Economics of Shoulder Ballast Cleaning

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ABSTRACT

Railway track ballast has a finite life that is largely determined by the amount of fine material filling the voids between the coarse ballast particles. An excessive amount of these fouling fines reduces the strength and drainability of the ballast and allows water to remain in a weakened ballast layer that is less resistant to deformation under loading. Ballast renewal through track undercutting and replacement is an effective means to remedy the fouled ballast condition, but has a high cost and requires significant track outages. However, shoulder ballast cleaning (SBC) provides lateral drainage of the ballast layer and also allows a portion of the fouling fines from under and around the ties to migrate laterally into the newly cleaned ballast shoulders. This paper presents results of recent laboratory and field testing that show the effects of SBC on track. Presented also are results of economical modeling that shows a two-fold Present Value cost savings by (1) requiring less frequent tamping due to an improved ballast condition, which also (2) allows the higher cost undercutting to be delayed until later years. The paper explores the cost benefit provided by SBC for different loading and traffic conditions, levels of ballast fouling and various economic considerations.

INTRODUCTION

The rate of ballast settlement under traffic loading for different levels of ballast fouling is understood after many years of field investigations and laboratory tests [1, 2, 3, 4]. The ballast settlement rate translates to increasing railway track roughness from accumulating differential ballast settlement. Knowing the rate of ballast settlement for specific operating conditions allows the prediction of when tamping must occur to smooth the track to within acceptable tolerances. The amount of track roughness which triggers the need for surfacing maintenance depends on the FRA Class of the track. When this knowledge is combined with economic information on labor and equipment costs for ballast-related maintenance, the maintenance option with the lowest life cycle cost may then be chosen for a given set of operating conditions [1].

This paper describes an approach that has been developed to make the best engineering and economics-based decision between the two options of 1) using repeated tamping to delay the eventual undercutting and replacement of a fouled ballast, and 2) using tamping in combination with shoulder ballast cleaning (SBC) to delay full ballast renewal through undercutting. Both options have the aim of pushing the high cost associated with undercutting and ballast renewal further into the future in order to reduce the ballast life cycle cost from a Present Value perspective. This paper also presents results from both full-scale laboratory testing and field results that show shoulder ballast cleaning effects on track drainage and fouling particles migration.

BALLAST LIFE

As with all track components, ballast has a finite life. Ballast is considered to be at the end of its life when the voids between the particles become filled with fine material to the extent that the drainability of the track is lost and the ability to maintain a durable track lift after tamping is greatly diminished. As the amount of void space between ballast particles diminishes with fouling, the void volume available to hold the fouling fines being generated diminishes, but never becomes zero. If ballast life is defined as the remaining void volume linked to this accumulating fouling material in the voids, it too does not actually attain a zero value but follows the trend shown in Figure 1. However, as a practical matter, a sudden observed decrease in ballast permeability at a Fouling Index of approximately 30% is often taken as the end of ballast life.

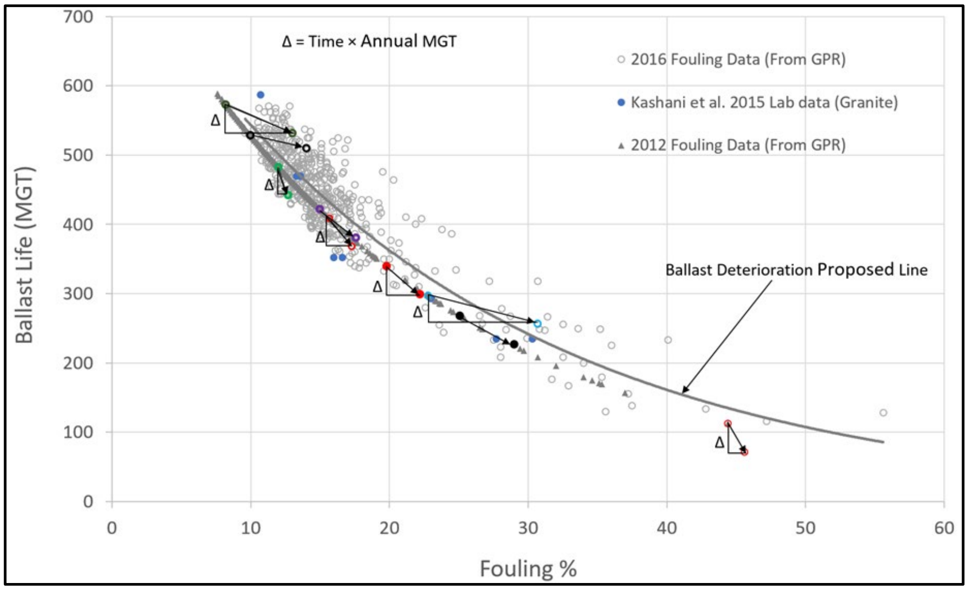

Figure 1: Remaining ballast life in MGT versus ballast fouling condition [adapted from 2].

Figure 2 provides an illustration of the effects of fouling on ballast settlement. This figure is based on the track deterioration rate of over 200 revenue-service sites [2], and clearly shows the significance of ballast fouling on the rate of settlement of the track. The sudden increase in settlement rate and higher variability at a Fouling Index greater than 30 corresponds to the mentioned decrease in permeability at this fouling level.

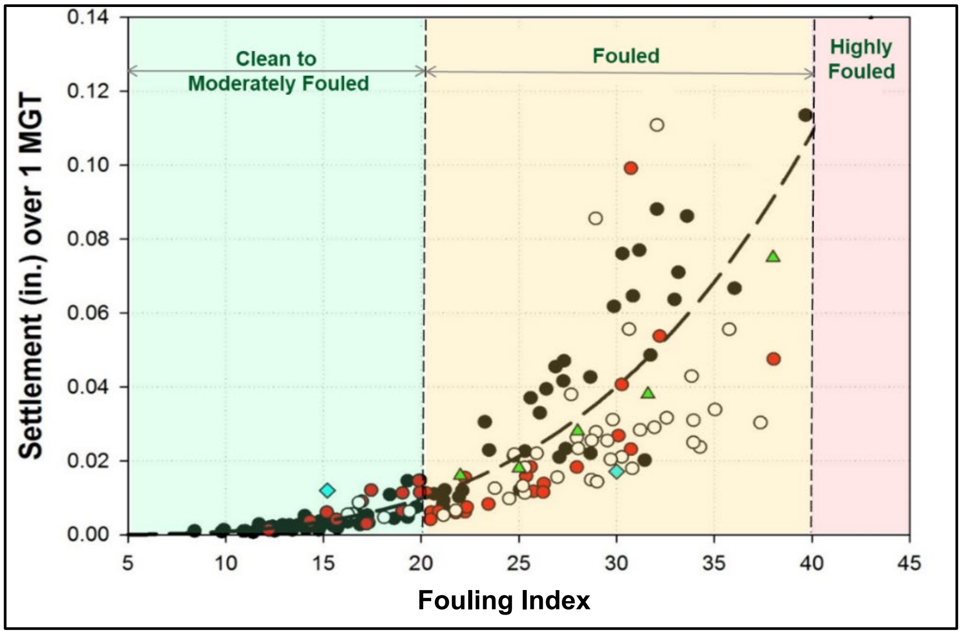

Figure 2: Ballast settlement for 1 MGT of traffic for a range of fouling index [adapted from 2].

Figure 3 shows the typical behavior of an increasingly fouled ballast just after it is tamped [5]. An increasing amount of fouling increases the ballast settlement rate as shown, however the settlement trend always increases at a decreasing rate for otherwise constant conditions. The “moderately fouled” variables of initial settlement (ε_1) and exponent (b) in Figure 3 are based on testing at the FAST site at TTCI in Pueblo, CO [4], and the “moderately clean” plot is based on laboratory testing results from University of Massachusetts [6]. The “highly fouled” and “clean” plots in Figure 3 were derived by adjusting the initial settlement and exponent relative to the other two settlement curves.

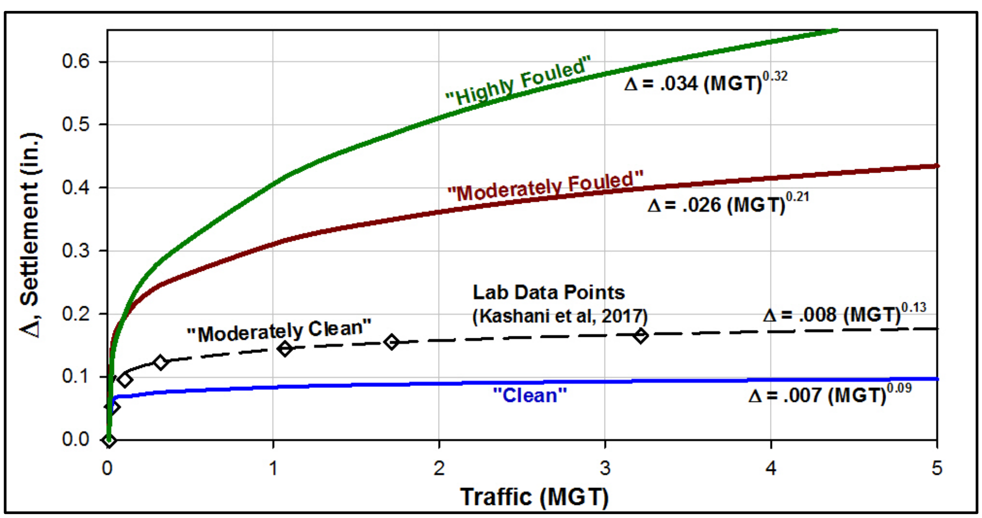

Figure 3: Ballast settlement after tamping for various fouling conditions [5].

Figure 4 illustrates the rate of increase of permanent strain with cumulative traffic for fouled ballast (30% fouling), and how this rate changes with increasing moisture content [6]. After initial settlement in the dry condition, the gradual increase in moisture, does not significantly change the rate of deterioration prior to saturation, because of high capillary tension between the fine particles and the higher relative density of the well-graded ballast. After saturation and the breaking the capillary tension bonds, the settlement increases drastically in amount and rate.

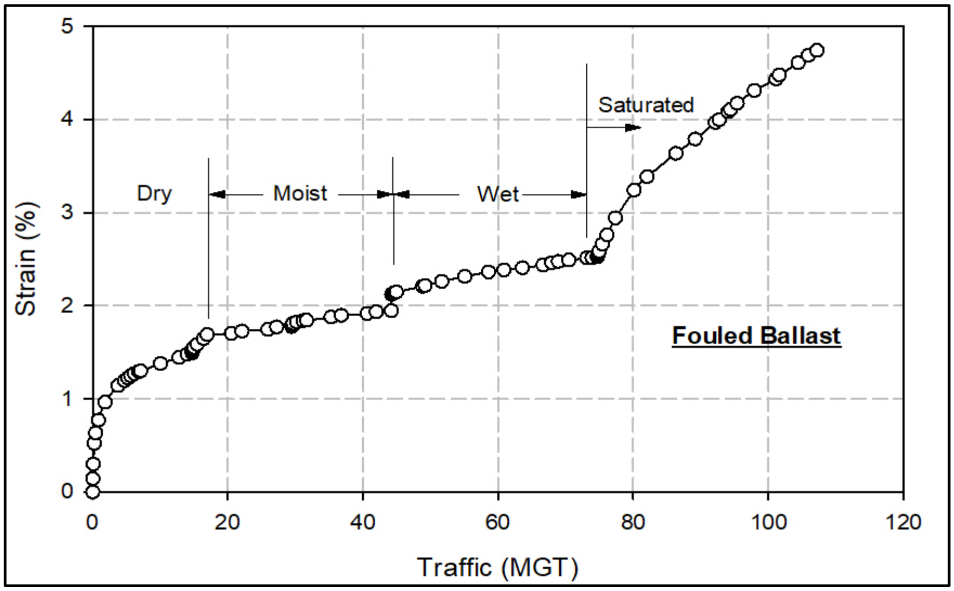

Figure 4: Plastic strain vs. accumulated traffic loading for fouled ballast with different moisture conditions [adapted from 6]

The end of ballast life is somewhat arbitrarily defined if it is based on rate of deformation, in that it is possible to indefinitely continue to tamp an increasingly fouled ballast without replacing it. As ballast fouling increases, the required frequency of tamping to maintain acceptable geometry also increases. For example, Figure 5 shows an idealized plot of ballast settlement for accumulating traffic. As depicted in the figure, each subsequent tamping cycle becomes successively shorter as the rate of ballast settlement increases due to the ballast becoming increasingly fouled over time [4].

