APPENDIX B
CURVE ANALYSIS, PHILADELPHIA TO HARRISBURG; SPEED ANALYSIS OF CURVES AND CIVIL IMPACTS

Recent simulations and analyses of future intercity, commuter, and freight operating requirements have concluded that significant track changes are required to achieve trip time goals, improve the reliability of intercity and commuter operations, increase capacity, and provide improved operating flexibility. These needs would be satisfied by reconfiguring major terminals and interlockings, removing existing crossovers and turnouts, and installing new (mostly higher speed) turnouts and crossovers to implement desired alignment and configuration changes. Revised interlocking layouts also will be required to optimize train operations entering and leaving the additional tracks, and passing sidings that also have been recommended. The number of interlockings that will be modified and the new interlockings that are recommended are significant. Details of recommended programs are contained in the body of the report. The proposed track configurations are illustrated in Appendix E. The interlocking changes that have been recommended are summarized in the body of the report.

Track curvature imposes the most severe constraint on trip time. Consequently, realigning or changing the physical characteristics of existing curves is a primary means of reducing trip times included in this program. Several types of fixed-plant improvements can minimize the constraints to speed associated with curves:

- increasing superelevation to the maximum allowable for a particular track alignment;
- changing horizontal and vertical alignment, either within the existing right-of-way, or by acquiring land outside the existing right-of-way;
- increasing the amount of unbalanced superelevation used to calculate speeds through curves to minimize track shifts; and
- modifying spirals (the length of track that provides a smooth transition from level, tangent track to curved, superelevated track) by eliminating superelevation runoff onto the adjacent tangent sections.

The rationale for the realignments recommended in this program is summarized in this appendix.

OBJECTIVE

The results of a speed analysis of curves, and the civil impacts associated with realigning them for the Keystone Corridor segment of the Northeast Corridor (between Philadelphia and Harrisburg) was performed by Parsons Transportation Group. The results of those analyses are summarized in the following subsection.

The goal of the Plan is to reduce the trip time between Philadelphia and Harrisburg to less than 90 minutes. There are several changes to the methods of operation, to the facilities, and to the equipment that can contribute to the overall goal.

One of these changes is to increase the speed of the trains. Increasing the speed may require one or all of the following:

- more powerful or additional locomotives;
- coaches that can provide comfort at greater unbalanced speeds, tilt vehicles will be needed for unbalanced superelevation greater than 5 inches;
- tracks and track beds that can withstand the energies transferred at higher speed (including greater imbalance); and
- alignments that can accommodate the greater speeds without exceeding acceptable limits for:
  - actual superelevation,
  - unbalanced superelevation,
  - lateral acceleration to the passenger
  - spiral lengths limited by:
    - rate of change of change of actual superelevation or twist,
    - rate of change of change of lateral acceleration to the passenger or jerk.

The objective of this analysis was to propose realignments to the existing curves so that proposed speeds can be reached and to identify civil impacts caused by the proposed realignments. The results of the analysis were used to develop a project estimate for realigning curves. The methodology employed to perform the analysis and the results of the analysis are presented in this subsection.

CRITERIA AND SCOPE

Criteria

The criteria utilized in the performance of this analyses were as follows.

Maximum actual superelevation should not exceed 6 inches. Actual superelevation was chosen in increments commensurate with the runoff rates specified by Amtrak and speed.

Maximum unbalanced superelevation should not exceed 5 inches; this assumes the use of conventional, non-tilt equipment.

Maximum lateral acceleration parallel to the floorboards should not exceed 0.15 g.

For conventional coach equipment at 6 inches of unbalanced superelevation the roll angle should be 2.87 degrees and lateral acceleration parallel to floorboards should be 0.15 g.

All actual superelevation should be introduced and removed over the entire length of the spiral; actual superelevation should not be introduced and removed on the adjacent tangents.

Maximum jerk rate through the spiral should be 0.04 g per sec.

Maximum track twist rate (introduction and removal rate of actual superelevation) through existing spirals for speeds less than, and equal to 90 miles per hour, should be 3/8-inch in 31 feet. For speeds greater than 90 miles the maximum twist rate through existing spirals should be 1/4" in 31 feet.

Track twist rates for alignments specified by Amtrak at proposed speed:

- speeds from 0 to 50 miles per hour, 1/2-inch per 31 feet;
- speeds from 51 to 70 miles per hour, 3/8-inch per 31 feet; and
- speeds from 71 to 125 miles per hour, 1/4-inch per 31 feet.

Scope

The curves to be considered in the analysis were those located between Philadelphia 30th Street Station and Harrisburg Station. Studies recently performed for PaDOT proposed maximum speeds for individual curves. These were speeds were used as initial speed goals, but were modified as necessary to reflect the iterative analysis process subsequently defined. Maximum speed sought was 110 mph.

Presently maximum speed for passenger trains in the corridor is 90 mph. Maximum authorized speeds vary by location and are specified in the Amtrak Employees Timetable. The analysis was based for the most part on data for Track 1; where data was unavailable Track 3 data was used.

