Real Time Kinematic Global Navigation Satellite Systems in Railroad Transportation

Peter J Dailey

West Virginia University
College of Engineering and Mineral Resources
Department of Civil Engineering
2 June 2010

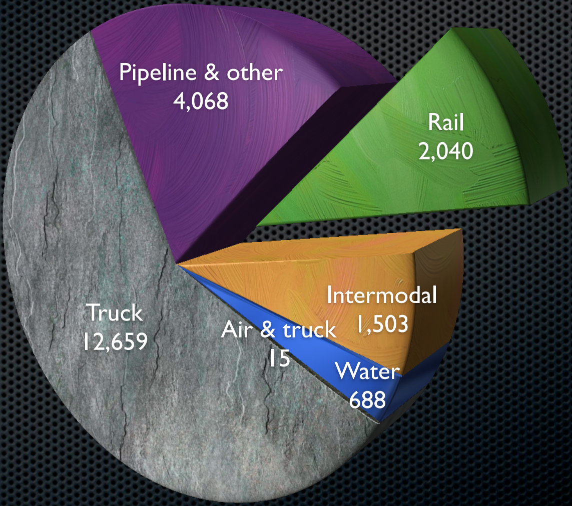
Agenda

- Motivation for the Research
- Research Purpose
- Experiments 1-3
  - Research questions to be answered
  - Motivation for the experiment
  - Brief genesis & history
  - Method
  - Results
- Conclusions

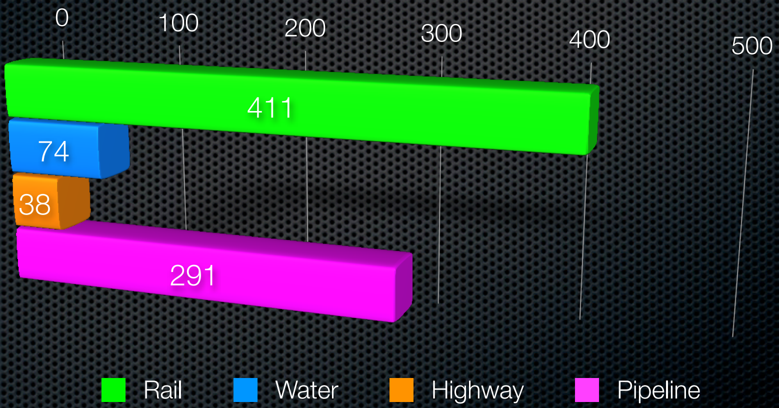
Motivation

- Freight traffic dominates the NA rail network
- Maintenance of infrastructure is critical and costly
  - Not completely data-driven, reliance on inspector skill and diligence
- Loss of freight revenue relative compared with overall freight growth
  - Interstate highway system
  - Rail's quality of service issues (Moorman)
- Train location depends on wired track circuits
  - Est. replacement cost of signals: $125,000/mile

US Transportation Network Weight of Shipments, Million Tons (2006 STB)

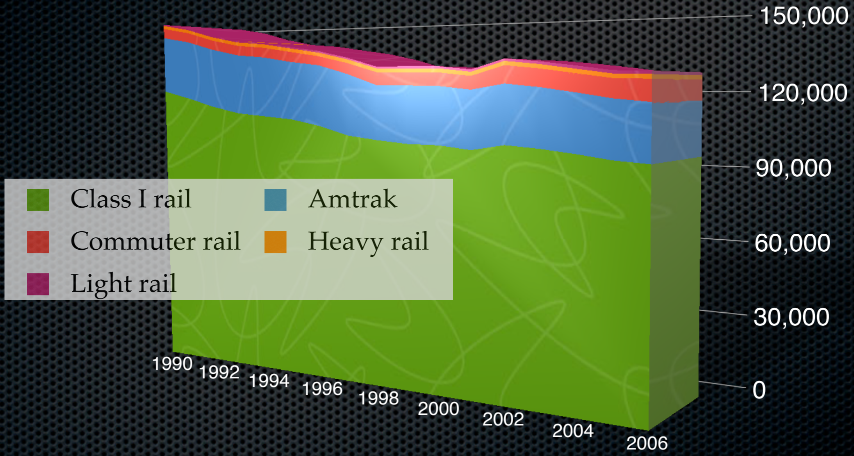


Transportation Mode Efficiency
Ton-miles/gallon Diesel* (2004 STB)



*or equivalent BTU

Rail Network Milage† by Type (miles)



†Association of American Railroads. 2006, 2007. Railroad Facts 2006, 2007 and previous


Class I Railroads of North America
BNSF
CN/GTW
CP/SOO
CSX
FXE
KCS/KCSM
NS
UP

Class I Railroads

- Burlington Northern Sante Fe Railway
- CSX Transportation
- Norfolk Southern Combined Railroad Subsidiaries
- Union Pacific Railroad
- Kansas City Southern Industries
- Canadian Pacific Railway/Soo Line Railroad
- Canadian National Railway/Grand Trunk Corporation
- Ferrocarril Mexicano and Kansas City Southern de México

92% of all operating revenues

STB: Class I railroads had minimum carrier operating revenues of $346.8 million (USD) in 2006

Research Purpose

Determine the applicability of RTK GNSS to railway infrastructure measurement problems

1) 2008 USDOT final report on NDGPS stated that RTK augmentation is "unsuitable for transportation applications"

- The research posits that a knowledge gap exists in the application of RTK GNSS to railroad transportation rail measurement

Research Purpose, cont.

2) Bridge a gap in railway inspection between multi-million dollar track geometry cars and FRA mandated visual inspections.

- The research posits that RTK GNSS can fill a gap in track measurement between:
  - Expensive, specialized inspection vehicles
  - Labor intensive
    - Differential level surveys
    - Visual mainline inspection

Research Purpose, cont.

- 3) Bridge a gap in track occupancy determination methods:
  - Wired track circuits (e.g., insulated track segments, proximity switches)
  - Wireless (e.g., GNSS, RFID)
- The research posits that RTK GNSS can produce reliable indication of track occupancy meeting the requirements for a location determination system (LDS).

Research Objectives

- Design an experiment to asses RTK GPS onboard a locomotive and obtain a data set to profile the bowl area of a humpyard during car handling operations
- Design an experiment to asses RTK GNSS onboard a track inspector's Hi-Rail and obtain a dataset to determine track alinement over mainline track
- Design an experiment to asses the ability of RTK GNSS to be uses as a wireless track vehicle location determination system (LDS)