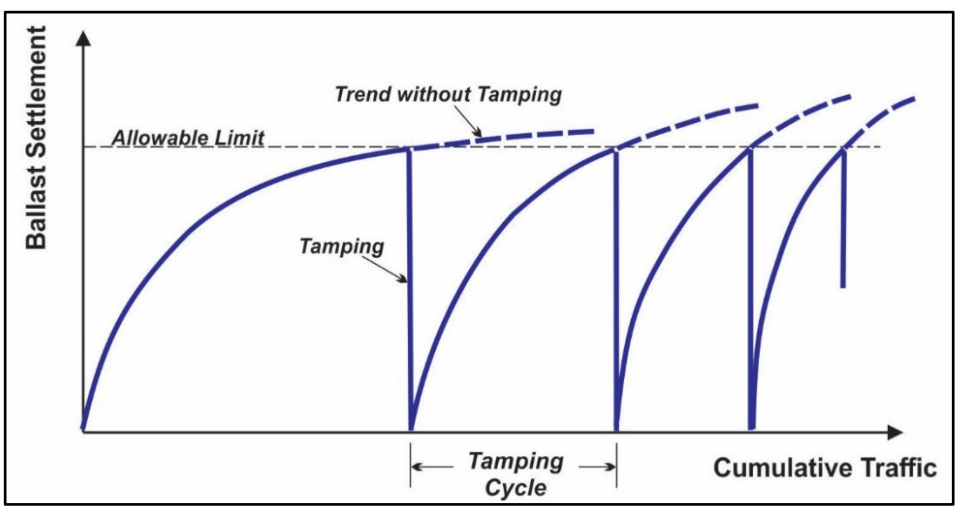

Figure 5: Effect of increasing fouling on length of tamping cycle [adapted from 4].

However, despite the apparent arbitrary nature of selecting a Fouling Index at which ballast life ends, the choice is actually rooted in economics and the engineering behavior of fouled ballast. A reasonable cutoff point for the Fouling Index (FI) of 30 has been proposed to represent the end of ballast life [1, 5]. At a Fouling Index of 30, the ballast layer exhibits a marked decrease in the ability for ballast to drain and also exhibits a significant increase in the rate of settlement, as shown in Figure 2.

Shoulder Ballast Cleaning to Extend Ballast Life

Shoulder ballast cleaning (SBC) allows improved drainage of the fouled ballast layer and an increased protection against full saturation of the ballast layer. In addition, the increased drainage ability and the increased void space in the ballast shoulder, can result in the migration of some fouling fines away from the ballast under and around the ties and into the shoulder. Figure 6 provides a good example of the increase in ballast layer drainage following SBC. The results shown in Figure 6 are from the Rainy Section test site at the Facility for Accelerated Service Testing (FAST) in Pueblo, Colorado [7] for the conditions of a short duration, high intensity rainfall.

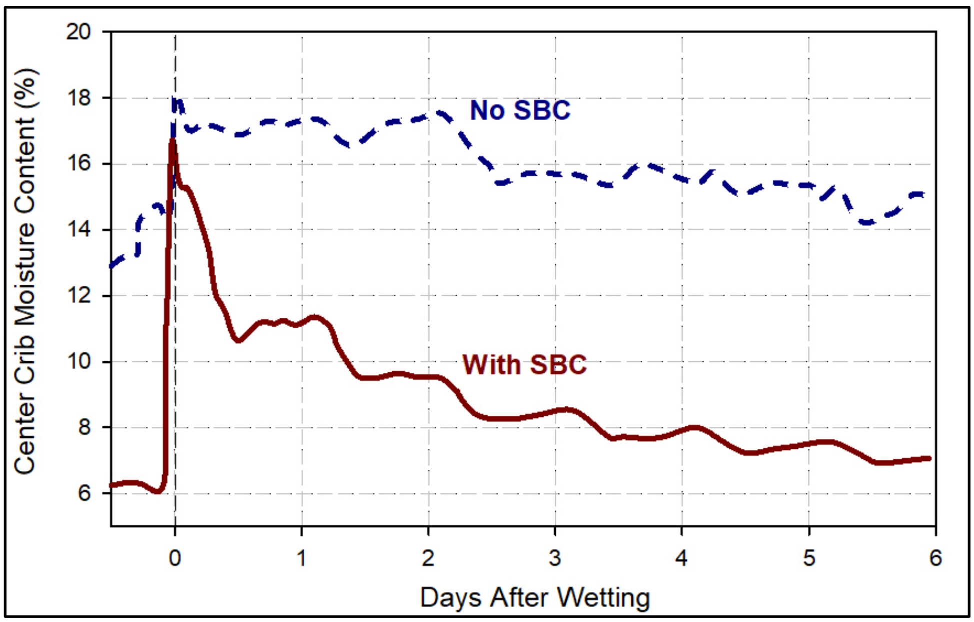

Figure 6: Effect of shoulder ballast cleaning (SBC) on crib moisture content reduction [adapted from 7].

Figure 7 shows results from SBC testing at a Class 1 revenue in-track test site , in which the ballast fouling condition was monitored over a two-year period at two track sections. In both track sections, the portion of the track that had SBC performed exhibited a much lower accumulation of fines, than the track portions that did not receive SBC. For instance, in track section 1 where there was no SBC performed, the Fouling Index of the “moderately fouled” ballast increased due to ballast deformation from traffic loading by nearly 6 points, whereas the track portion that was shoulder ballast cleaned increased by less than 2 points. This 75% reduction in the Fouling Index [(5.9 – 1.5)/5.9]*100% indicates a significant migration of fine material from the track center to the shoulders. The Fouling Index reduction due to SBC in all four ballast sampling locations of “moderately fouled and “fouled” from Test Sections 1 and 2 ranged from 43% to 75% due to fines migration.

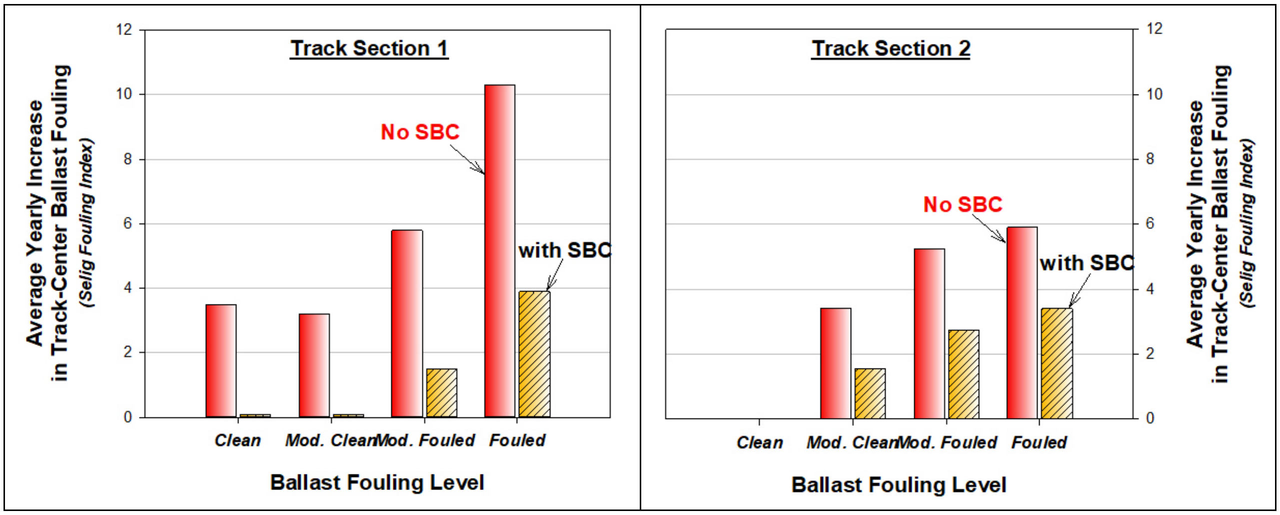

Figure 7: Effect of shoulder ballast cleaning on the accumulation of fines in the center of the track [adapted from 7]

A full-scale track section is built in an innovative transparent ballast testing tank in the laboratory at the University of South Carolina to quantify the ballast permeability before and after shoulder ballast cleaning and study the migration of fouling particles in ballast matrix after shoulder ballast cleaning. Figure 8 shows a view before and after shoulder ballast cleaning of ballast with Fouling index of 23 after 6 hours of raining at a constant rate of 32 gallons per hour which corresponds to 38 inches of rainfall per year. The red box shows a section in the crib and the blue box shows the shoulder cleaner cut section at shoulder. Comparing the red boxes before and after shoulder ballast cleaning shows how fouling particles have migrated from the surface to the depth of ballast in the crib. Comparing the blue boxes before and after shoulder ballast cleaning shows how the intersection between clean and fouled ballast has moved from the black marker line to the red marker line and migrating fouling particles are making their path toward the shoulders by making a small triangle shaped fine accumulation.

Figure 8: A view of full-scale laboratory set-up at the University of South Carolina showing before and after "Rain" for a ballast with FI = 23.

Economic Benefits of Shoulder Ballast Cleaning

Based on the findings described above, the economics of SBC are calculated using a ballast life-cycle cost model that determines how much of a cost savings are produced from: 1) a reduction in the frequency of needed tamping, and 2) an extension of ballast life which allows postponement of a costly undercutting and ballast renewal operation. The ballast life-cycle cost model is based on the relationship between the settlement behavior of ballast and the ballast fouling condition. The model calculates the amount of ballast breakdown that results over time from the combined degradation mechanisms of loading and tamping. The model then considers the costs of future undercutting and repeated tamping over the time period in years, and lastly, the Present Value (PV) calculation is used to put these costs in terms of present-day dollars. The model may show that the lowest cost results from using SBC to delay ballast undercutting and renewal for a number of years, or it may show it is more economical to forego SBC and replace the ballast by undercutting and renewal in the present year, depending on the input data provided by the user.

To demonstrate the potential cost savings provided by SBC, consider Figure 9 which shows the cumulative tamping maintenance costs (per mile) that accrue over time due to the repeated tamping required to maintain a Class 4 track with an annual tonnage of 60 MGT, and with a moderately strong and moderately fouled ballast (Abrasion Number = 35, Fouling index = 20). The total cost increases as shown because an increasingly fouled ballast requires more frequent tamping, as depicted in Figure 5. For the "Tamping Only" case the ballast fouling was assumed to increase normally due to loading and tamping, but for the "Tamping & SBC" case it was assumed that four applications of SBC in Year 1, 5 and 9 each resulted in a decrease of the current FI by 20% (a conservative estimate based on test finding shown in Figure 7) and that this migration of fines occurred over the following three years after each SBC application. The difference between these two lines shows the savings that is predicted by performing SBC, reducing the amount of tamping required due to the reduction of fouling in the ballast.

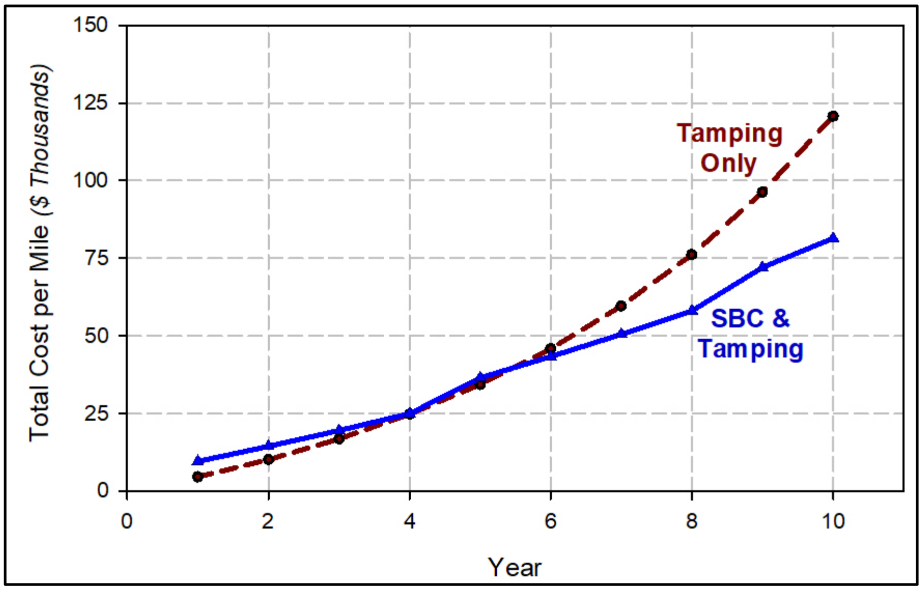

Figure 9: Total cumulative cost (per mile) for Tamping Only and Tamping and SBC (Initial FI = 20, Class 4 Track, Abrasion number (AN) = 35, 60 MGT per Year)

However, as mentioned, reduced tamping is only part of the potential benefit from SBC because the cost reduction from delayed ballast renewal should also be considered. The following figures use a Present Value (PV) cost analysis to account for both the benefit from both reduced tamping and delayed undercutting.

An example Present Value (PV) economic analysis is shown in Figure 10 for the case of an FRA Class 6 track with an annual tonnage of 15 MGT, a moderately strong ballast Abrasion Number (resistance to breakdown) of 35, and considering three values of fouling index (FI) in the initial year of the analysis. The year in which the minimum cost occurs (if a minimum is indicated) is the year that ballast renewal by undercutting and replacement is recommended because this produces the lowest life cycle cost. For the case in Figure 10 with an initial FI of 30, the minimum cost is in Year 4, and for an initial FI of 25 it is in Year 9. Figure 11 shows that for the same FI of 25 but with an annual tonnage of 30 MGT the minimum cost occurs in the initial year, Year 1, meaning that the ballast is already worn to the point that, for these particular conditions, it is more economical to renew the ballast now rather than use SBC to delay undercutting.