One product of the analysis was the conclusion that, with a limited number of exceptions, each curve on the corridor had to be modified to some degree - usually both spiral length or superelevation changed. For each curve the highest speeds that can be reached without realignment or adjustment to the actual superelevation on each of the existing curves, while satisfying safety and comfort criteria, were calculated. An iterative process was then followed to identify the maximum speed attainable (in five mph increments) on each curve. Changes to superelevation and spiral length were determined.

The analysis indicates that the speed improvements can be attained in many instances by merely surfacing and aligning the track as part of a normal maintenance cycle.

The study did not identify specific curves that should have their degree of curvature decreased to enable speeds to be increased. Curves whose degree of curvature is 1.1 degree or more would not support speeds of 110 mph or more[1], and therefore would be candidates for further detailed analysis in subsequent studies. Curves to be modified should be selected on the basis of their cost effectiveness - the cost per minute saved as the result of the modification. The analysis will require that Train Performance Calculation (TPC) runs be made to determine the time savings as the result of each curve modification. The cost of each modification also will have to be estimated, and by dividing the cost by the time for all curve modifications a cost effective listing could be developed, which would assist the planner in evaluating which improvements should be funded.

A second product was the calculation of the highest speeds that can be reached with realignment to improve spiral lengths and with adjustment to the actual superelevation, while satisfying safety and comfort criteria. The result of the analysis was a list of proposed realignments to reach the proposed speeds. In addition to safety and comfort criteria the proposed realignments will comply with standard Amtrak field maintenance practices. No required shifts in excess of three-feet. Curves requiring shifts between 6 inches and 3 feet are shown in Table 1. Curves requiring shifts of about 6 inches are shown in Table 2.

Actual bridge impacts will need to be confirmed on a bridge-by-bridge basis. Where there are no undergrade bridges and the shifts are less than 6 inches, the realignments can be performed with regular maintenance procedures, and will not result in significant additional civil costs. Curves that have turnouts to industrial spurs within their length have not been identified, but need to be; since turnouts will limit the actual superelevation and the speed in the curve. In these cases the realignment will be more significant resulting in increased costs.

The analysis technique (a spreadsheet) made it easier to answer "what-if?" questions, such as, how much will the proposed speed be reduced if the realignment shift was reduced so as not to impact bridge B? Or, how much additional shift would be required to increase the proposed speed on curve A?

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[1]Assuming maximum actual superelevation of six inches and maximum unbalanced superelevation of five inches.

Table 1
Curves Requiring Shifts Between 6 Inches and 3 Feet

Cve No.	Trk No.	Curve degrees	Radius feet	West Spiral	East Spiral	Total Measured length	Avg Ea Exist	110 mph V	Avg Ea Prop	Optimal Ls	Expected Max Shift
616	3	2.0000	2,865	350	510	2,000	5.25	80	4.13	512	**2.02**
679	1	1.0000	5,730	550	640	2,460	3.25	110	3.50	434	**1.61**
692	1	0.7667	7,473	400	620	3,420	2.00	110	2.50	310	**1.61**
617	3	2.0000	2,865	410	400	1,640	5.00	80	4.13	512	**1.48**
649	1	1.0833	5,289	340	570	3,220	3.00	110	4.25	527	**1.28**
624	3	4.0000	1,432	300	190	1,640	4.50	50	4.50	279	**1.21**
671	1	2.0333	2,818	530	650	3,480	5.50	80	4.75	589	**1.12**
695	1	2.1000	2,728	490	560	1,800	5.75	80	4.50	558	**1.09**
688	1	0.7000	8,185	570	330	2,090	1.75	110	2.75	341	**1.06**
706	1	0.5000	11,459	320	560	3,180	1.50	110	1.50	186	**1.01**
663	1	**3.9000**	1,469	430	370	2,220	5.50	60	5.00	413	**0.96**
669	1	1.5833	3,619	680	550	3,040	5.50	95	5.00	620	**0.94**
630	1	2.1167	2,707	430	510	2,080	5.50	75	4.00	496	**0.94**
657	1	2.0000	2,865	510	430	4,160	5.00	80	4.00	496	**0.89**
708	1	0.9000	6,366	340	560	1,520	2.25	110	3.50	434	**0.82**
629	1	2.0000	2,865	440	530	1,680	5.75	80	4.00	496	**0.76**
694	1	1.0333	5,545	530	430	1,560	3.50	95	3.50	434	**0.70**
639	1	**2.3500**	2,438	400	350	2,610	5.75	70	4.88	403	**0.68**
612	1	2.3167	2,473	350	430	4,840	4.75	70	4.88	403	**0.67**
1a	1	4.8000	1,194	270	220	970	2.50	50	3.75	233	**0.66**
691	1	0.5000	11,459	300	450	3,790	0.62	110	1.25	155	**0.65**
675	1	1.0000	5,730	400	500	2,050	3.00	100	3.25	403	**0.64**
686	1	1.2000	4,775	470	300	940	3.25	95	3.25	403	**0.63**
651	1	0.7500	7,640	340	170	2,530	2.50	110	3.00	372	**0.60**
710	1	2.1000	2,728	280	350	900	5.40	70	2.75	341	**0.58**
638	1	3.0000	1,910	430	370	2,270	5.50	65	4.88	403	**0.56**
0a	1	4.9000	1,169	70	130	800	1.75	45	2.25	140	**0.52**
661	1	2.0167	2,841	530	470	2,240	5.75	75	4.00	496	**0.51**
664	1	2.0000	2,865	530	480	2,660	5.50	80	4.00	496	**0.51**
652	1	0.7667	7,473	330	220	990	2.00	110	3.00	372	**0.50**