Commercial Constraints to Research Activities

Safety and access considerations of a Class I railroad

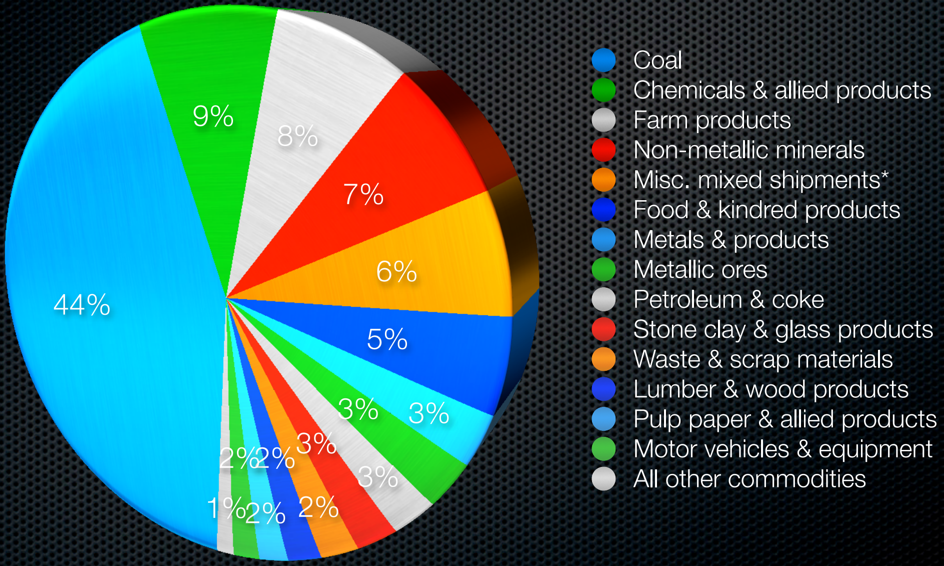
- Availability of track foul time ($1,500 fine per occurrence)
- Training Requirements of USC 49§214 On-Track-Worker Safety
- All field work superintended by a rail company employee-in-charge (subject to availability)
- $5M insurance policy, required by rail company for access

Background: NA Rail Freight

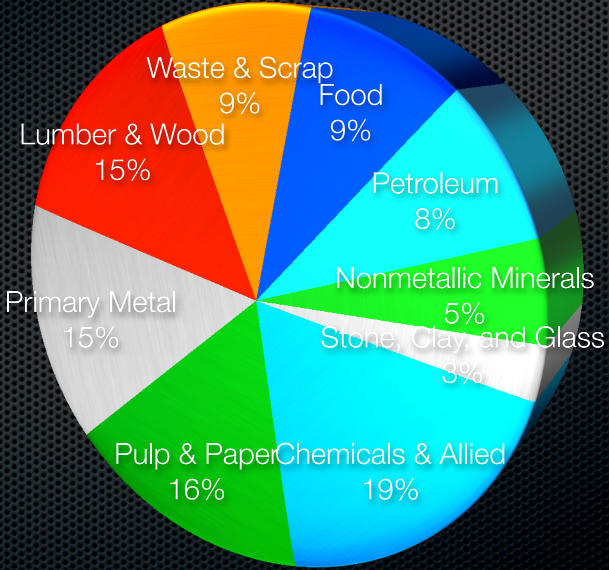
Two broad categories for shipping goods by rail

- Unit Shipments = “Unit Train”
  - Shipping a single commodity (unit) to a single location, i.e., coal from mine to power plant
- Manifest/Car Load Freight
  - Shipment from multiple sources to multiple locations
    - Train’s cargo listed in a manifest

NA Rail Freight Market



Principal Carload Commodities



Carload Freight

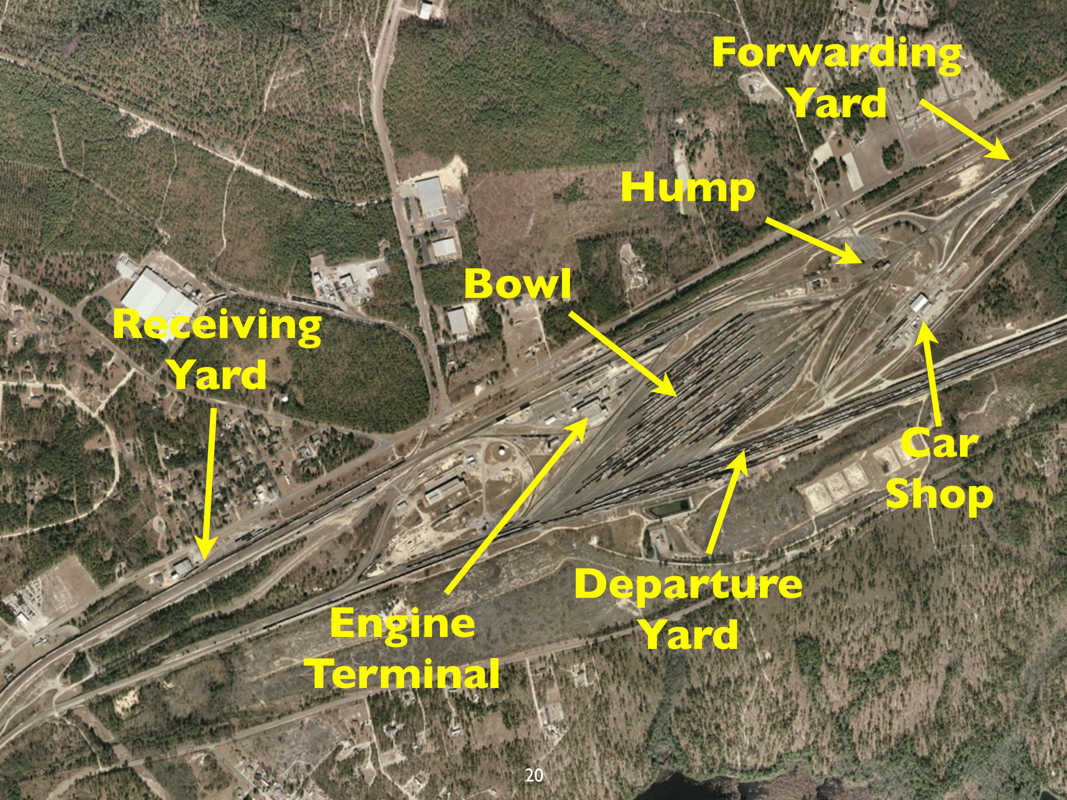
- Carload Freight relieves the highway system of 21 billion additional truck-miles annually (73 billion total TrkMi in FY 2000)
- Effective rail freight scheduling depends on
  - Rail capacity to decrease the probability of delay between segments: $P_1 * P_2 * P_n = P_{delay}$ (Mooreman)
- Carload traffic lags behind the overall growth rate in rail freight
- Production of goods increasingly at sites not served by rail
  - A rail siding is not viewed as a necessary business component

Experiment 1
Hump Yard Profile Survey

Determine track grades in a hump yard by an RTK equipped locomotive during humping operations.