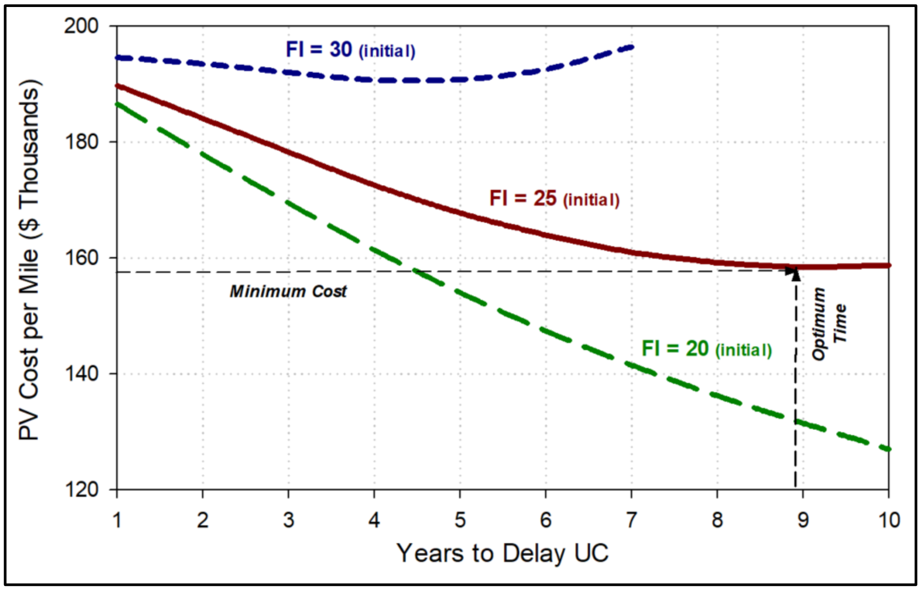

Figure 10: PV Cost of Delaying UC by Using SBC for Class 6+ Track (15 MGT per Year and An = 35)

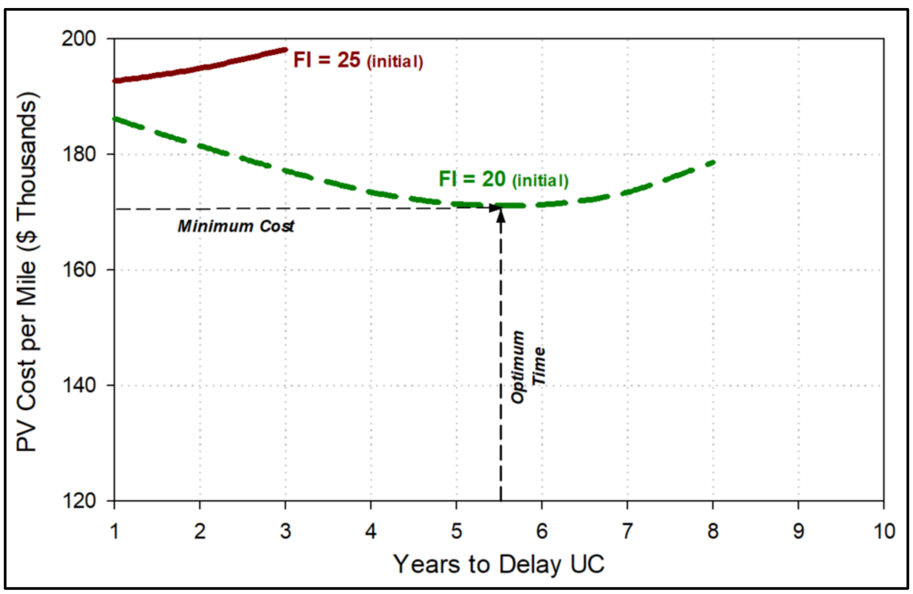

Figure 11: PV Cost of Delaying UC by Using SBC for Class 6+ Track (30 MGT per Year and An = 35)

Figure 12 and Figure 13 provide the range of PV costs from the economic model for the relevant range of variables assuming a Class 4 track.

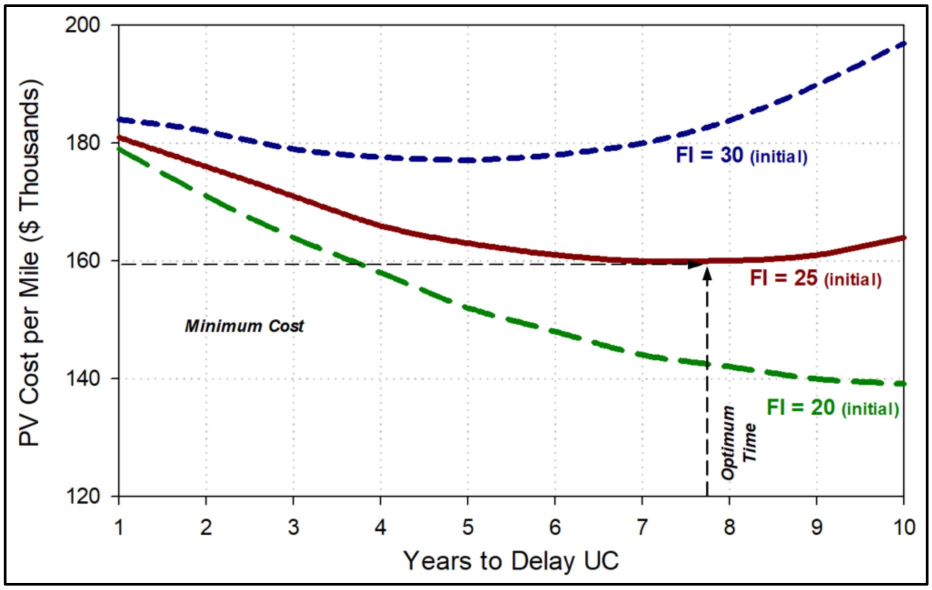

Figure 12: PV Cost of Delaying UC by Using SBC for Class 4 Track (50 MGT per Year and An = 35)

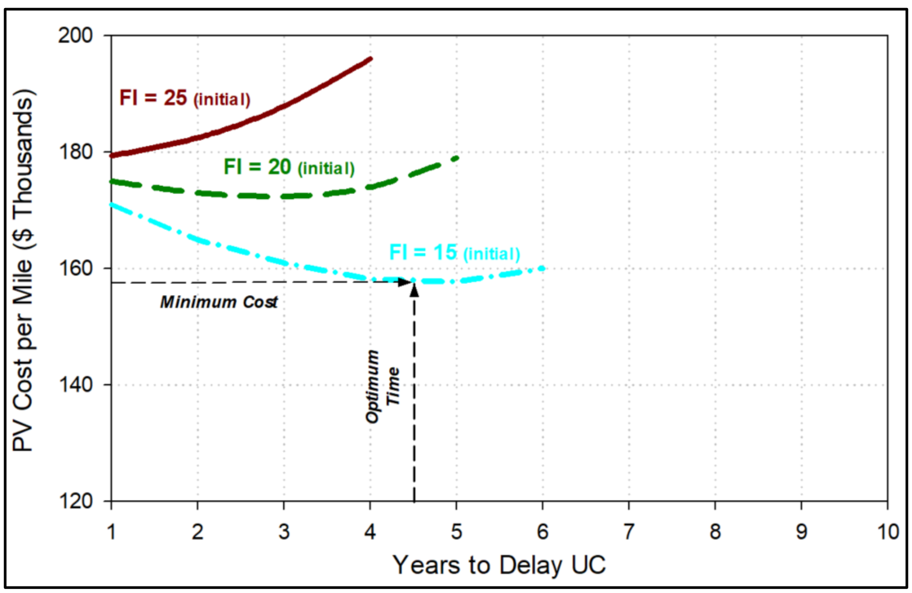

Figure 13: PV Cost of Delaying UC by Using SBC for Class 4 Track (100 MGT per Year and An = 35)

Lastly, Figure 12 above is modified to directly identify the cost savings attributable to SBC for the two initial Fouling Index values shown in Figure 14. The PV cost comparisons, with and without using SBC, show that a lower life cycle cost is achievable in both cases by using SBC.

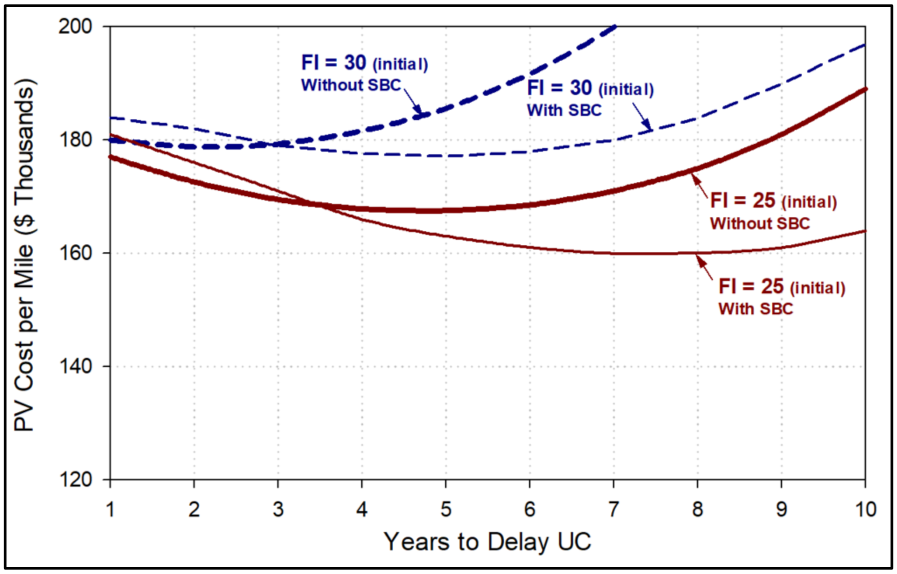

Figure 14: Comparing PV Cost of Delaying UC by Using SBC with PV Cost of Delaying UC by Not Using SBC for Class 4 Track (50 MGT per Year and An = 35)

CONCLUSIONS

Evidence from in-track testing of fouled and wet ballast indicates that SBC provides a significant reduction of moisture and fouling fines due to migration of fine material toward the newly cleaned ballast shoulders. Measured reductions in Fouling Index ranged from 43 to 75% and full scale laboratory tests also corroborate these findings. The improved ballast condition provides an increased ballast strength that is more resistant to deformation under load. Based on these findings, the economic benefit of SBC was determined for various scenarios. This benefit is two-fold: decreasing the frequency of needed tamping cycles and delay of ballast renewal by undercutting and replacement. These cost reductions due to SBC provide a reduced ballast life cycle cost as calculated using Present Value economic analysis.

Work remains to more definitively quantify the benefits of, needed frequency of, and repeated applications of SBC. This further work should focus on more varied operating conditions than has been considered so far. Lastly, it is desired to explore future collaboration of SBC with a partner railroad.

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Economics of Shoulder Ballast Cleaning

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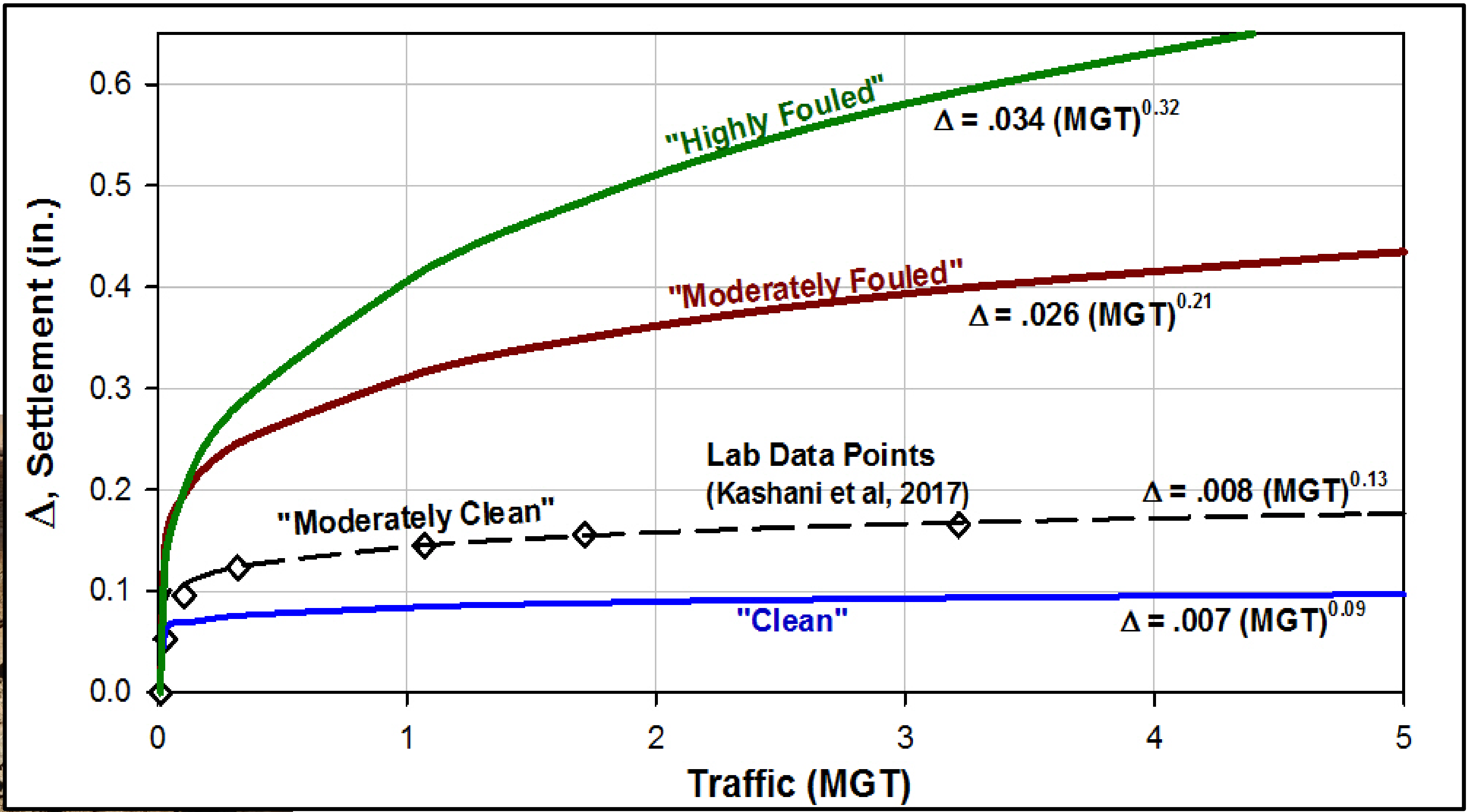
Technologies