Table 2
Curves Requiring Shifts of About 6 Inches

Cve No.	Trk No.	Curve degrees	Radius feet	West Spiral	East Spiral	Total Measured length	Avg Ea Exist	110 mph V	Avg Ea Prop	Optimal Ls	Expected Max Shift
627	1	1.1000	5,209	330	110	1,760	3.00	75	1.75	217	**0.49**
682	1	1.0833	5,289	400	500	2,970	2.00	100	3.50	434	**0.49**
698	1	0.9833	5,827	460	530	3,760	3.50	110	3.75	465	**0.46**
678	1	1.0833	5,289	580	550	4,160	3.50	110	4.25	527	**0.46**
628	1	2.0333	2,818	530	570	1,370	5.75	80	4.50	558	**0.45**
659	1	1.0000	5,730	500	430	1,800	3.50	110	4.00	496	**0.44**
700	1	1.4000	4,093	490	450	2,360	4.50	95	4.00	496	**0.44**
653	1	0.7500	7,640	420	390	1,810	2.50	110	2.50	310	**0.44**
699	1	1.9500	2,938	530	550	3,400	5.75	80	4.50	558	**0.43**
621	3	1.5000	3,820	280	370	1,370	3.50	80	2.75	341	**0.41**
648	1	1.0000	5,730	440	520	2,790	3.25	110	4.00	496	**0.38**
681	1	1.0000	5,730	430	490	2,620	3.50	105	3.50	434	**0.38**
667	1	1.0000	5,730	500	450	4,590	2.75	110	4.00	496	**0.32**
683	1	1.0000	5,730	480	440	1,950	2.50	105	3.50	434	**0.31**
620	3	3.0000	1,910	340	310	1,120	5.75	65	4.00	331	**0.29**
647	1	0.5000	11,459	280	330	970	1.50	110	1.50	186	**0.27**
626	3	1.1667	4,911	370	330	860	3.00	90	3.00	372	**0.25**
650	1	0.5000	11,459	360	170	3,810	1.50	110	2.00	248	**0.25**
690	1	1.0000	5,730	470	400	2,330	2.50	105	3.50	434	**0.24**
689	1	0.6667	8,594	260	370	1,240	2.75	110	2.75	341	**0.24**
618	3	1.1167	5,131	340	260	880	3.75	85	2.50	310	**0.23**
641	1	1.0000	5,730	430	440	2,120	3.25	105	3.75	465	**0.23**
660	1	1.0000	5,730	430	470	1,430	3.25	105	3.75	465	**0.23**
672	1	2.0000	2,865	480	480	2,700	5.25	80	4.00	496	**0.23**
614	1	0.3667	15,626	330	320	2,080	1.25	110	1.25	155	**0.23**
634	1	0.5000	11,459	330	320	1,240	1.75	110	1.75	217	**0.22**
703	1	0.7500	7,640	420	320	1,160	1.25	110	3.00	372	**0.21**
608	1	1.2000	4,775	270	330	870	2.50	85	2.50	310	**0.20**
696	1	0.5000	11,459	320	250	1,190	1.50	110	1.75	217	**0.20**
673	1	1.0833	5,289	420	460	2,560	3.25	100	3.50	434	**0.18**
653E	1	0.5000	11,459	330	250	690	1.00	110	2.00	248	**0.17**
704	1	1.0000	5,730	450	440	2,250	3.25	110	3.75	465	**0.16**
654E	1	0.5000	11,459	300	270	1,120	1.00	110	1.75	217	**0.16**
642	1	0.8333	6,876	370	420	1,530	2.75	110	3.25	403	**0.15**
613	1	1.5000	3,820	400	420	3,540	4.00	85	3.25	403	**0.15**
654	1	0.5000	11,459	320	140	780	1.25	110	2.00	248	**0.15**
674	1	0.5000	11,459	320	160	1,410	0.50	110	2.00	248	**0.15**
702	1	0.4000	14,324	290	210	1,170	1.50	110	1.50	186	**0.14**
668	1	0.8000	7,162	320	270	1,620	1.25	100	2.50	310	**0.13**
670	1	1.2000	4,775	420	390	890	3.75	95	3.25	403	**0.12**
677.1	1	0.5000	11,459	180	260	510	1.00	100	1.50	186	**0.12**
12A	3	0.6000	9,549	200	110	510	0.75	80	1.00	124	**0.11**
623	3	2.3333	2,456	320	310	1,890	5.50	70	3.75	310	**0.11**
676	1	0.3000	19,099	240	240	3,960	0.75	110	0.75	93	**0.11**
605	4	1.2500	4,584	0	0	0	1.00	70	1.00	108	**0.11**
645	1	**0.2500**	22,919	320	200	1,810	1.75	110	1.75	217	**0.10**
684	1	0.2000	28,648	280	200	2,780	1.00	110	1.00	124	**0.09**

