study period, runtimes have basically remained at about 4:45 from Albany to Buffalo,
punctuated by periods when specific technical issues (only some of which are known from this analysis)
have elongated travel times followed by recovery once issues were addressed. One can either rejoice in
the successful achievement of state-of-good-repair, or regret that no true speed improvements were
evident from this data.

IT’S NOT ABOUT SPEED: CASE STUDY OF METRO-NORTH’S NEW HAVEN LINE

Scheduling is a delicate balancing act. Here, we get behind the scenes a little to understand decisions
and analytics supporting these actions performed every day in railroad scheduling offices nationwide.

The Long View: 1940~2009

Figure 4(a) shows running times for one New Haven Line early morning express train (Grand Central
arrival at ~08:30) over the last 75 years. Journey times did not change from 1940 to 1970, excepting
one minor revision in stopping pattern between 1940 and 1955. Ownership and sponsorship of
commuter services turned over to the public sector on October 27, 1970 under a purchase-of-service
contract, leading to dramatic changes. Train paths formerly serving intercity clientele originating from
far as Springfield, Mass. were truncated to New Haven, Conn. and saw extra stops added for
commuters’ benefit. In 1973, new ‘Metropolitan’ M-2 electric multiple unit equipment with better
acceleration and top speed was introduced, together with high-level platforms, which enabled additional
stops to be added while triptime was further reduced. Timings remained relatively stable until 2009,
although increasing customer demand and expectation for service reliability caused slight upward
trends. Nonetheless, express trains were still scheduled 14% faster in 2009 versus 1940.

Service Reliability: 1983~2012

Customer demands and operational achievements for more reliable service is borne out in Figure 4(b).
From 1983~2012, trade-offs moved towards scheduling longer running times to assure better reliability
and to account for expected delays due to track congestion. This was a period of tremendous growth in
train volumes and ridership, particularly during rush-hours at Mott Haven Junction in the Bronx (MO)
which came to be operated near design capacity. Despite MO having been rebuilt in a new layout with higher-speed switches and CTC cutover in June 1993, it remained a flat junction. Figure 4(c) shows all trains approaching MO from all three lines during typical morning peak. Higher throughputs required more precision in operations (because each train slot was now open for a shorter time-window), which translated into incremental needs for additional recovery time on the approach to MO, adding two minutes. Schedulers carefully balanced triptime, capacity, and reliability but it resulted in a little runtime elongation.

**Impacts of Extraordinary Incidents: 2013**

Figure 4(d) shows impacts of three major incidents in 2013. In May, a joint-bar failure resulted in changes to track inspection procedures, which required more on-track time \( T_I \); in July, a freight-train derailment resulted in an emergency four-month program to eliminate “mud spots” within a busy track section, which introduced TSRs and impacted reliability. In December, an overspeed accident resulted in FRA Emergency Order (EO) 29 requiring a second headend crewmember at braking distance from where MAS decreases by more than 20 mph unless civil speed protection via cab signal modifications were in place.

Impacts of these changes are best visualized in Figure 4(e), a colour-chart of minimum observed (i.e. best-case achieved) inbound running times. In Period 1 (before May), peak trains had correct SRTs to maintain reliable service. During Period 3, when TSRs and track outages were in effect for infrastructure remediation, normal recovery times were simply insufficient to absorb delays incurred particularly near MO during morning rush. There was a brief reprise during Period 4 after work completion, but during Period 5 due to operational changes required by EO29, actual running times lengthened again. These impacts were not reflected in public timetables due to their varying nature.

**Addressing the Maintenance/Operation Balance: 2009–2016**

Figure 4(f) shows differential SRT analysis from Control Point (CP) to CP drawn from recent operating schedules. We discussed rationale behind each change with section schedulers responsible for the territory. Two changes (green) relate to permanent infrastructure change (two new stations opened); the blue change accounts for EO29 cab signal modifications to provide civil speed protection; and two changes (orange) relate to colour-chart work (Figure 4(e)) that identified increasing congestion around Stamford for which insufficient SRT were previously allocated. Majority of triptime increases (red) are due to planned temporary construction conditions, which are restored when maintenance work was complete.

Main reasons behind apparent cumulative increases in triptimes were in fact specific changes happening at accelerated pace due to simultaneous New Haven Line infrastructure improvements taking place. Many projects—like catenary replacement, track maintenance, bridge reconstruction, drainage improvement, and PTC installation—are absolutely vital to state-of-good-repair and usually invisible to commuter ridership. Combination of construction volume and train frequency simply got to the point where moving the few available minutes of engineering allowance around was insufficient to cover all work required, resulting in net journey time increases.

**The Nuances of Speed on the Railroad**

Through technical material presented and case studies, we have seen that right-of-way, track, infrastructure, vehicle characteristics, and operating practices can all affect scheduled times. To properly understand all speed constraints, timetable special instructions, general orders, bulletin orders,
and potentially even specific train orders should be studied. When constructing timetables, we add
engineering, routing, and performance allowances, and station dwell times to pure run time to arrive at a
realistic schedule. Therefore, it is impossible to infer what was happening on the railroad by reading a
public timetable.