Importance of Clean Ballast

- **Less deformation**
- **Stiffer support**



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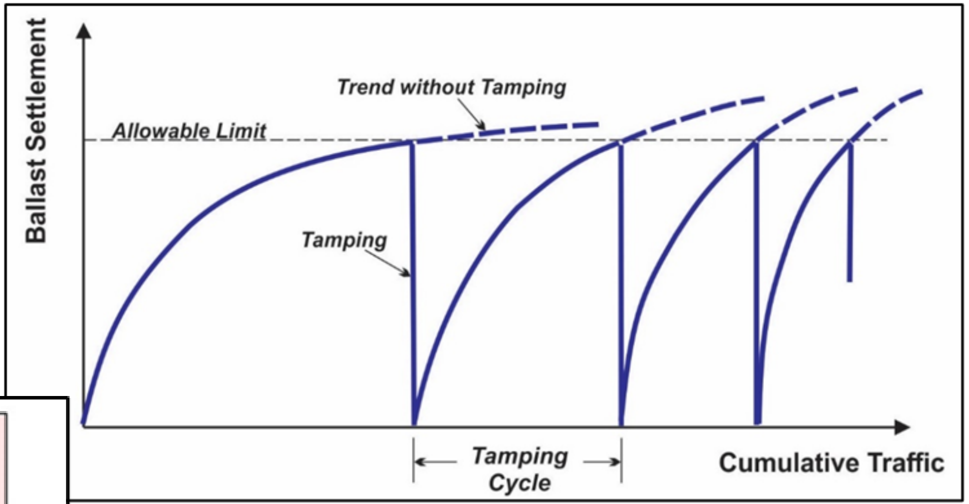
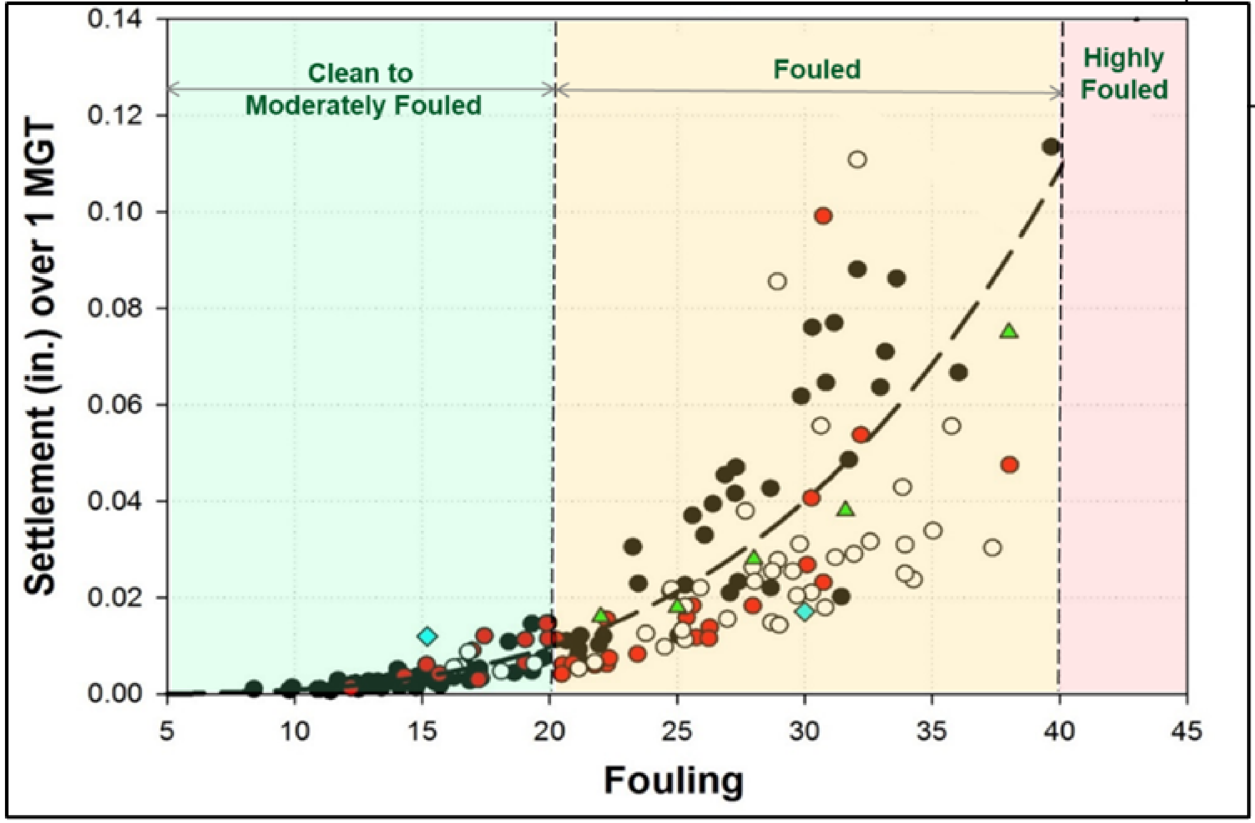
Importance of Clean Ballast

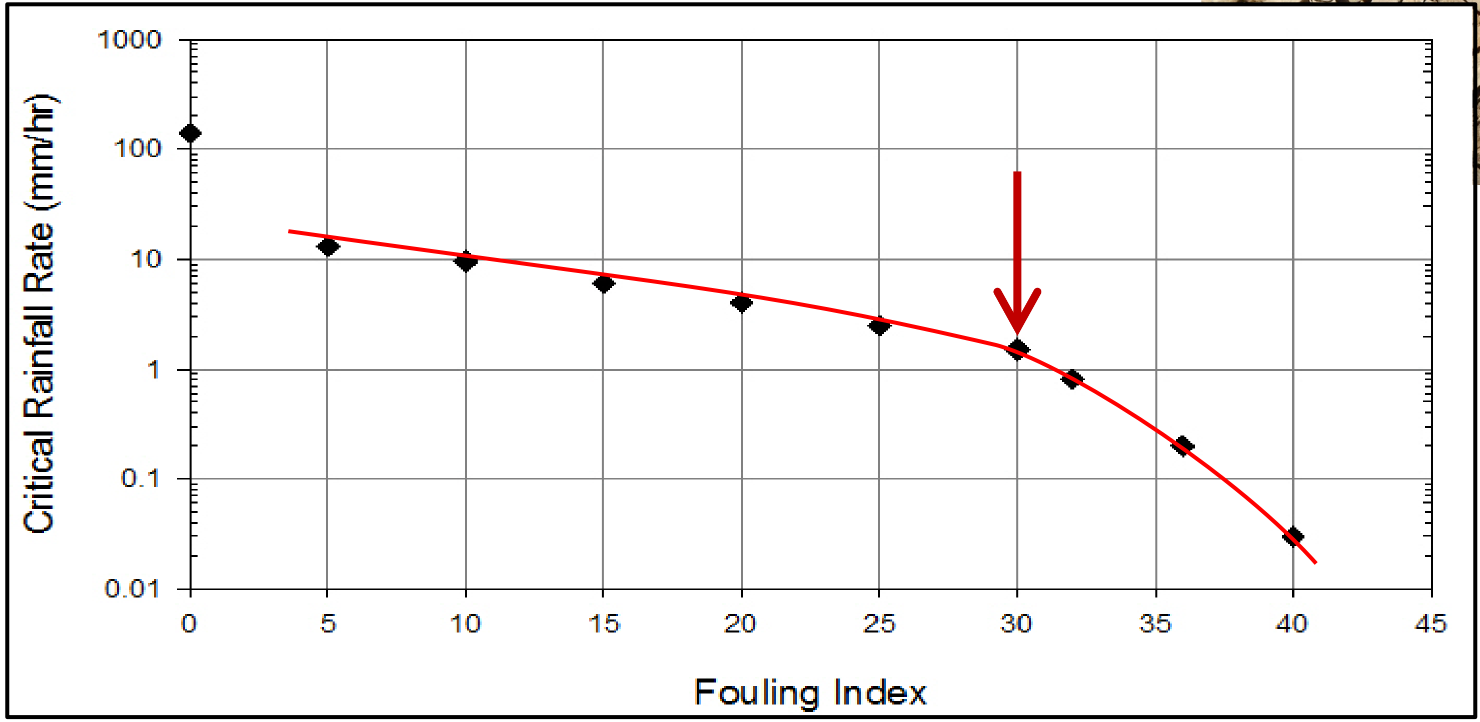
- Less deformation
- Stiffer support
- **<u>More durable geometry after tamping</u>**