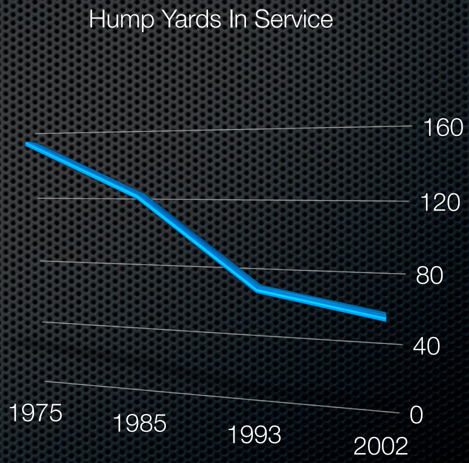
The Hump Yard

- An efficient mechanism engineered and constructed for the specific purpose of breaking apart a consist and reassigning individual units for outbound shipment
- AKA: Automatic Classification Yard, Freight Terminal, Class Yard
- Characterized by
  - An elevated inlet
  - Remotely operated electro-mechanical switching
- Automated car speed control


Forwarding Yard
Hump
Bowl
Receiving Yard
Car Shop
Engine Terminal
Departure Yard

Decrease in NA Hump Yards

- Mergers and acquisitions since Staggers Act
- Move away from box cars to containers
- Motor freight hub & spoke model
  - Rail for long hauls



Assertion: Hump Yard Grades Affect Freight Service Quality

- Grade degradation and settlement from
  - Railcar loading forces
  - Weather & geology
- Outdated design grade
  - Railcar Journal to frictionless roller bearings
- Application of TQM & Lean Manufacturing principals
  - “Right train, right track” through improved control systems increased sensitivity to infrastructure effects

Hamlet Terminal Video Study

1. Car stall blocks group switch, classification to blocked group impossible
2. Hump operations interrupted
3. Trim engine moves to clear stall

Total ET 21 minutes

Track Profile Survey
Differential Level

Research Question

Can RTK GPS instrumentation attached to a locomotive, be used to survey an automatic classification yard during humping operations?

Hump Yard Profile Survey Purpose & Objectives

Profile the bowl area of a humpyard in support of yard-wide resurfacing project

- Collect a data set by and RTK GPS equipped locomotive
- Minimize disruption to operations
- Maximize safety for surveyors
- Minimize impact on continuous car handling operation
  - Track closure and rail car reroutes
- Minimize demand for trained safety support personnel
- Determine the effects on GPS position due to signal distortion from multipath reflections
- Time lapse video study of yard delays

Hump Yard Research History

1. Norfolk Southern Norris Yard - 2004
2. Indiana Harbor Belt Blue Island Terminal - 2006
3. CSX Boyles Yard - 2007
4. CSX Frontier Yard - 2007
5. CSX Hamlet Terminal - 2008

Genesis of Locomotive Surveying

- Unplanned use of a locomotive to survey track profiles
- Tested transit of trim end retarder
  - Stuck Hi-Rail
- Duct taped range pole sections to locomotive handrail

Locomotive as a Survey Tool

- Indiana Harbor Belt RR, Blue Island, IL
- CSX Boyles Yard, Tarrant, AL
- CSX Frontier Yard, Buffalo, NY

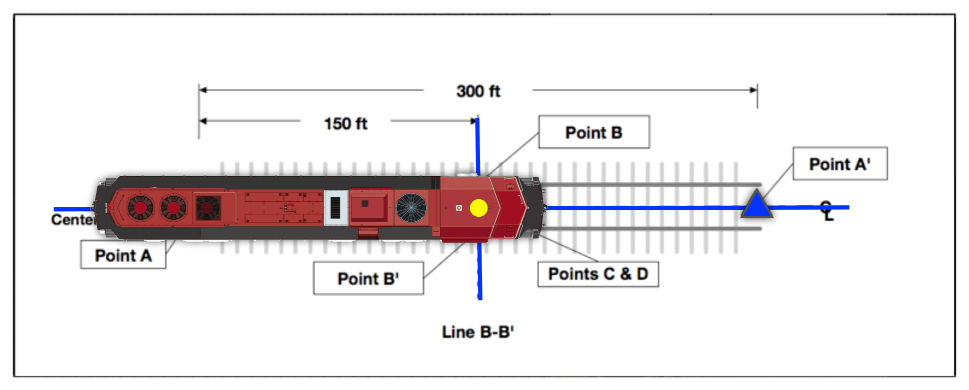
Experiment 1
Hump Yard Survey

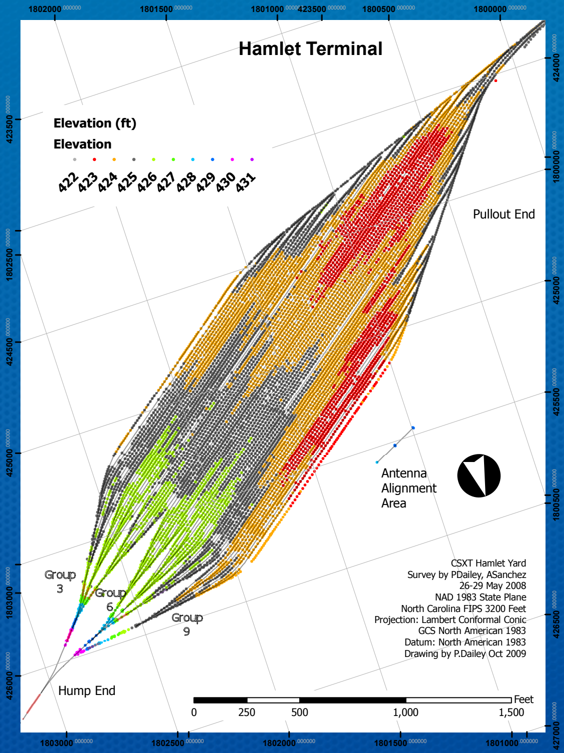
- CSX Hamlet Terminal, Hamlet, NC
- Objectives
  - Time lapse study of railcar movement
  - Bowl profile survey
  - Study effect of multipath distortion

Hamlet Terminal Profile Survey

- 58 bowl tracks
  - 7 groups
    - 5 groups of 8 tracks
    - 2 groups of 9 tracks

