Ballast Shoulder Cleaning: Issues and Economics

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The repeated heavy loading experienced by railroad tracks under freight traffic can result in degradation of track structure, and its key components. In particular the ballast materials and ballast section can deteriorate with a corresponding loss of performance. The maintenance of a clean well-draining ballast section is critical to the overall stability of the track structure.

Ballast refers to the upper layer of the track substructure upon which the superstructure (i.e. the rails and ties) is placed. It generally represents a permeable granular materials placed around and under the ties to promote track stability[1]. The ballast section is the layer of the track structure that is located between the ties and the subgrade. The primary function of the ballast section is to promote track stability. The principal parts of the ballast section are ballast cribs (ballast between ties), ballast shoulders (ballast located outside the ends of the ties), and the ballast layer beneath the bottom of the tie extending to the subgrade. The ballast shoulders are usually configured with a flat portion extending beyond the end of the ties, at a height equal to the top of tie, and a sloping portion that continues until it reaches the subgrade layer. Thus the ballast shoulder represents a major portion of the ballast section.

Functions

The primary functions of the ballast shoulder, within the context of the overall ballast section, are as follows[2]:

1) Provide lateral resistance to unloaded track in order to minimize the potential for buckling

This is a key function of the ballast shoulder for CWR track. The ballast shoulder accounts for between 10% to 23% of the total tie/ballast lateral resistance. The lateral resistance of the shoulders becomes even more important when a train passes over the track. In this case, the track will have an "uplift" wave in front of the lead unit and between trucks of each car. This "uplift" behavior can result in the slight lifting of the tie especially when the rail/tie fastening system is secure (as in the case of elastic fasteners). This, in turn, results in the loss of the frictional contact between the tie bottom and the ballast. In this situation,

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the ballast shoulder provides the required lateral resistance to prevent track buckling, and this resistance can be over 40% of the total tie lateral resistance.

2) Provide lateral resilient resistance to maintain alignment of the track

The lateral resistance contribution by the ballast shoulder to the overall lateral resistance is important in maintaining the lateral geometry of the track, i.e., the alignment of the track. Regular maintenance of an adequate ballast shoulder (with the required shoulder width) is necessary to prevent deterioration of the alignment geometry.

3) Function as an integral part of the track drainage system

The ballast shoulder plays an important role as a "run-off" path for water, particularly rain water. It allows the water to be carried away from the ballast and subgrade to the drainage ditches located at the ends of the track section. Thus the ballast shoulder must be maintained in a clean well-draining condition in order to maintain the drainage of the track structure. It should not impede a rapid seepage of water away from the ballast-subgrade interface.

4) Prevent vegetation growth close to the track superstructure

The ballast shoulder presents an opportunity for encroachment of vegetation onto the track due to close proximity to the ends of track and the adjacent right of way. It is important to prevent this encroachment of vegetation by keeping the shoulder clean.

5) Add lateral confinement to ballast under track

In addition to preventing the lateral geometric deterioration of the track structure, the ballast shoulder also aids in reducing the vertical (cross-level, profile) deterioration of the track geometry. This is due to the action of the ballast shoulder in "confining" the ballast underneath the track structure, and preventing its migration away from the center of the track. This improves the stress transfer from ties to subgrade, and slows the rate of profile deterioration by decreasing lateral ballast movement. This confining effect increases the strength of the ballast, subballast, and subgrade layers.

Shoulder Ballast Deterioration

The primary method of deterioration of the ballast section is "fouling" of the ballast, which takes place when small particles or "fines" intermingle with the ballast particles and fill the open spaces or "voids" in the ballast section. Fouling of the ballast can impede drainage, and reduce the strength and load carrying capacity of the ballast layer.

The presence of water in fouled ballast section can result in mud pockets, and cementation of the ballast either at the ends of ties, or underneath the track section[3]. The presence of this condition at locations with large vertical impact loading (such as joints) results in "pumping" action that draws water and dirt from the subgrade. This condition of the ballast leads to increased deterioration of the track geometry as well as abrasion of both the ballast particles and the tie surface.

Ballast fouling affects the properties and performance of the ballast section in general and the ballast shoulder in particular. When contaminated by fine particles the ballast loses its frictional strength, interlocking ability, and its permeability decreases. This results in the loss of the shoulder ballast's resiliency property to plasticity, and allows accumulation of lateral permanent displacements. In addition, its increased water retention capacity accelerates its deterioration through freeze/thaw cycles. The effect of this fouling of the ballast shoulder can be defined as follows[3] (Note that the following effects are specifically related to the fouling of the ballast shoulder, independent of the fouling of the remainder of the ballast section).

1) Loss of (total) ballast section effectiveness

Fouling of the ballast shoulders results in a decrease in effectiveness of the overall ballast section due to decreased shoulder permeability. This loss of shoulder permeability will increase the drainage path and the time for drainage of excess water from under the track will be prolonged accordingly. This extra seepage time may be 30% to 50% longer when compared to the case of *clean shoulders and fouled ballast* under the track. In addition, the adverse effects of pumping action, and freeze/thaw cycles will be enhanced due to the longer presence of water in the track. As a result, the track geometry (profile) will deteriorate at a faster rate than with clean shoulders, potentially shortening the resurfacing cycle by as much as 25%[4].