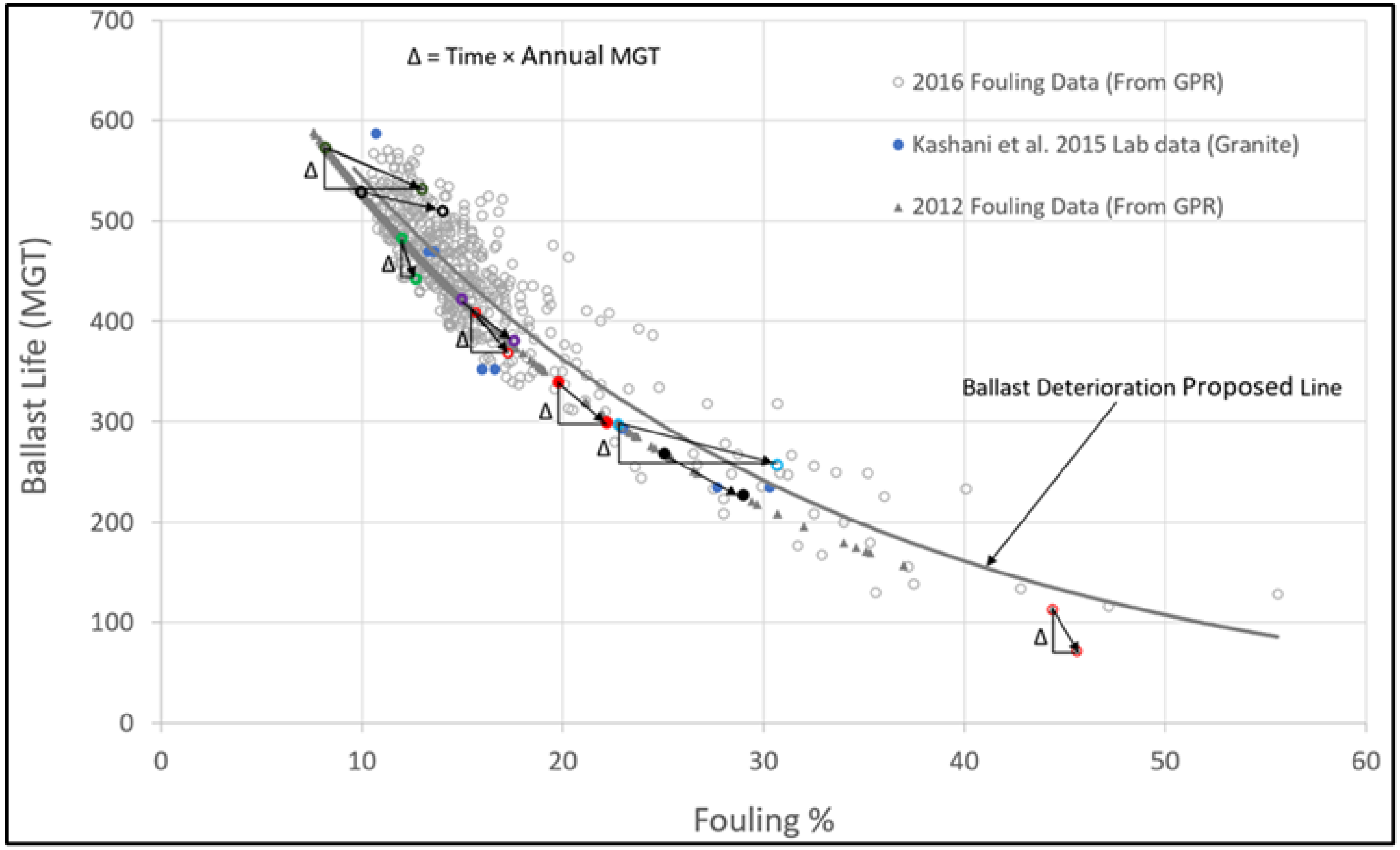


Importance of Clean Ballast

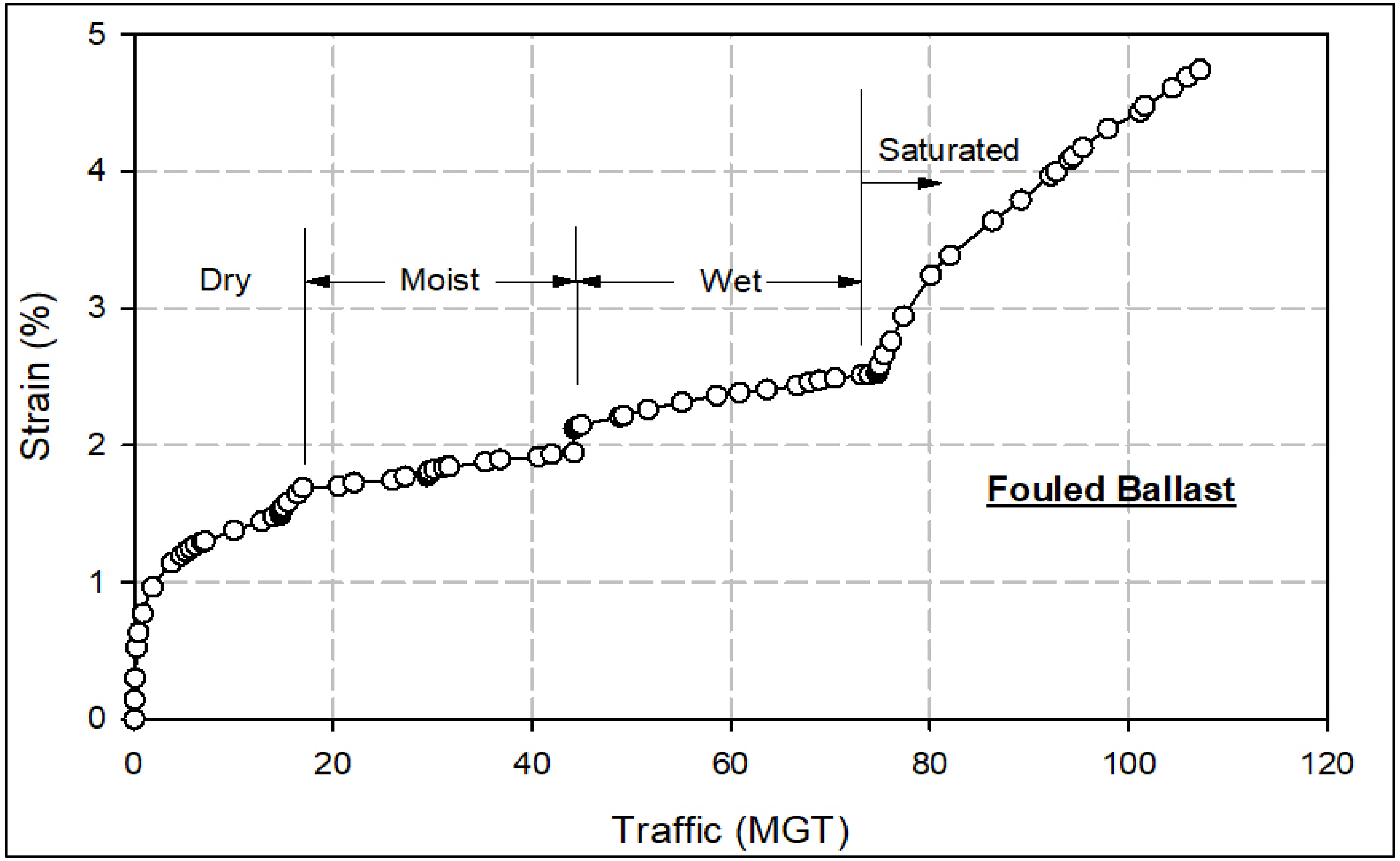
- Less deformation
- Stiffer support
- More durable geometry after tamping
- **Better drainage**



Ballast Life is Defined by Fouling Condition



Ballast Deformation is Highly Affected by Water



Ballast Cleaning Options *(Production)*

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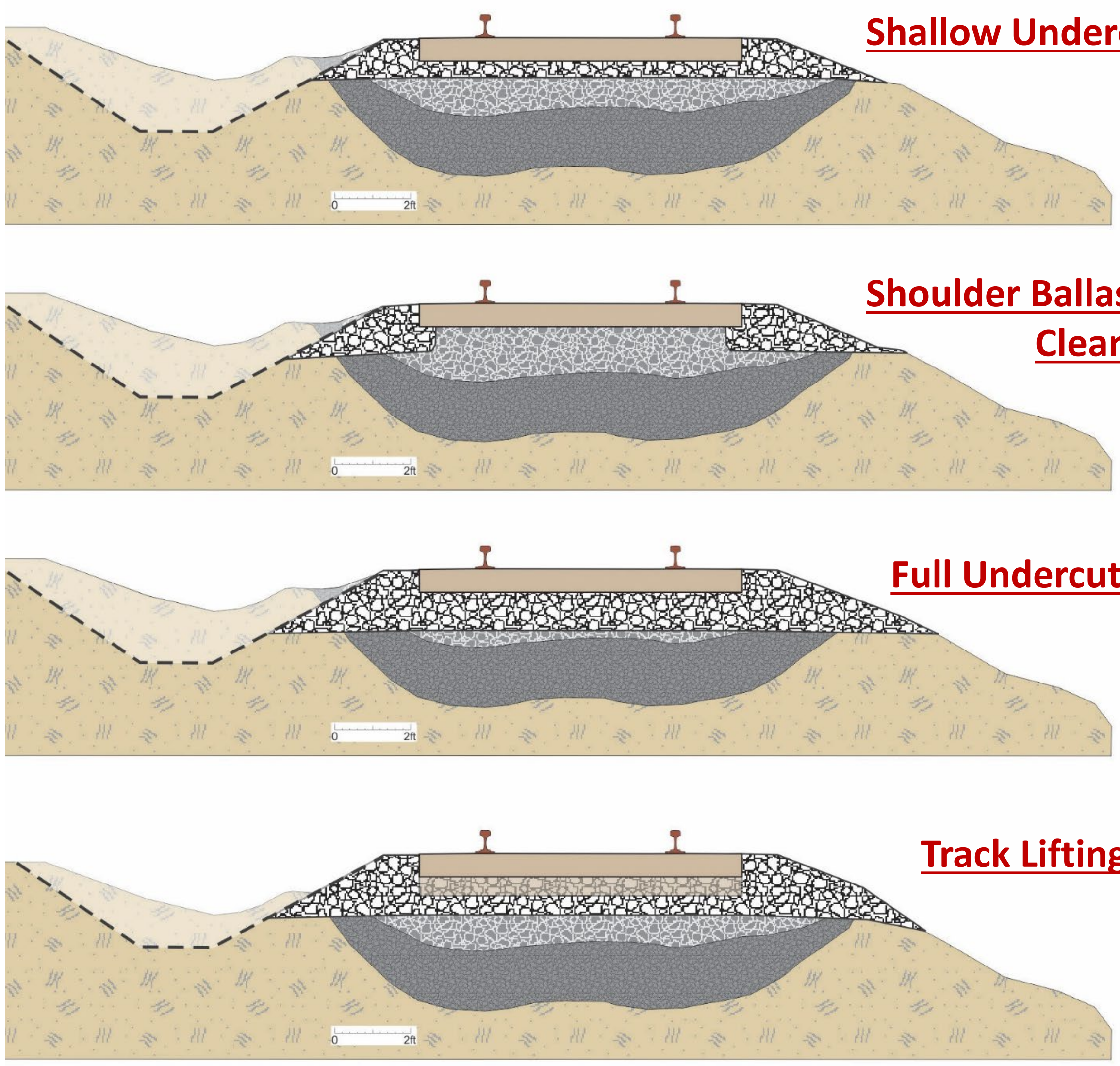
Ballast Cleaning Examples