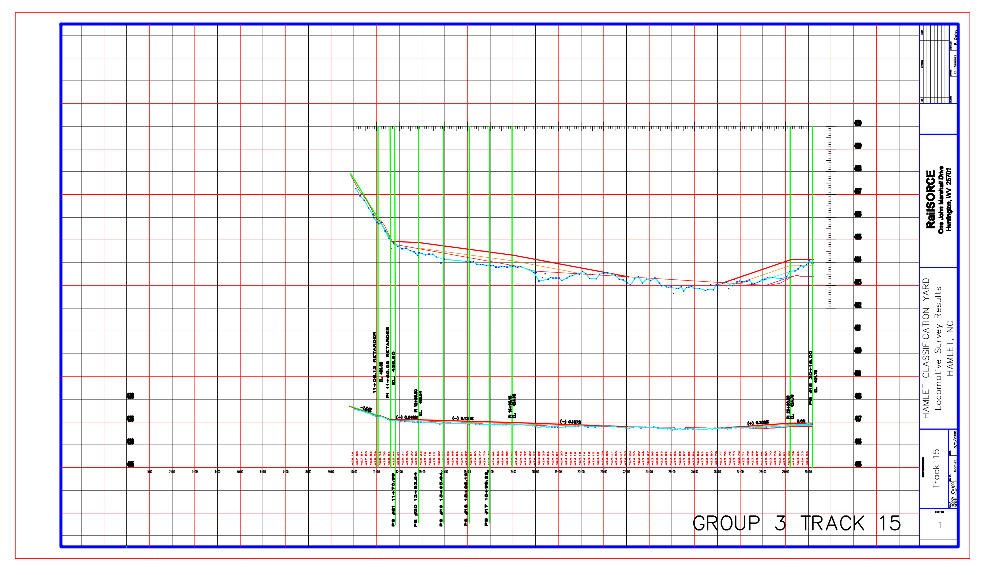
Antenna Alignment



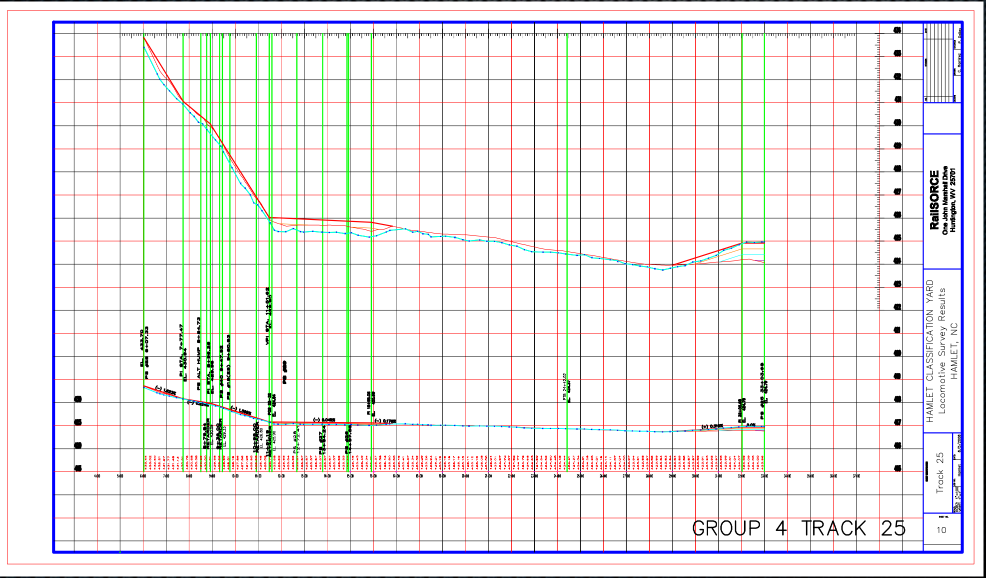


Hamlet Terminal
Elevation (ft)
Elevation
422
423
424
425
426
427
428
429
430
431
Pullout End
Antenna Alignment Area
Group 3
Group 6
Group 9
Hump End
CSXT Hamlet Yard
Survey by PDailey, ASanchez
26-29 May 2008
NAD 1983 State Plane
North Carolina FIPS 3200 Feet
Projection: Lambert Conformal Conic
GCS North American 1983
Datum: North American 1983
Drawing by P.Dailey Oct 2009
0
250
500
1,000
1,500
Feet