Table 2
Curves Requiring Shifts of About 6 Inches

Cve No.	Trk No.	Curve degrees	Radius feet	West Spiral	East Spiral	Total Measured length	Avg Ea Exist	110 mph V	Avg Ea Prop	Optimal Ls	Expected Max Shift
697	1	1.0167	5,636	430	420	1,890	3.50	105	3.50	434	**0.09**
2a	1	1.3000	4,407	180	160	580	1.00	70	2.25	186	**0.09**
655	1	0.5000	11,459	200	230	630	0.50	110	2.00	248	**0.08**
687	1	0.5000	11,459	200	230	800	1.25	110	2.00	248	**0.08**
685	1	1.2000	4,775	360	380	1,190	2.00	90	3.00	372	**0.08**
631	1	0.2000	28,648	120	260	1,320	1.00	110	1.00	124	**0.08**
709	1	0.2500	22,919	200	200	630	0.50	70	0.50	62	**0.07**
705	1	0.2000	28,648	190	220	1,870	1.00	110	1.00	124	**0.05**
646	1	0.5000	11,459	220	240	890	1.25	110	2.00	248	**0.05**
693	1	1.9833	2,889	530	530	3,500	5.75	80	4.25	527	**0.05**
2b	1	1.2000	4,775	170	160	610	0.75	70	1.88	155	**0.04**
632	1	0.5000	11,459	240	270	1,550	1.25	110	2.00	248	**0.04**
680	1	1.0833	5,289	430	440	2,570	3.50	100	3.50	434	**0.04**
640	1	1.6000	3,581	530	530	1,720	6.00	90	4.25	527	**0.04**
658	1	1.0833	5,289	460	460	2,060	3.25	105	3.75	465	**0.04**
637	1	0.2000	28,648	140	180	5,050	0.75	110	0.75	93	**0.03**
707	1	0.3500	16,370	270	260	2,200	2.00	110	2.00	248	**0.03**
666	1	0.5833	9,823	240	260	1,220	0.75	105	2.00	248	**0.03**
665	1	0.5000	11,459	210	200	1,780	0.75	105	1.75	217	**0.03**
625	3	0.5000	11,459	260	240	5,630	1.25	110	2.00	248	**0.02**
656	1	0.5000	11,459	240	260	880	0.50	110	2.00	248	**0.02**
615	1	0.9667	5,927	400	400	1,370	3.75	105	3.25	403	**0.02**

The analysis technique resulted in an estimate that is considered accurate to plus and minus 0.1-foot for simple spiraled curves, provided that the radius (degree of curvature) was not changed or the spirals were not changed by a significantly unequal amount. For compound curves the analysis technique is not reliable. For these more challenging realignments dummy cogos should be run to determine the shifts. A dummy cogo[2] is a cogo that properly uses all of the geometric elements (degree of curvature, spiral length, and intersection angle) of the alignment but the coordinates are not associated to any specific location. A dummy cogo previously was performed on a two centered compound curve on the New Haven Line between New Rochelle, NY and New Haven, CT, which was judged to be an extreme case[3]. From this cogo analysis it was judged that the maximum predicted shift will not be exceeded throughout the curve. However, the general characteristics of the shifting shown for compound curves should not be relied upon. The eight compound curves in the Keystone Corridor would require much more detailed investigation than was possible in this study, if the contemplated improvements are undertaken.

METHODOLOGY

Soft Realignments

There are two types of alignment changes: soft and hard. Soft alignment changes are changes in unbalanced superelevation, lateral acceleration to the passenger, and jerk that do not require physical changes. Therefore, there would be no cost associated with obtaining desired the speeds. These realignments would assume that the existing track twist (rate of introduction of superelevation) is acceptable. However, the present analysis did not identify any soft realignments between Philadelphia and Harrisburg.

Hard Realignments

Hard alignment changes are changes to actual superelevation, degree of curvature, and/or spiral lengths. Hard changes result in a physical change to the track, and when certain thresholds are reached, hard changes will impact adjacent or supporting facilities, such as, overhead bridges, undergrade bridges, signal towers, catenary towers, station platforms, etc.

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[2]Cogo, short for coordinate geometry, is a technique used to verify the mathematical feasibility of a concept.

[3]The Northeast Corridor Transportation Plan, New York City to Boston, Volume 2, Appendix I, July 1995.

Actual Superelevation on Tangent, Maximum Twist, etc. To meet comfort standards it was not considered acceptable to extend actual superelevation or track twist on to the tangents. Introduction and removal of actual superelevation should be linear, and should occur over the length of the spiral. As curve improvements are implemented occurrences of superelevation on tangents should be eliminated.