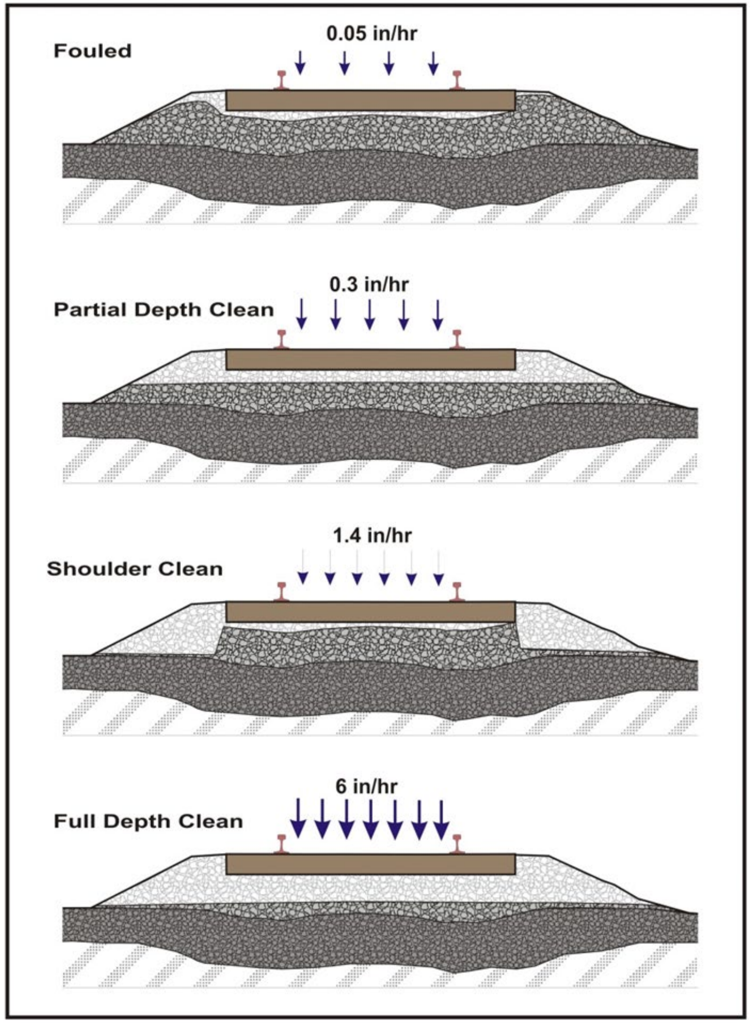


Shallow Undercutting

Shoulder Ballast Cleaning

Full Undercutting

Track Lifting



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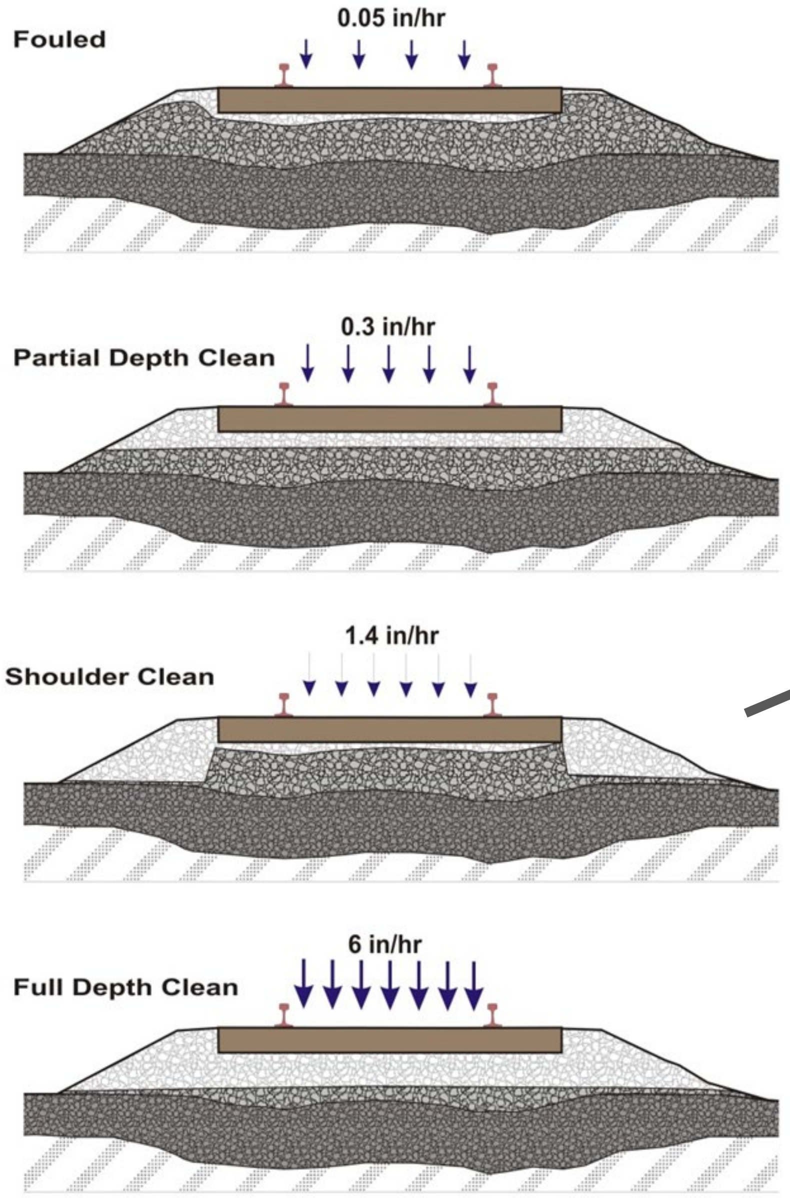
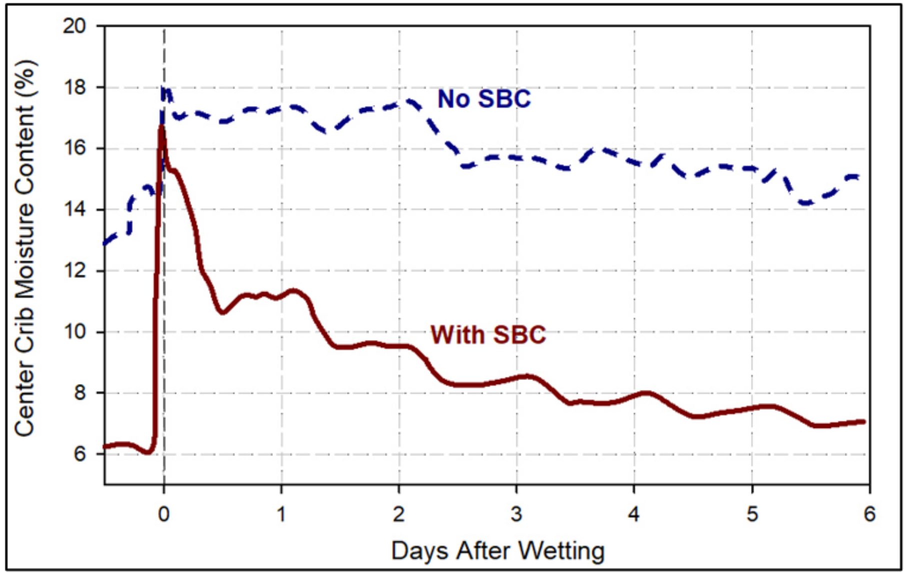
Ballast Cleaning Effects on Drainage

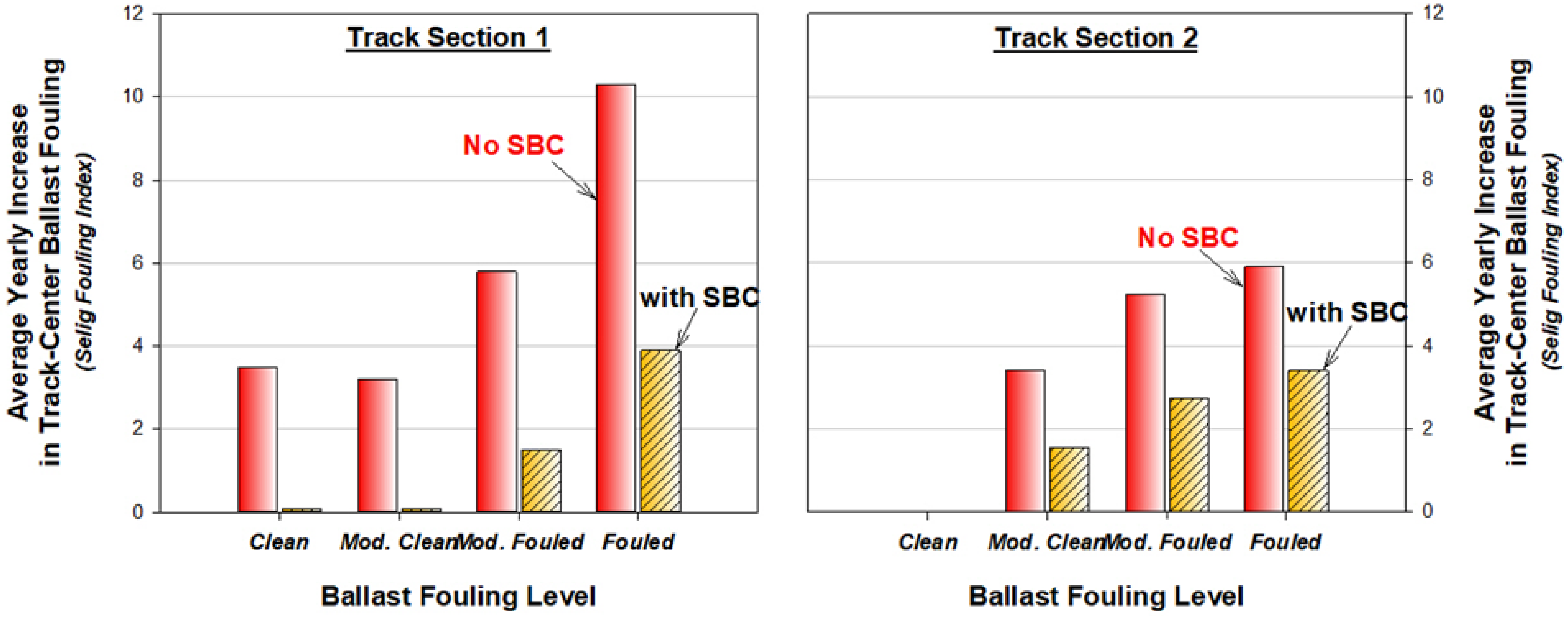




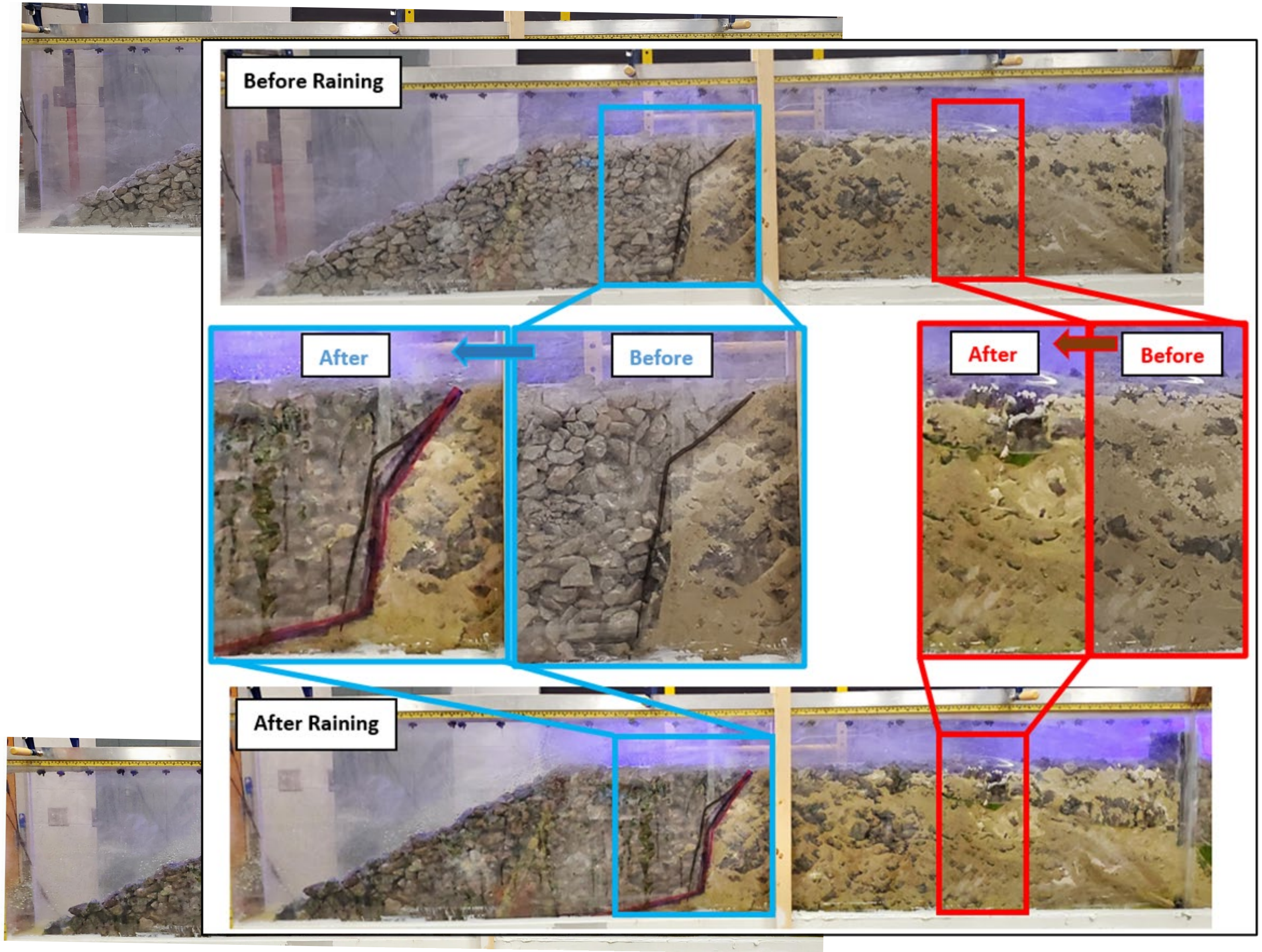
Shoulder Ballast Cleaner (SBC)

- Excavate up to 20" below tie, 36" from end of tie
- 1,500+ yd3/hour cleaning capacity
- Up to 2 mph working speed at 6-8" below bottom of tie
- 50 mph travel speed
- No tamping/stabilizing required after machine works

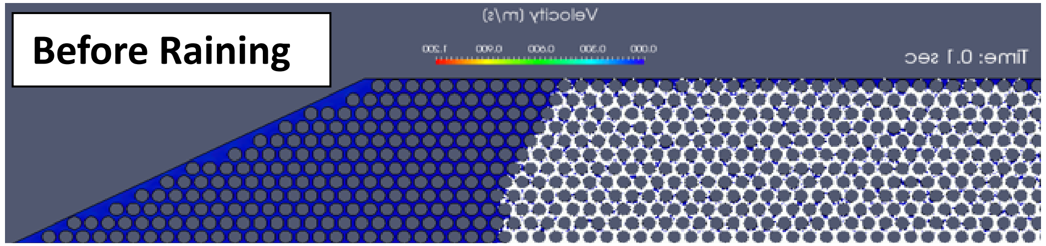
SBC and Migration of Fines *(Revenue-service Test)*

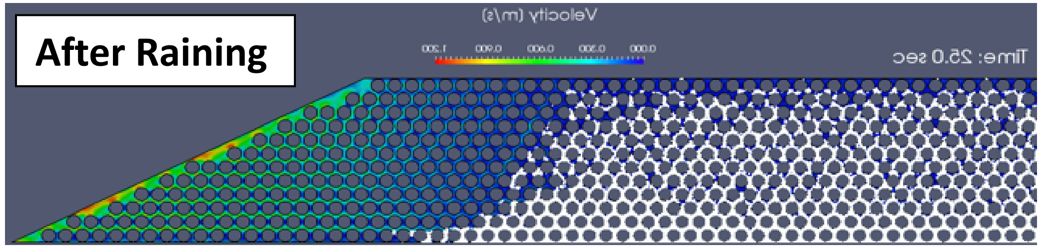


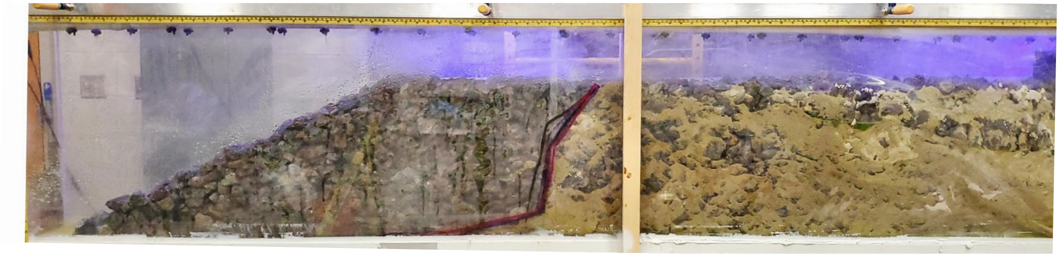
SBC and Migration of Fines – Laboratory *(U. of South Carolina)*