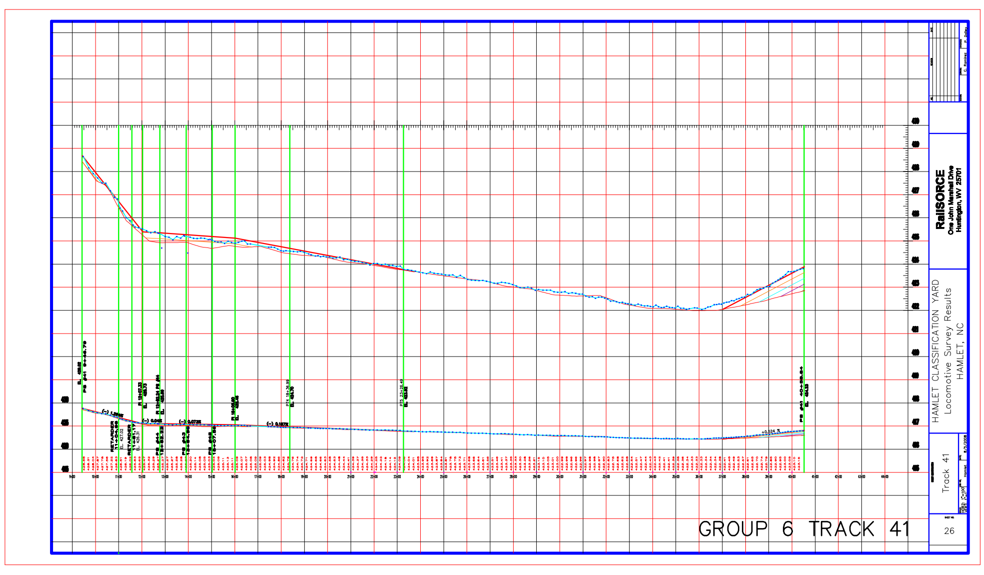
Group 3, Track 15



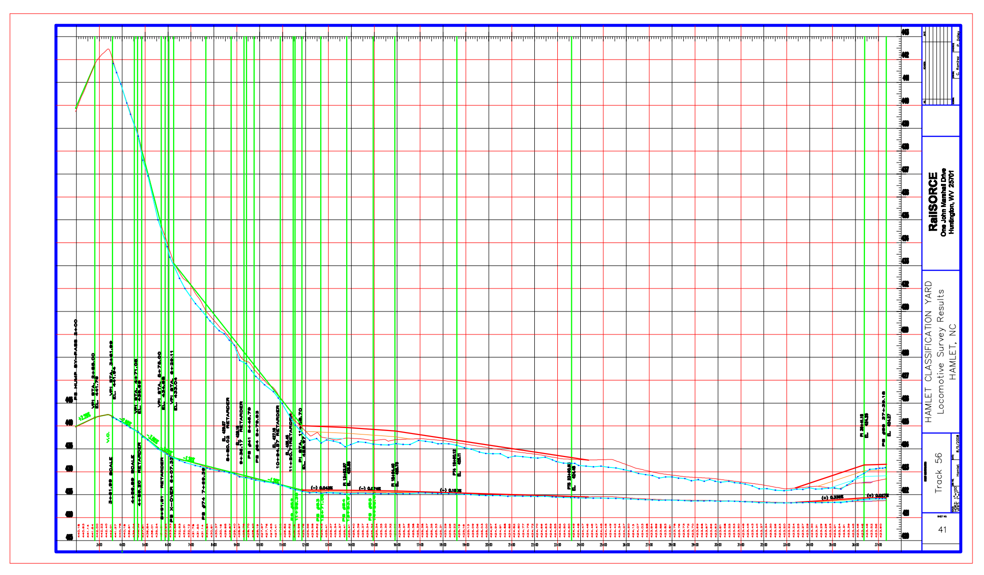
Group 4, Track 25



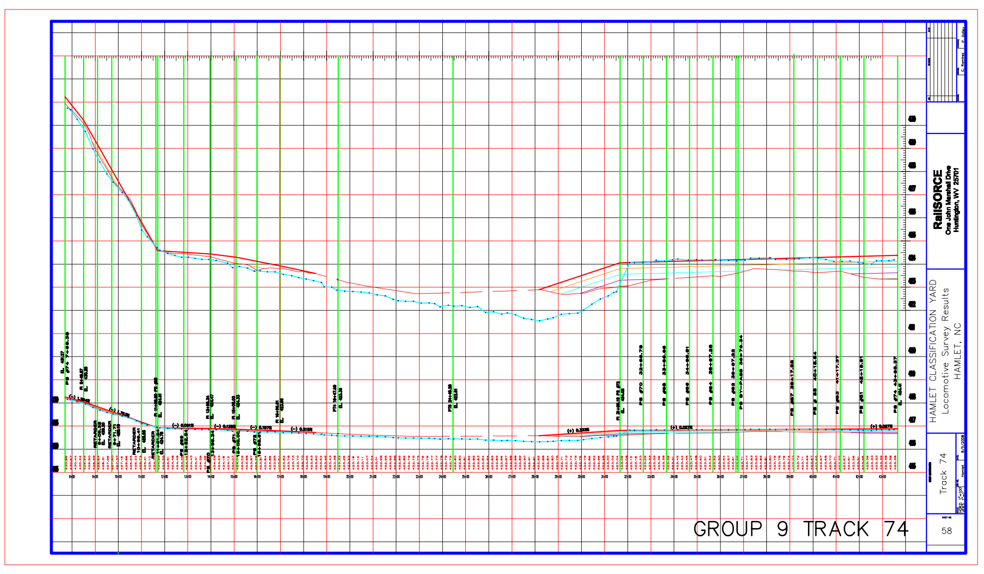
Group 6, Track 41



Group 7, Track 56



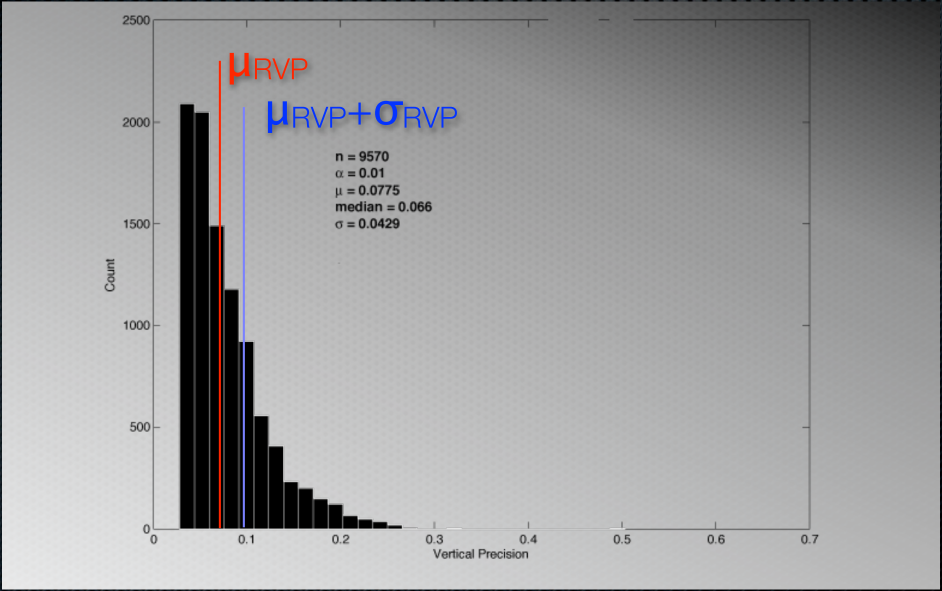
Group 9, Track 74

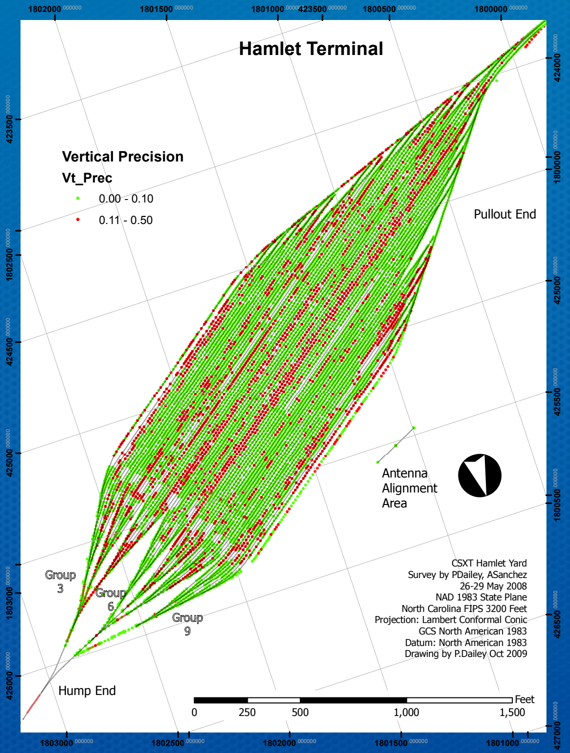


Multipath Analysis

	Reference Station cycle slips / total obs.	Locomotive Relative Vertical Accuracy
μ_{RVP} σ_{RVP}		0.08 ft (2.4cm) 0.043 ft
MP1 cycle slips 1575.42 MHz, λ = 19 cm	121 / 9,112 1.32%	
MP2 cycle slips 1227.60 MHz, λ = 24.4 cm	119 / 9,112 1.30%	±2cm (0.066ft)

Relative Vertical Precision




Hamlet Terminal
Vertical Precision
Vt_Prec
0.00 - 0.10
0.11 - 0.50
Pullout End
Antenna
Alignment
Area
Group
3
Group
6
Group
9
Hump End
CSXT Hamlet Yard
Survey by PDailey, ASanchez
26-29 May 2008
NAD 1983 State Plane
North Carolina FIPS 3200 Feet
Projection: Lambert Conformal Conic
GCS North American 1983
Datum: North American 1983
Drawing by P.Dailey Oct 2009
0
250
500
1,000
1,500
Feet

Research Result

Characteristic	Value
Safety, exposure hours	6
Labor efficiency, man hours	97
Time to completion, days	4-1/2
Track observations	9,570
Nominal observation stationing, feet	10
Operation disruption, hours	2

Conclusions

- Safer than differential level survey
  - 6 vs 500 exposure hours (est. Kerchoff & Szwilski)
- Greater data density than differential level survey
  - 10 ft vs 100 ft stations
- Faster than differential level survey
  - 4-1/2 days vs 25 days
- Fewer labor hours than differential level survey
  - 100 vs 500 man-hours (est. Kerchoff & Szwilski)

Conclusions, cont

- RTK GPS shows little effect of multipath signal distortion
- RTK GPS unaffected by weather
  - Day-long torrential rain

Implications

- Follow up on resurfacing project:
  - Operator skill and judgement used during regrading
    - Not data driven - what are the as-built grades?
  - Implies additional research needed to implement RTK GNSS measurement on track resurfacing equipment

Experiment 2
Track Alinement

Determine degree of curvature (D_C) from an RTK equipped track inspector's Hi-Rail during routine inspection of mainline track.

Mainline Track

§213.9 Classes of track: operating speed limits

9(a) Except as provided in paragraph (b) of this section and §213.57(b), 213.59(a), 213.113(a), and 213.137(b) and (c), the following maximum allowable operating speeds apply:

Over track that meets all of the requirements prescribed in this part for	*The maximum allowable speed for freight trains is*	*The maximum allowable speed for passenger trains is*
Excepted	*10*	*N/A*
1	*10*	*15*
2	*25*	*30*
3	*40*	*60*
4	*60*	*80*
5	*80*	*90*

Table 1

Alinement Defects

§213.55 Alinement

Alinement may not deviate from uniformity more than the amount prescribed in the following table:

Class of Track	Tangent Track	Curved Track	
	The deviation of the mid-offset from a 62-foot line [1] may not be more than—	The deviation of the mid-ordinate from a 31-foot chord [2] may not be more than—	The deviation of the mid-ordinate from a 62-foot chord [2] may not be more than—
1	5"	N/A [3]	5"
2	3"	N/A [3]	3"
3	1¾"	1¼"	1¾"
4	1½"	1"	1½"
5	¾"	½"	⅝"

[1] The ends of the line must be at points on the gage side of the line rail, five-eighths of an inch below the top of the railhead. Either rail may be used as the line rail, however, the same rail must be used for the full length of that tangential segment of track.