*Speed, Capacity, and Reliability Trade-Off*

Figure 4(g) represents one way to consider these issues. To maximize system performance, train
operators must balance trip-time, capacity, and reliability subject to an overarching constraint of safe
operations. Minimizing advertised journey time is no more of an appropriate goal for the passenger rail
industry than maximizing trains-per-hour or on-time performance. Infrastructure investments, when
complete, can typically improve all three variables in absolute terms, but when projects seek to
“maximize” one variable, they typically do so at the expense of the other two equally important service
attributes.

The authors hope that complex relationships between published journey time and state of the industry is
better understood in the public sphere from considerations outlined in this paper.

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Figure 2 Operating documents relating to railway speed restrictions. Permanent speed restrictions: (a) Schedule pages from New York Central Railroad Timetable Mohawk-Syracuse-Buffalo Divisions No. 19, p.53, effective 1966-04-24; (b) Penn Central Transportation Company (PCRR) Northeastern Region Timetable No.6, pp.188-189, effective 1972-10-29—Line Speeds; (c) Civil Speed Restrictions; (d) Equipment Restrictions. Temporary speed restrictions: (e) Penn Central Transportation Company (PCRR) Northeastern Region General Order No.604, effective 1972-12-26; (f) PCRR Northeastern Region, Buffalo Division Bulletin Order No. 6-185, effective 1974-02-20; (g) PCRR Train Order (“Form 19”) advising southbound trains of a track obstruction at Milepost 113-114; (h) PCRR Manual for Construction and Maintenance of Track (MW-4) detailing speed restrictions for each type of track defect. Schedule detail resulting from permanent and temporary speed restrictions: (j) Railtrack Working Timetable showing use of Square, Circle, and Triangle times and Consist-based Timing Loads on the East Coast Mainline in Scotland.

Figure 3 Longitudinal Analysis of Schedules and Speeds on the Penn Central Northeastern Region, Mohawk and Buffalo Divisions, 1956-2010: (a) Lake Shore Limited Dwell Time Analysis; (b) 1963 NY Central Railroad Dwell Time by Train; (c) Sectional Running Time Analysis; (d) Maximum Authorized Speeds; (e) Train Performance Curve from Albany to Utica; (f) Minimum Achievable Running Time per Simplified Train Performance Calculator.

Figure 4 Case Study of Schedules and On-Time Performance (OTP) on the Metro-North New Haven Line: (a) Express train running times by line segment 1940~2016; (b) OTP history 1983~2016; (c) Train tracker showing peak utilization at around 7:45 AM weekdays; (d) Monthly OTP in 2013; (e) “Heat maps” showing OTP by train by location in 2013; (f) Running time revisions 2002~2016 with reasons for changes; (g) Maximizing system performance requires train operators to balance trip-time, capacity, and reliability subject to overarching constraint of safe operations.
FIGURE 1 Tools for speed research: (a) Conrail track chart from the vicinity of Herkimer, N.Y.; (b) Sketch curve radius measurements in the vicinity of Berlin, Conn.; (c) Speed impacts of junction layouts (43); (d) Special timetables issued by railroads showing specifically journey time impacts of rehabilitation projects.
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Consist-based timing profiles:
InterCity 125 diesel trainset with 2 power cars and 9 coaches.

Class 91 electric locomotive with 410 trailing tons.

Due to maintenance activity in this section, all trains traversing it are given two [2] extra minutes on approach to a critical junction.

Non-stop trains are given one [1] extra minute for performance in case they lose time en-route.

Diesel freight train, 595 gross tons.

Trains switching from express to local tracks ahead of main interchange station are allotted one (1) minute to make the move.

FIGURE 2 (CONTINUED) Operating document showing schedule detail: (j) Railtrack Working Timetable showing use of Square, Circle, and Triangle times and Consist-based Timing Loads on the East Coast Mainline in Scotland.
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Running time studies showed that trains are short on time in this area due to increasing congestion from additional movements in Stamford.

Cab signal drop downs provided for MAS reductions of more than 20 mph. Running time added to reflect new infrastructural constraint.

Effective Date: 10/27/02 10/01/06 10/18/09 04/07/13 07/01/13 11/17/13 05/11/14 11/09/14 04/03/16 10/02/16

Train # 1527 1527 1527 1527 1527 1527 1523 1523 1523 1523

Time needed for crossing moves due to bridgeplates being needed at local stations to support track and catenary renewal projects requiring continuous track outages.

Running time added to accommodate track remediation work in the Bronx. Removed when project complete.

Additional two minutes needed to accommodate Devon Transfer project. Upon project completion, extra time was removed.

Maximizing system performance requires train operators to balance trip-time, capacity, and reliability subject to overarching constraint of safe operations.