SBC and Migration of Fines – Modeling *(U. of South Carolina)*

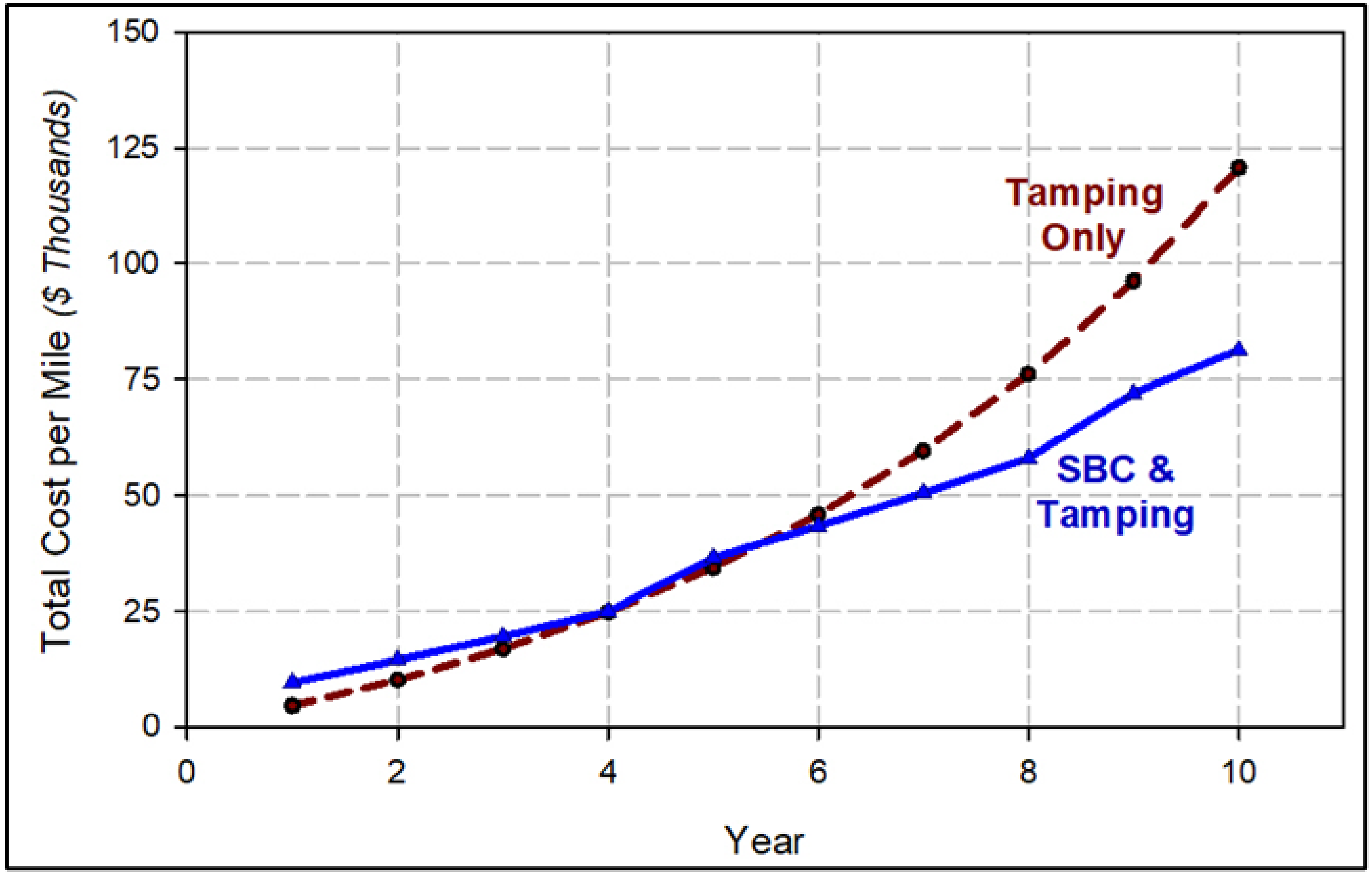






SBC Reduces Needed Tamping due to Fines Migration

(Comparison of total cumulative tamping costs w/ & w/o SBC)



Present Value (PV) Analysis of SBC Cost Benefits

- PV to show if SBC provides cost benefit by reducing tamping frequency & delaying undercutting
- Labor, ballast and equipment costs of tamping and undercutting operations are considered
- Ballast life (in MGT) and ballast breakdown rate due to tamping and traffic loading are considered

PV Cost Example for Class 6 Track

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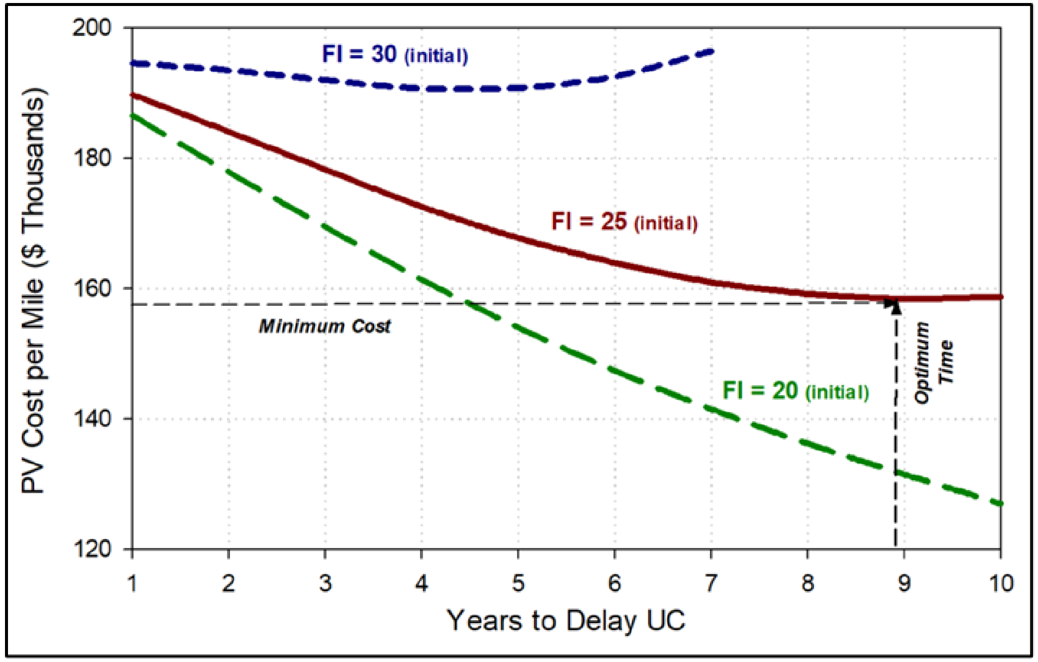
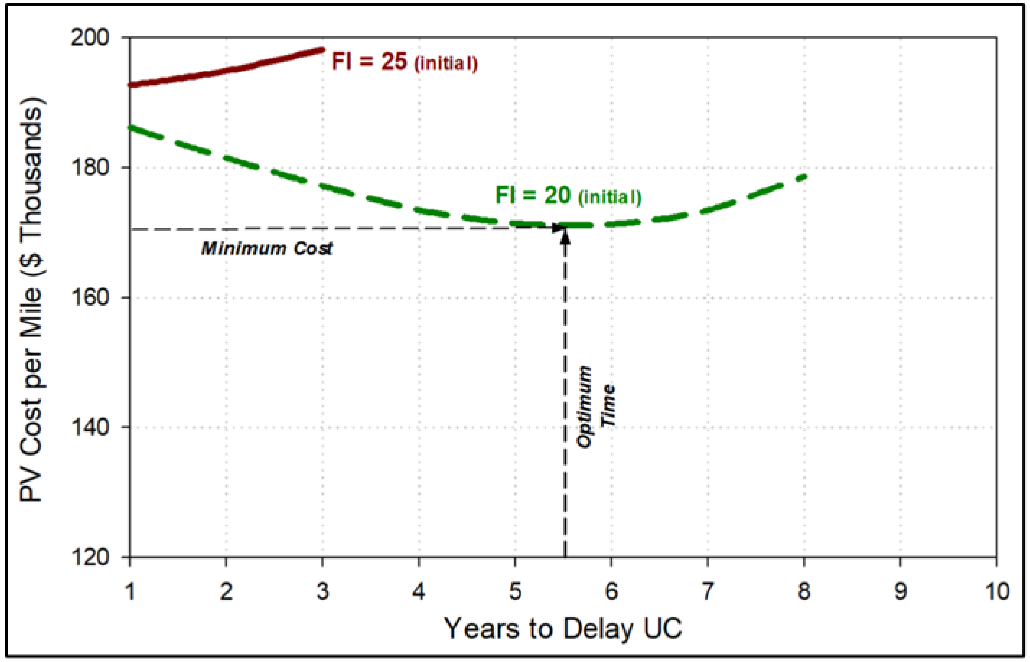
15 MGT/yr