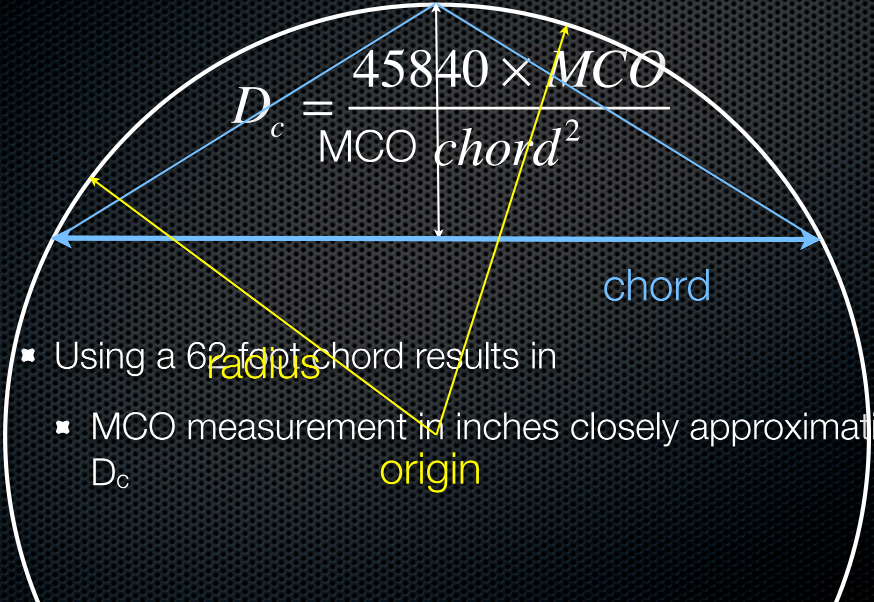
[2] The ends of the chord must be at points on the gage side of the outer rail, five-eighths of an inch below the top of the railhead.

[3] N/A - Not Applicable.

Table 4

Degree of Curvature (D_c)

$$D_c = \frac{45840 \times MCO}{chord^2}$$



- Using a 62 foot chord results in
  - MCO measurement in inches closely approximating D_c

Visual Track Inspection

- FRA Mandate
  - Every track at least every 2 weeks
  - Inspection duties include light repair
    - e.g., broken frog bolts, insulated joint replacement, guard rail maint.
- Rail companies specify greater frequency based on
    - Load MGT/yr
    - Cargo
      - Gain/coal/intermodal vs. HAZMAT
    - Inspection History

SOA Track Measurement and Defect Measurement

- CSX TGC-2
  - heavy / train / $$$
- NS TGC
  - heavy / train / $$$
- CSX GRMS-2
  - light / self-propelled / $$$
- CSX GRMS-1
  - light / self-propelled / $$$

Research Question

Can RTK GNSS instrumentations mounted to a track inspector’s Hi-Rail be used to determine the degree of curvature (D_C) across mainline track comparable with specialized track geometry cars?

Mainline Track Alinement Purpose & Objectives

Determine the D_c across a track inspectors area of responsibility

- Equip a track inspector's Hi-Rail with RTK GNSS instruments in communication with a VRS server to maximize observation accuracy
- Observe track position continuously across an inspector's 29 mile area of responsibility at track speed between 10 and 40 mph
- Model the FRA sting line method for determining degree of curvature (D_C)
  - Verify model output against rail company track charts
- Compare D_C with track geometry car measurements

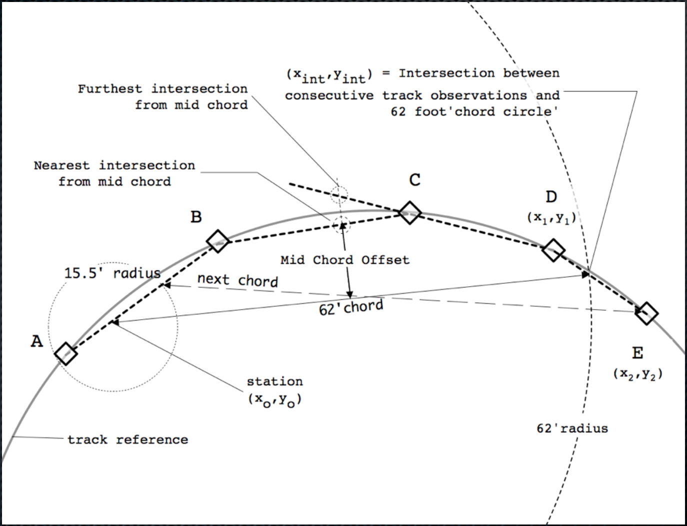
May
2010


THE American Surveyor
A Foot In The Past… An Eye To The Future
Vol. 7, Issue 3
SMART Surveying
Ashtech is Back!
An interview with François Erceau
The Birthplace of VRS
Great ideas from Bavaria
The Center of Section
Which corner controls?
GRP System FX

Mainline Survey Genesis

- Integrated Track Stability And Measurement System (ITSAMS) 2003
  - GPR - ballast
  - EMI - moisture
  - GPS - enable location for GPR & EMI
- GPS track measurement
- Experiment 2 setup

Modeling D_c from XYZ



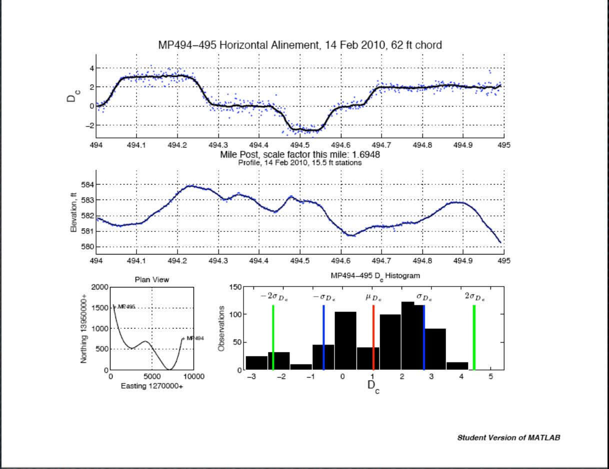
Experiment 2 Results

- Continuous segment of mainline track
  - 29 mile traverse of a track inspector's area of responsibility
- Networked CORS & VRS server minimize proximity error
- Expected LOS due to overhead obstructions