Shifts and Impacts

Right of way is generally not considered a factor unless the shift is very large and in those cases right of way would have been considered separately. The shifts identified in this study were not considered sufficient to require right-of-way acquisition. In general, the impacts of track shifts on overhead and undergrade bridges are of greatest concern, as is a determination whether the change can be made as part of a routine track maintenance surfacing operation.

Although each bridge located on the body of a curve ultimately will have to be individually evaluated to determine the impact of the assumed track shift, for these analyses it was generally assumed that if a specific shift exceeded the followings limits, the bridge would be impacted:

- open deck bridges with no additional improvement work proposed--any shift or change in superelevation;
- open deck bridges with through girders, or through deck girders scheduled for tie replacement--6 inches;
- open deck bridges with deck girders scheduled for tie replacement--1-foot;
- open deck bridges scheduled for conversion to ballasted deck--2 feet;
- ballasted bridges--2 feet; and
- overhead bridges--3 feet.

Bridges requiring replacement should be designed to accommodate the proposed alignment changes.

It also has been assumed that realignments that require shifts of 6 inches, and less, would be accomplished through regular maintenance practices and procedures. If the shift exceeds 6 inches, the track shifting cannot be done as part of maintenance and will require an independently scheduled effort.

Analysis Guidelines, Assumptions and Techniques

The analysis process utilized to analyze speeds and curves, and evaluate impacts on structures is subsequently described. The following are the guidelines, assumptions, and techniques for doing the analysis.

Degree of Curvature, Radius

The radius and degree of curvature were not changed.

Actual Superelevation

For curves whose superelevation is proposed to be changed, superelevation has been assumed to be implemented in increments in accordance with the way superelevation is introduced in the spiral by railroad maintenance personnel.

Unbalanced Superelevation

Unbalanced superelevation was computed from the following equation.

$$E_u = 0.0007 * D_c * V^2 - E_a$$

where E_u is unbalanced superelevation in inches
E_a is actual superelevation in inches
D_c is degree of curvature in decimal degrees
V is speed in miles per hour.

In accordance with previous agreed assumptions, unbalanced superelevation was limited to a maximum of 5 inches.

Lateral Acceleration Parallel to the Vehicle's Floor boards

When unbalanced superelevation occurs, passengers are subjected to a steady state lateral acceleration. This acceleration is the component of centripetal acceleration that is parallel to the floor boards of the vehicle. The calculation for this component takes into account the floor board rotation due to actual superelevation and the roll of the car body as it's suspension responds to the centripetal lateral acceleration. The lateral acceleration is computed from the following equation.

$$A_L = \{[(E_a + E_u) / G * COS(THETA - PHI * E_u / 6)] - SIN(THETA - PHI * E_u / 6)\} * g$$

where, A_L is lateral acceleration parallel to floor boards in g
THETA is the angle due to the actual superelevation = ARCSIN(E_a /G)
G = distance between rail head centers = 60 inches
PHI is the vehicle roll angle per 6 inches of unbalanced superelevation = 2.87 degrees per 6 inches of E_u.

The PHI value of 2.87 was derived from conventional coach data provided on page 21 of the report for the FRA entitled *Railroad Passenger Ride Safety*, revised April 1989.

Conventional non-tilting equipment has to be considered since either tilting or non-tilting equipment ultimately may be used. The tests reported indicated that both the LRC Coach (non-banking, with tilt capability cut out) and the Amfleet Coach reached 0.15 g of steady state lateral acceleration at 6 inches of unbalanced superelevation. By substituting these values into the above equation a PHI value of 2.87 is found calculated all values of actual superelevation up to 6 inches.

For prior projects, review of previous research and consultation with the FRA lead to the recommendation that 0.15 g should be the lateral acceleration limit. This analyses performed assumed that 0.15 g to be the lateral acceleration limit. Vehicle test data indicates that 0.15 g will be reached at 6 inches of unbalanced superelevation, therefore as long as unbalanced superelevation is limited to 5 inches, the lateral acceleration limit of 0.15 g will not be exceeded.

The PHI value is based upon available data for conventional non-tilting equipment. It is unlikely that new, non-tilting equipment will have a larger PHI coefficient, however, it might have a smaller value. A smaller PHI value would result in smaller lateral accelerations (good for passenger comfort) and in shorter comfort spiral lengths that would be based on a maximum jerk rate (jerk rate and comfort spiral are discussed in the following subsection). Consequently, spirals established based on the PHI value of 2.87 will be longer than necessary if the new non-tilting equipment has a smaller PHI. Therefore, the construction impacts resulting from shifts determined by the PHI value established for this report will be conservative.

The Comfort Spiral, Jerk, and Jolt

The comfort spiral transitions the passenger through a change in lateral acceleration (unbalanced superelevation) at a comfortable rate. Assuming that a vehicle's speed is constant, while traversing a spiral, unbalanced superelevation (lateral acceleration) changes linearly as the passenger travels along the spiral. This is because: degree of curvature changes linearly along a spiral; actual superelevation is introduced linearly along the spiral; and vehicle roll is linearly related to lateral acceleration. The change in lateral acceleration is referred to as jerk, with units of g per sec.