30 MGT/yr



PV Cost Example for Class 4 Track

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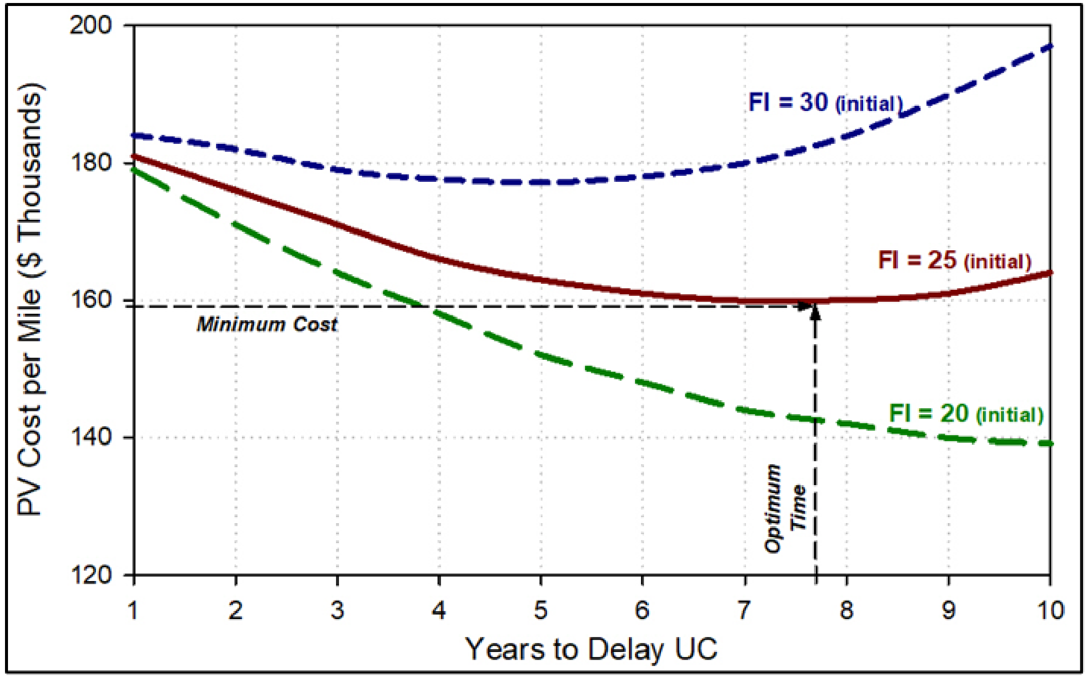
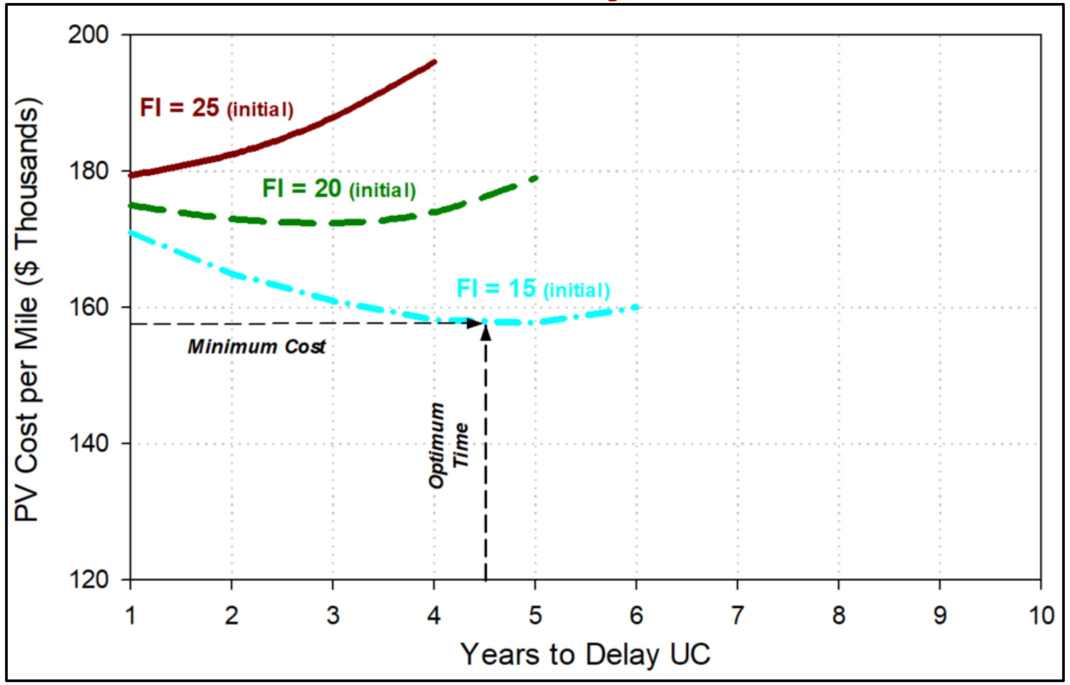
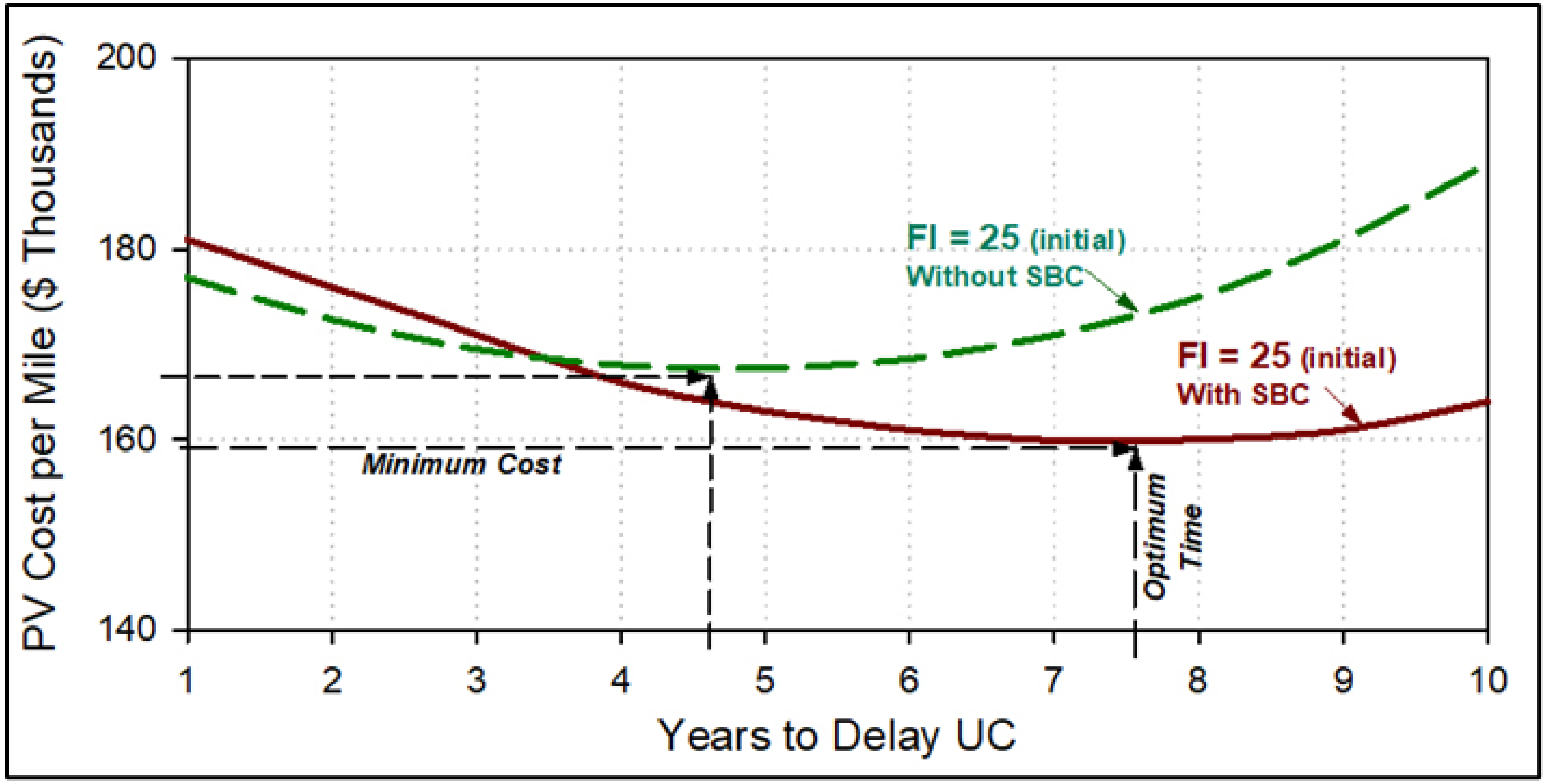
50 MGT/yr



100 MGT/yr



PV Costs with and without SBC: *initial* *FI = 25*



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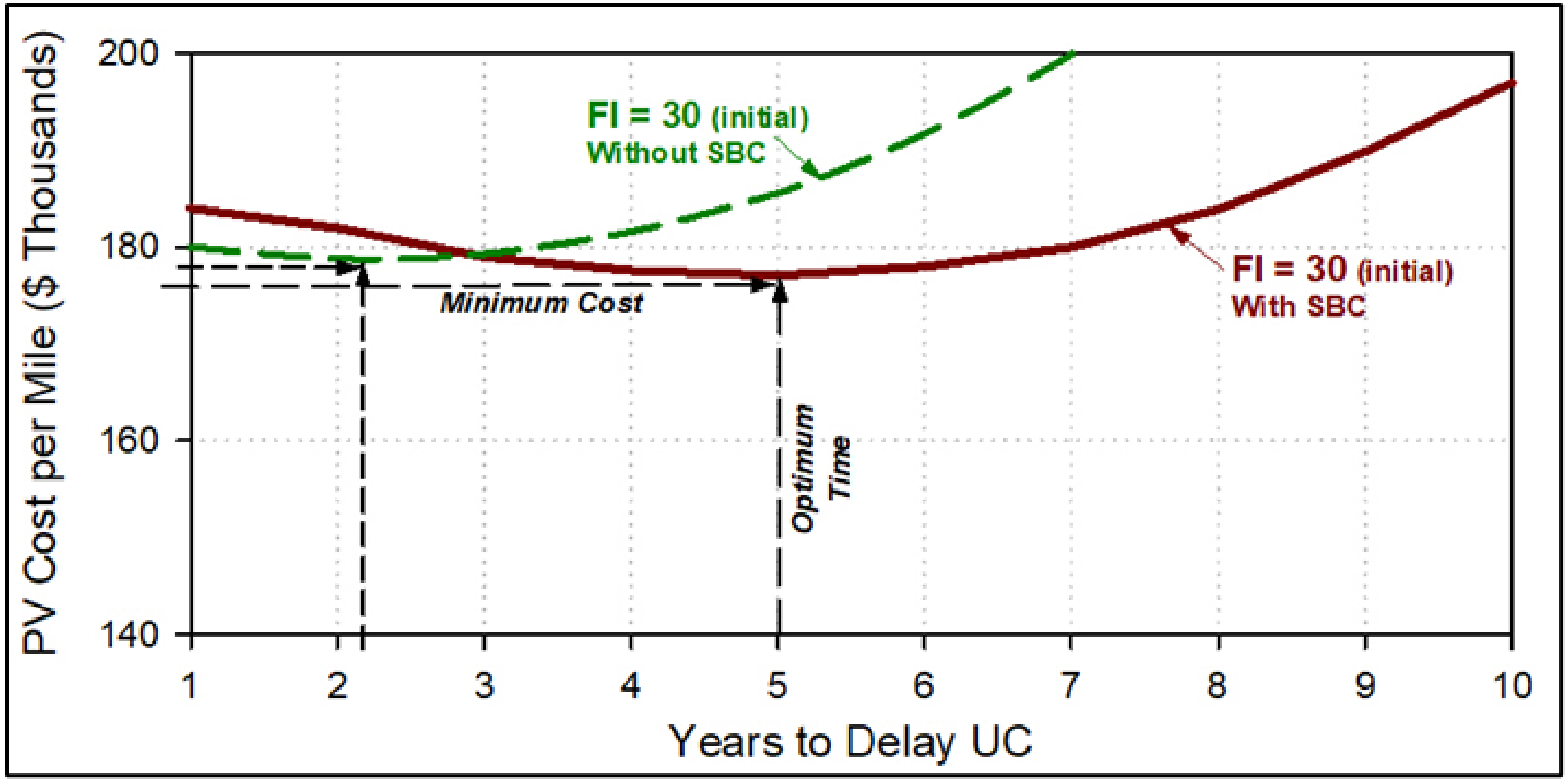
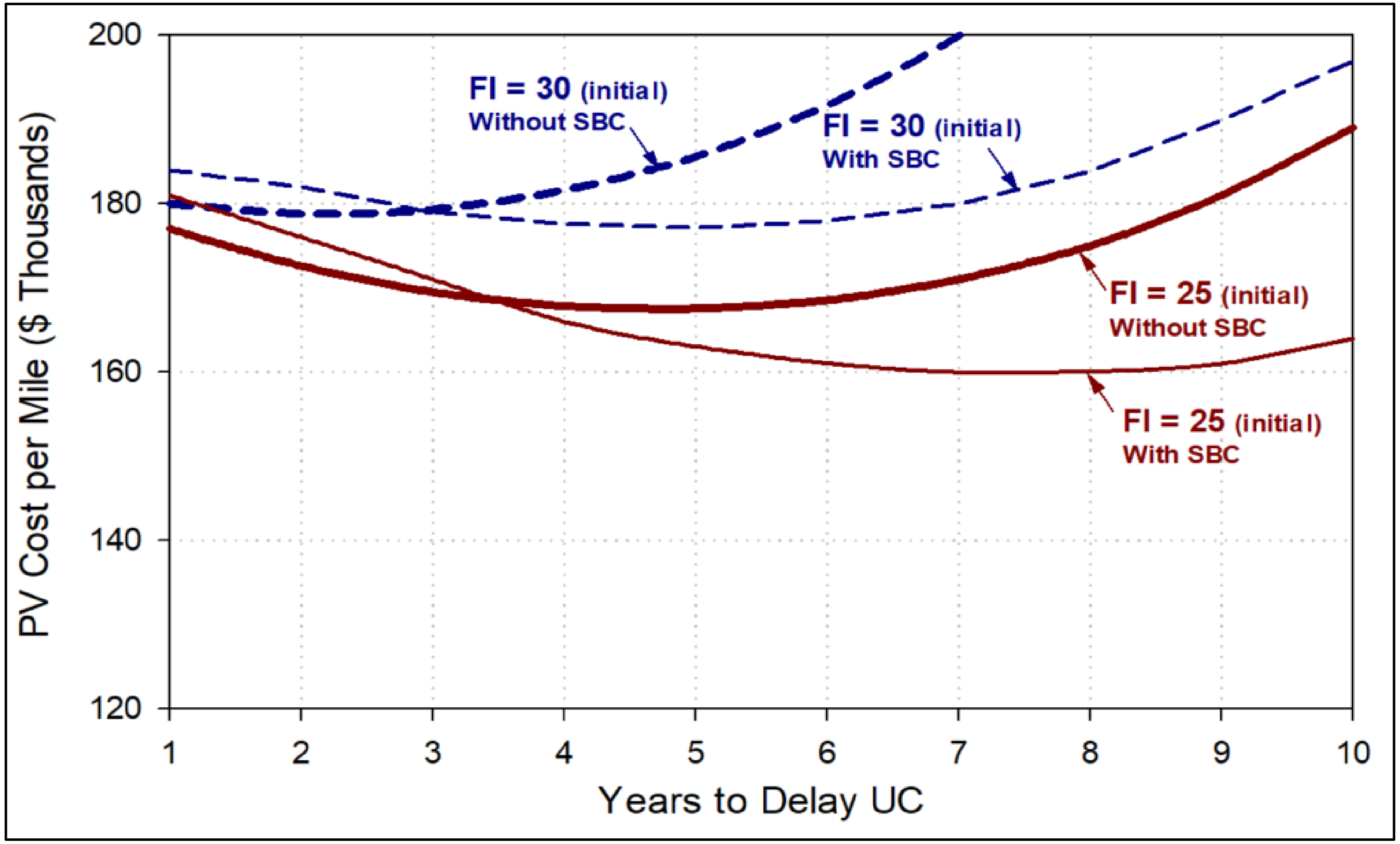
PV Costs with and without SBC: *initial FI = 30*



PV Costs with and without SBC for FI = 30 and 25

(I think the following comparison has lots of value (maybe as an additional slide or replacement for the last two slides) - HK



Conclusions

- Field & laboratory tests show SBC reduces fines and moisture in fouled ballast
- Reduced fines and moisture in ballast increases ballast strength and make it more resistant to deformation under load
- Reduced fines and moisture in ballast lower costs by increasing tamping durability and making it less frequently required
- SBC can provide further cost benefit by delaying need for costly undercutting
- Economic analysis developed to determine if SBC produces a cost savings depending upon conditions