Survey	Observations
A	18,095
B	15,225
C	22,866
D	19,993
E	21,001

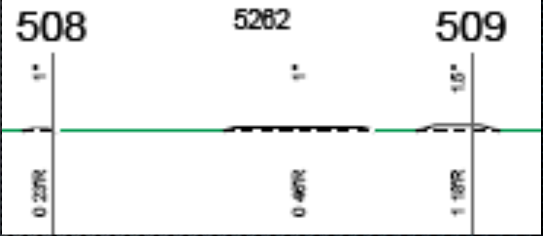
Results
XYZ to D_c Model Output

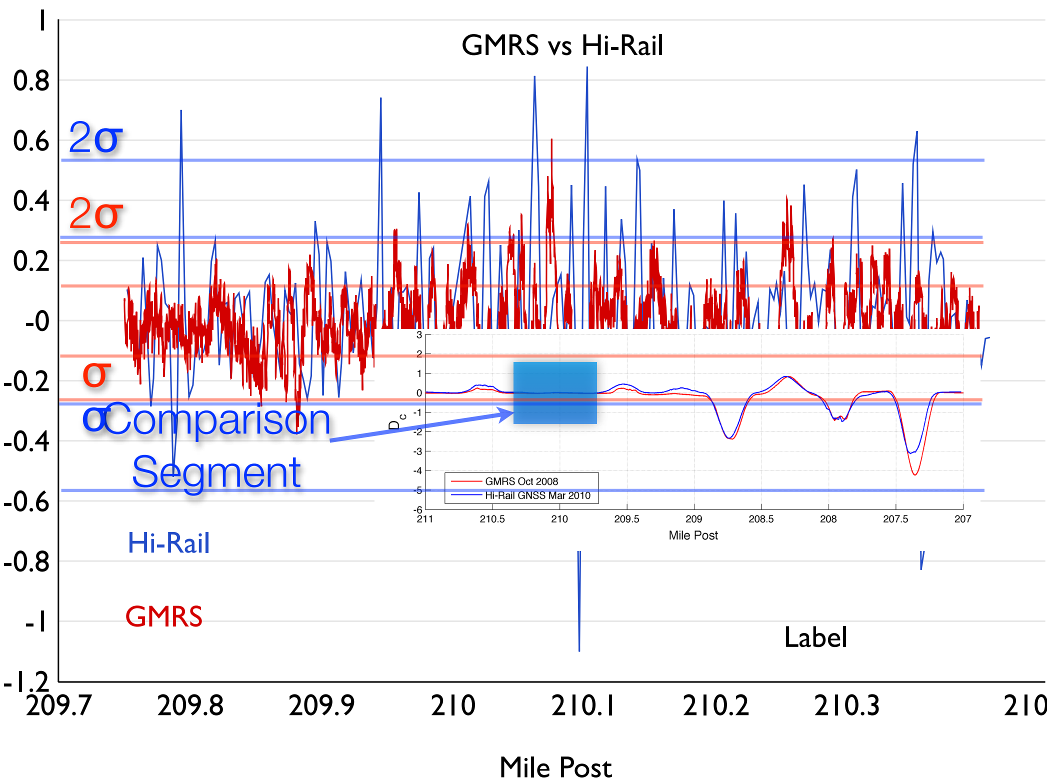
- MP 494-495
  - verify curves
- MP 499-500
  - tangent
- MP 500-501
  - exit spiral
- MP 521-521
  - LOS



Model Discrepancies with Rail Company Track Charts

- MP 508.9 curve direction
  - TC: 1°18’ right
  - Model: left
- MP 521.15 curve length
  - TC: 0.15 miles
  - Model: 0.65 miles




GMRS vs Hi-Rail
2σ
2σ
σ
σ
Comparison
Segment
Hi-Rail
GMRS
Label
Mile Post
1
0.8
0.6
0.4
0.2
-0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
209.7
209.8
209.9
210
210.1
210.2
210.3
GMRS Oct 2008
Hi-Rail GNSS Mar 2010
D_c
Mile Post

Conclusions

- XYZ to D_c model verified by rail company information
- Hi-Rail not equivalent to track geometry car
  - RTK capable of detecting actionable defects
    - Track classes 1-4
    - Class 5 with additional research/improved modeling
- Hi-Rail & XYZ to D_c model near limit of the instrument
  - ±1 cm (0.39 in) @ 95% CI
- At present, continuous RTK GNSS track observations are impeded by LOS due to overhead obstructions

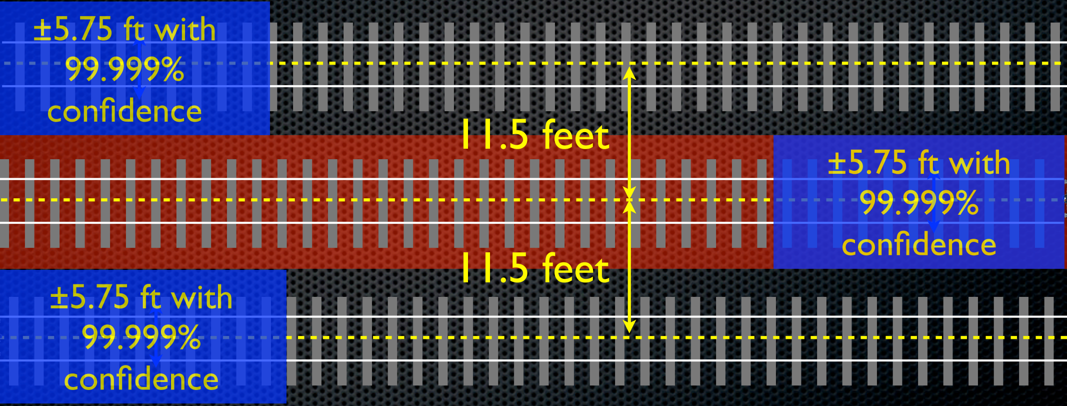
Implications

- Further study & improved model may produce actionable track alinement information from Hi-Rail borne RTK GNSS measurements.
- Additional GNSS sensor(s) would provide 2nd axis for
  - Measuring superelevation
  - Measuring grade
  - Modeling twist

Experiment 3
Determining Track Occupancy

Assess the ability of RTK GNSS to determine the track occupancy of a Hi-Rail vehicle meeting the definition of a location determination system.

FRA Wireless Track Occupancy



1995 Federal Railway Administration Report

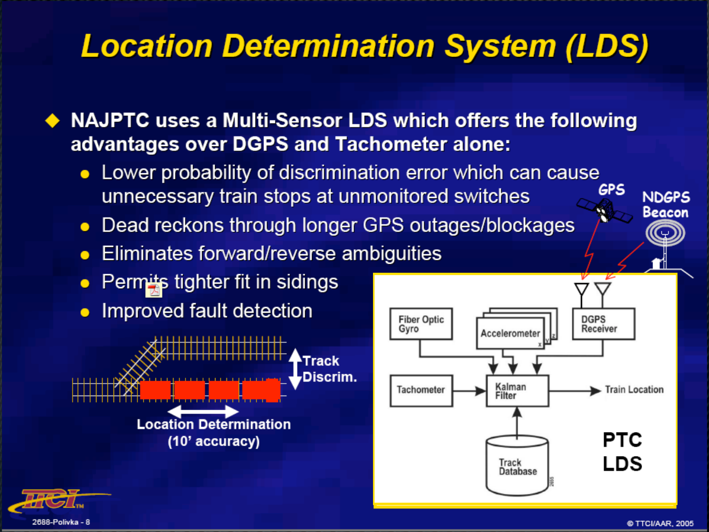
Motivation

- Track occupancy presently determined by wired track circuits
  - Insulated joints between CWR segments
    - Axle completes low voltage circuit across rails
  - Proximity switches (magnetic)
  - Loop detectors
- Replacement value for signals: \$125,000 / mile (Moorman)
- No wired circuits or signals = “Dark Territory”