The jerk is computed by dividing the change in lateral acceleration (which is found by using the above equation and the change in unbalanced superelevation) by the time it takes for the passenger to travel over the spiral. The time is found by dividing the spiral length by the vehicle speed, with appropriate adjustments for units.

After a jerk rate has been established for a project, the minimum comfort spiral length can be computed by dividing the change in lateral acceleration by the jerk rate, and multiplying the quotient by the vehicle speed:

$$L_s = A_L / J * V = A_L / 0.04 * 88 / 60 * V = 36.67 * A_L * V$$

where, L_s is minimum comfort spiral length in feet
J is maximum jerk rate in g per sec
A_L is found from the earlier equation as a function of unbalanced superelevation.

AREA recommends 0.03 g per sec as a maximum jerk rate, when conditions permit. But where the cost of the realignment of existing tracks will be excessive the AREA recommends that the jerk rate should not exceed 0.04 g per sec. For this analysis a jerk rate of 0.04 g per sec for non-tilt train equipment was assumed.

The *Railroad Passenger Ride Safety* report, cited above, lists the lateral acceleration and jerk limits for several railroads. Jerk limits range from 0.03 to 0.1 g per sec. It is generally true that when a railroad accepts a higher jerk rate, it accepts a lower lateral acceleration. This is consistent with the observation reported in the same report that people are able to tolerate larger jolts when they are in a lower steady state lateral acceleration environment.

A jolt is also a rate of change of lateral acceleration per second, but it is considered as an occurrence that occurs in 1 second. A jolt is usually a response to a track irregularity. When jolts exceed 0.25 g per sec it is usually a sign that, for that speed, the track needs adjustment. The jerk through a spiral usually occurs over several seconds and, therefore, is not considered a jolt.

Usually back and forth car body rolling occurs when a track irregularity is encountered. The more violent the rolling the greater the jolt. When the jolt is measured as a lateral acceleration parallel to the floor boards, the position of the accelerometer affects the magnitude of the reading. In a double deck car, for the same track irregularity, a passenger on the lower level near the roll center of the car body will feel a smaller jolt than a passenger on the upper level.

The *Railroad Passenger Ride Safety* report also indicates that the researchers did not find any evidence that jerk is a comfort concern. This suggests that the comfort spiral could be shortened until the jerk is 0.25 g per sec. The problem with this approach is that the track has to be maintained in perfect condition. Any track irregularity would result in a total change in lateral acceleration that exceeds 0.25 g per sec.

The SNCF was found to have the highest limits, 0.15 g and 0.10 g per sec. Since comfort is a subjective feeling of the passenger, the SNCF may be recognizing that the French have a higher threshold to discomfort, or that they may be willing to tolerate a higher percentage of the passengers to be uncomfortable. Or, and perhaps more likely, SNCF has made a commitment to high quality track with tight maintenance tolerances for their high speed lines. (The British and American comfort criteria were established at comfort limits where 50 percent of the passengers will be satisfied. The Japanese desire to have 90 percent of the passengers satisfied.)

Track Twist

If the track twist, the rate of introduction or removal of superelevation, is too large, safety is impaired. When computing the maximum allowable speed for the existing alignment, the analysis performed verified that the ratio of the existing spiral length to actual superelevation was equal to, or greater than, 62 for speeds below, and including, 90 miles per hour. For speeds above 90 miles per hour, the ratio would be equal to, or greater than, 83.

When the maximum allowable speed did not reach the proposed speed the spirals were lengthened and the actual superelevation adjusted, as necessary, to maximize the speed. A third alternative, decreasing the degree of curvature and adjusting spiral lengths and superelevation was not utilized in this study. Where these alignment changes were required the spiral lengths were changed to satisfy the appropriate actual superelevation runoff rate assumed for the Keystone Corridor. The new spirals also were checked for jerk. The actual superelevation was adjusted until the jerk criteria was satisfied. The following are the runoff rate criteria specified for by Amtrak:

Speed Range, miles per hour	Runoff per 31'
0 to 50	1/2"
51 to 70	3/8"
71 to 125	1/4"

Track Shifts

For this analysis, shifts between the existing and the proposed alignments were computed at 2 points: near each of the curve spiral points. A third possible point, near the mid-point of the curve was not calculated. The shifts near the curve spiral points were estimated as the difference between the spiral offsets, the "p" distance, for the proposed and existing spirals. At the curve's mid-point the difference in the external distances for the proposed and existing alignment would have been estimated to be the amount of shift required.

The estimated shifts were checked for an earlier NEC study by running several dummy cogos using typical alignment curve data, and calculating offsets. A range of intersection angles, radii, spiral lengths, and differential spiral lengths, when the existing spirals are unequal, were tested. For simple, spiral curves it was found that the estimated shifts were within 0.1 feet and that they were usually on the conservative side, i.e., 0.1-foot larger than actual. If the proposed alignment has a different intersection angle or a significantly different radius, the estimated shifts become less accurate.

Compound Curves

Compound curves (a combination of two or more curves connected by transition spirals) added another level of complexity to the analysis. Except for the following modifications, the method used to estimate the amount of shift was basically the same as for simple curves. The following labeling was used:

Existing Compound Curve
- A-spiral length between tangent and longer radius curve
- B-longer radius curve
- C-combining spiral length
- D-shorter radius curve
- E-spiral length between tangent and shorter radius curve

Proposed Compound Curve
- PA-spiral length between tangent and longer radius curve
- PB-longer radius curve
- PC-combining spiral length
- PD-shorter radius curve
- PE-spiral length between tangent and shorter radius curve.

Each curve in the compound curve was analyzed separately. For the first curve the following curve elements were used:

Existing
- A-spiral length
- B-curve radius
- E-C-spiral length

Proposed
- PA-spiral length
- PB-curve radius
- PE-PC-spiral length.

For the second curve the following curve elements were used:

Existing
- A+C-spiral length
- D-curve radius
- E-spiral length

Proposed
- PA+PC-spiral length
- PD-curve radius
- PE-spiral length.

From initial checks it was found that the external distance is very dependent upon the intersection angle, but that the difference in external distances is not very sensitive to the intersection angle. Therefore, using data from track geometry car graphs provided by Amtrak, it was assumed to be sufficient to divide the total intersection angle in the same proportion as the curve lengths.

Dummy COGO checks indicated that the largest shift found using the estimating method is similar to the largest found with the dummy COGO but the location of the peak shift may not be correctly represented. To check for impacts at specific locations dummy COGO should be used.

Basis for Existing Curve Data

As with any analysis, the results of the curve analyses performed were only as good as the quality of the available existing data. The best source of data is good mapping or surveyed data points of the existing tracks. Description of an alignment by degree of curvature is incomplete, it is similar to describing a line by its slope. The description of a curve is not complete until the Y intercept is known. Stringline data and track geometry car data also are not ideal sources of data. The degree of curvature is never uniform, always varying. The result is that data elements assumed to describe the alignment may vary greatly from the actual configuration. The variation cannot be determined without mapping or surveyed data points.

The existing data sources used to develop information for the analyses performed were as follows:

- Amtrak track geometry car charts;
- earlier work performed by various consultants for PaDOT; and
- track charts.

The track charts were used for general orientation, but not to define spiral lengths, curvature, etc. The previous work efforts was used for background information only; data on proposed curve speeds and previous recommendations were obtained from the reports developed by those studies.

Data relative to the existing superelevation, spiral lengths, curve lengths, and degree of curvature were primarily developed from an analysis of recent Amtrak Track Geometry Car Charts, which were the result of a round-trip run of the corridor.

Although there were possible inconsistencies in the track geometry car data, it was necessary to use them in most instances. The data was valuable for providing the spiral lengths, which were measured directly from the charts of the individual simple and compound curves.

The track geometry car chart data was reduced as follows. The track geometry produces strip charts with fluttering lines. A visual average was made for the degree of curvature and actual superelevation. If the data was not uniform, the curve was subdivided into a compound curve. The distance between uniform curvature data points was assumed to be spiral lengths. The distance between uniform actual superelevation data was not assumed to have any relationship to spiral length because actual superelevation may have been run off onto the tangents and into circular curves.

It was assumed that tracks 3 and 4 and sidings also will be shifted, as necessary, when either would be the inside track on a curve, and thus need to be shifted to maintain adequate clearance to the shifted inner tracks. The costs for this effort were included in the project estimate, but it was assumed that the magnitude of shifts and, therefore, impacts on adjacent right-of-way structures would be driven by the changes required to the high-speed tracks, tracks 2 and 3.

For each curve, the existing data from each source was tabulated. The source data was compared, curve by curve, and data type by data type. Finally, one set of existing data for each curve was selected and compiled. The compiled data is the most conservative.

Speeds

The existing speeds were taken from the existing Amtrak Employees Timetables. The proposed speeds were initially taken from the speeds proposed in earlier PaDOT studies. Proposed speeds have been established in multiples of 5 miles per hour.

When determining the maximum allowable speed within the criteria the speed is shown to the nearest downward five miles per hour.

The Spreadsheet

To facilitate the analysis a spreadsheet was developed that allows for the existing speed, degree of curvature, spiral and curve lengths, and superelevation to be input. The input was utilized to perform a variety of calculations. The spreadsheet determined the maximum speed obtainable given the existing alignment and actual superelevation, by only making soft changes, i.e., only changes to speed, unbalanced superelevation, and jerk. For this initial analysis no change to curvature, spiral lengths, and actual superelevation were made. In general it was assumed that the proposed curvature will remain unchanged.

For those instances when superelevation and spiral length changes were analyzed, the spreadsheet was used to determine the shifts associated with changes in actual superelevation and spiral lengths that would satisfy railroad and comfort criteria, and attain the proposed speeds. For the proposed alignment only the proposed speed and actual superelevation had to be input. Unbalanced superelevation, optimal spiral lengths, and shifts were computed. "What if" questions about speeds were asked, and answered, by using different proposed speeds and superelevation for input. Limitations concerning the shift calculations were discussed earlier.