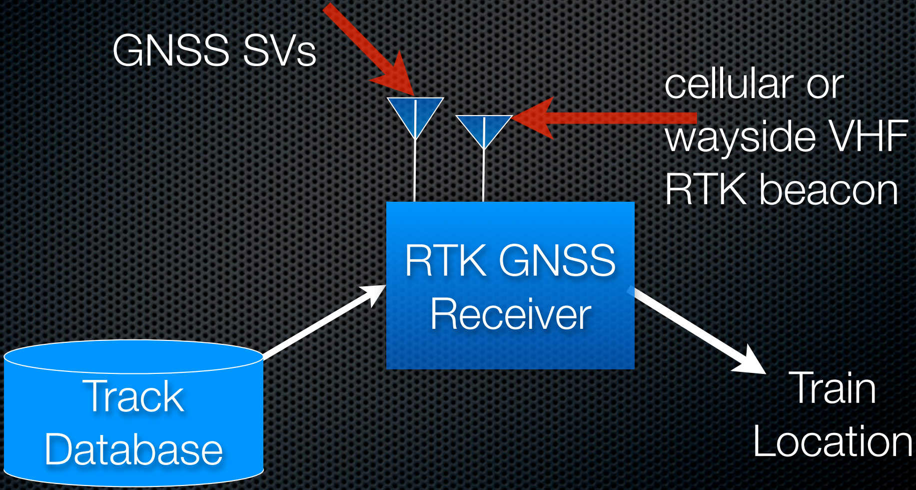
Motivation

- Railroad Safety Improvement Act of 2008
  - Class I railroads, as well as intercity passenger and commuter railroads, must install PTC on main line tracks by Dec. 31, 2015.
    - Act defines mainline as > 5 MGT/Y

Transportation Technology Center, 2005 LDS concept



Research Postulates that RTK GNSS will simplify LDS



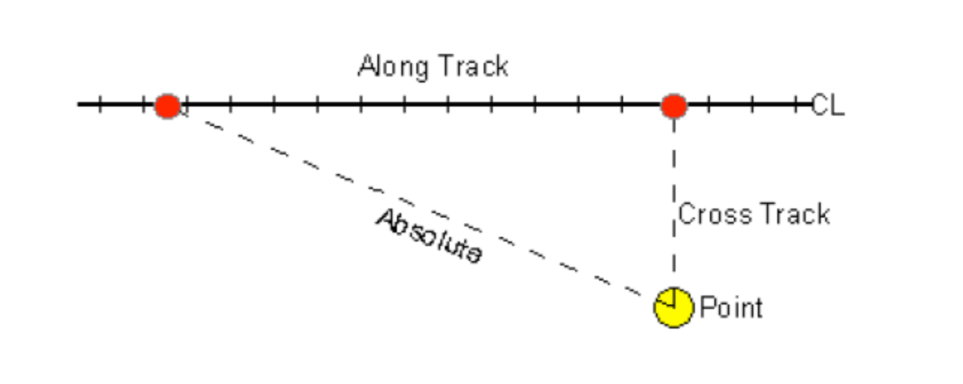
Research Question

Can RTK GNSS determine track occupancy meeting the FRA specifications for a location determination system?

Observation Data

- Mainline tangent and circular track segments
  - Three parallel tracks
  - Five traverses
- Tangent 498.9 to 500.2
- Curve

Tangent Segment



Distance to reference centerline is cross track error

(Allen, et.al.)

Track Occupancy Null Hypothesis - Tangent

- Z-test uses standard deviation of X-track distances from reference tangent dataset
  - Eliminate track roughness from test tracks
- Test that the mean is a random sample from a normal population with a cross track error less than half a centerline to centerline distance of 11.5 feet
- CI = 100(1-α)
  - α=0.00001

$$h_0 : \mu_d \le \frac{11.5}{2}$$

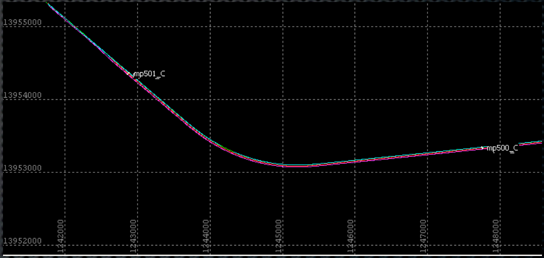
$$h_1 : \mu_d > \frac{11.5}{2}$$

Hypothesis Test Result
Tangent Track

Track	N	μ_d	σ_d	Reject h_0?
2_A-2_A	1,189	0.13’	0.08’	no
2_B-2_A	1,244	0.13’	0.08’	no
3_C-2_A	1,152	13.10’	0.35’	yes
1_D-2_A	1,158	13.51’	0.20’	yes
3_E-2_A	1,156	13.05’	0.31’	yes

Curve Segment

- Circular portion (full body) of curve
- First traverse reference centerline
- Regression to establish curve coefficients
  - Origin & radius
- Distance to reference curve determined from subsequent traverse observations



Hypothesis Test Result Circular Curve Track

$Track_{traverse}$	N	μ_r	σ_r	Reject h_0?
2_A-2_A	85	0.00’	0.03’	no
2_B-2_A	98	0.03’	0.04’	no
3_C-2_A	98	-14.53’	0.16’	yes
1_D-2_A	97	13.93’	0.10’	yes
3_E-2_A	92	-14.57’	0.14’	yes

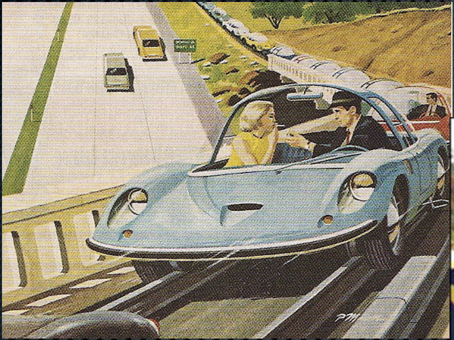
Conclusions

- Given a priori track centerline locations and a network RTK VRS server, track occupancy can be determined by single epoch RTK observations over a wide area meeting the accuracy requirement for an LDS.

Implications

- Occupancy determination by locomotive
  - Receiver, database, processor
- RTK positions transmitted through wayside voice repeater enable real time tracking/track occupancy determination external to track vehicle
- Can be applied to any track vehicle
- Could be applied to individual on-track workers

Wider Transportation Implications



Highway

- Vehicle / Highway Interaction
  - RTK GNSS lane deviation
    - RTK GNSS driver attentiveness
  - RTK GNSS Vehicle guidance

Aeronautical Engineering

- RTK GNSS precision landing
  - Auto land w/o barometric altimeter
  - Precision approach program for any major/minor airport
    - Contrast with FAA LAAS (RTK @ airport)

Waterways

- River profile mapping
- Water level & bridge clearance
- Auto guidance systems
  - Lock & dam
  - Dock

Pipeline

- Above ground pipe monitoring
  - e.g., Alaska - seasonal effects/abnormal

Civil Engineering

- Structure monitoring
  - Bridge
  - Dam
  - Impoundments
    - coal slurry