ANALYSIS PROCESS

The following questions for each curve were answered and the analysis proceeded as indicated.

1 What is the existing?:
   a. Amtrak curve number
   b. speed
   c. degree of curvature or radius
   d. actual superelevation[4]
   e. spiral length(s)

   The following were computed:
   f. maximum speed with existing superelevation, not taking spiral length into consideration;
   g. unbalanced superelevation;
   h. steady state lateral acceleration to the passenger;
   i. minimum spiral length based on unbalanced superelevation;
   j. Minimum spiral length based on actual superelevation and railroad runoff rate criteria;
   k. Optimal spiral length as the maximum of (i) and (j); and
   l. spiral offset(s) and external.

2. Since it was assumed that the superelevation does not run onto the tangent and circular curve then the following were computed/developed:

   a. steady state jerk(s) based on optimal spiral length (k).
   b. track twist(s), rate of change of change in actual superelevation, i.e., ratio of existing spiral length to existing actual superelevation.
   c. list of bridges with no planned work.
   d. list of ballasted bridges.
   e. list of overhead bridges.
   f. list of bridges to be replaced.

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[4]Whether superelevation ran onto either the tangent or circular curve was not determined.

3. Assuming that the superelevation does not run onto the tangent and circular curve, then the following were computed/developed:

    a. if 2.b. was greater than 83, the highest speed that does not exceed 5 inches of unbalanced superelevation, nor exceed 0.15 g lateral acceleration, nor exceed 0.04 g per sec jerk was determined. The existing radius, superelevation, and spiral length(s) were to remain unchanged. This speed was considered as the highest speed attainable with no impacts, no shift, and not requiring an alignment change. Note: when the existing spirals were of unequal length, the shorter spiral was used to compute jerk. The analysis proceeded to 4.

    b. if 2.b. was greater than 62, the highest speed less than or equal to 90 miles per hour that does not exceed 5 inches of unbalanced superelevation, nor exceed 0.15 g lateral acceleration, nor exceed 0.04 g per sec jerk was determined. The existing radius, superelevation, and spiral length(s) were assumed to remain unchanged. This speed was assumed to be the highest speed with no impacts, no shift, and that did not require an alignment change. Note: when the existing spirals were of unequal length, the shorter spiral was used to compute jerk. The analysis proceeded to 4.

    c. if 2.b was less than 62 a spiral length change was required. The spreadsheet would report that an alignment change was required. The analysis would proceeded to 4.

4. Steps 1-3 were performed for all the curves, a curve list showing the highest speed determined in 3.a. and 3.b was developed. The proposed speed for each of these curves was listed. The curves whose highest speed met or exceeded their proposed speed were highlighted. The list was entitled *Highest Speeds for All Curves without Alignment Changes*. Proceed to 5.

5. For all curves that were not highlighted in 4 (i.e., those curves that will need alignment changes, and/or changes in superelevation, radius or spiral length-to achieve the proposed speed, without changing radius) increase actual superelevation in increments specified for the segment and speed, without exceeding 6 inches, until the proposed speed was reached without exceeding 5 inches of unbalanced superelevation or exceeding 0.40 g/sec jerk rate. If the proposed speed could not be achieved without exceeding the above limitations, the speed was decreased in 5 mph increments until the limitations were not exceeded. Proceed to 6.

6. If 1.g (maximum speed with existing superelevation, not taking spiral length into consideration) exceeded the speed calculated in step 5 by five or more mph the following steps were followed -

1. maximum speed was increased in five mph increments;
2. actual superelevation was increased in increments specified for the segment and speed, without exceeding 6 inches, until neither 5 inches of unbalanced superelevation or exceeding 0.40 g/sec jerk rate were exceeded.
3. 6.1 and 6.2 were repeated until a further five mph increase would require more than 6 inches of superelevation or the 0.40 g/sec jerk rate would be exceeded.
4. Using the superelevation that was determined to be necessary to achieve the maximum feasible speed, the shortest spiral length that satisfied Amtrak curve criteria and did not exceed the 0.04 g per sec jerk, was calculated. Spiral lengths were established as an integer multiple of either 31, 39, or 50 feet, depending upon the speed. Shifts to achieve the proposed alignment were calculated.
5. The impact of the proposed shifts on each bridge were evaluated. If the shifts exceeded the followings limits the bridge was considered to be impacted:

   - open deck bridges with no planned work-any shift or change in superelevation;
   - open deck bridges with through girders or through deck girders scheduled for tie replacement--6 inches;
   - open deck bridges with deck girders scheduled for tie replacement--1-foot;
   - open deck bridges scheduled for change to ballast--2 feet;
   - ballasted bridges--2 feet; and
   - overhead bridges--3 feet.

   Bridges listed for replacement were assumed to not be impacted by alignment changes.

A list all of the curves that required alignment changes to achieve the proposed or optimal speed was developed. It included: proposed speeds, curves requiring 6 inches or less of shift, and curves requiring between 6 inches and 3 feet of shift.