2) Accelerated loss of alignment

Fouled ballast shoulder can result in the loss in lateral resiliency and stiffness of the track due to the contamination of the shoulder by fines, and the corresponding decrease in inter-particle friction. As a result, track with fouled shoulders has a diminished ability to sustain repeated loads without deforming permanently and the associated alignment maintenance cycle is shortened. The effect of these fouled shoulders can be equivalent to track with effectively, one-half the actual shoulder width[5].

3) Accelerated loss of profile

In an analogous manner to accelerated loss of alignment, fouled ballast shoulder can result in an accelerated loss of vertical track geometry (profile) due to the decrease in resilience and stiffness of the fouled shoulders. This results in a loss of confinement for the ballast under the track, and the corresponding loss of vertical strength and prevention of lateral ballast migration. As a result, the track profile deteriorates under repeated train loading at a faster rate, which can be as much as 25%[5]. It should be noted here that this loss is in addition to the deterioration of the vertical profile associated with the loss of ballast section effectiveness.

4) Greater potential for buckling

The fouling of the ballast shoulders and the corresponding decrease in lateral resistance results in a greater potential for track buckling, due to the reduction in frictional and interlocking strengths by fine particles in the ballast shoulders. As a result, the corresponding unloaded track lateral resistance may decrease by as much as 10 to 30%[5]. The potential for track buckling may be more significant in areas that experience huge temperature swings between fall and spring seasons.

5) Increase in Ballast Compaction requirements

Fouled ballast shoulder results in a loss of the open gradation of the shoulder. This poor gradation decreases the permeability of the ballast, and leads to inefficient compaction of the ballast. As a result, the track disturbance (and associated loss of strength) is prolonged after maintenance operations because the actual densification and strengthening of shoulders is significantly slowed down. This can result in an extension of slow orders by as much as 25%[5].

6) Increased Ballast requirements

Reduction in the interlocking strength of the ballast results in a need for shallower slopes for the ballast shoulders. This reduction is from a nominal angle of 45 degrees (though it can be as much as 60 degrees for a clean shoulder ballast) to an angle of 35 degrees or less (corresponding to the angle of repose of the fouled ballast material). The effect of this reduction in ballast resistance and the flattening of the ballast shoulder slopes is an increase in the quantity of ballast required to maintain the ballast section's lateral strength.

7) Loss of sterility and resulting vegetation growth

The presence of fine particles (clay, silt) and the moisture content in the fouled shoulder ballast results in vegetation growth. Frequent application of herbicides may stop vegetation growth but the remaining organic residue may contaminate the ballast. The only remedy is to clean the shoulder ballast so that the ballast is clean, and dry ballast is sterile.

The above mentioned damage effects suggest the potential benefits for ballast shoulder cleaning, i.e.; to reduce or eliminate these damage effects. It should be noted here that these damage effects and their corresponding benefits are for average fouled conditions, and may vary from site to site, depending on specific soil types, ballast types, rainfall, traffic condition, etc.

Economic Analyses

By looking at the effects of ballast fouling, it is possible to determine the economic benefits of the ballast shoulder cleaning. These benefits are presented in terms of ROI (return on investment), where a positive ROI indicates that the investment (shoulder cleaning) has a positive payback, and a negative ROI indicates that it has a negative payback.

1) Extension of Surfacing Cycle

Ballast fouling and the resulting loss of ballast section effectiveness, accelerated loss of alignment, and accelerated loss of profile – all contribute to an increase in track geometry maintenance, i.e. surfacing. These effects are inter-connected and can result in a worst case scenario a reduction in surfacing cycle of up to 56%[3]. Based on a (conservative) reduction in surfacing cycle of 25% there will be an increase or extension of surfacing cycle of 33% when fouled shoulders are cleaned.

Using the following costs and assumptions, it is possible to determine the net benefit, and associated ROI of ballast shoulder cleaning's extension of surfacing cycle.

Cost:

- Cost of Surfacing: $12,000 per mile (including 2" to 3" of new ballast)
- Cost of Ballast Shoulder Cleaning: $2,100 per mile
- Discount Rate: 10%

[3] Based on a fouled ballast section as compared to same section with clean shoulders.

Effectiveness of Shoulder Cleaning:

- Shoulder Cleaning lasts 1 surfacing cycle

Extension of surfacing cycle by shoulder cleaning: 33%

- Surfacing Cycle – Fouled Shoulders; 3 years[4]
- Surfacing Cycle – Cleaned Shoulders; 4 years

Thus the extension of the surfacing cycle due to shoulder cleaning performed in year 0, results in a postponement of the next surfacing cycle from year 3 to year 4.

The equivalent annual cost of the three-year cycle is $3,625 per mile, i.e., the equivalent annual cost of a $12,000 surfacing every 3 years[5].

The equivalent annual cost of the four-year cycle is $2,593 per mile. Hence the net annual benefit is $1,032 per mile. The equivalent present worth of this one-year surfacing cycle extension is $3,264 per mile. Given that the cost of shoulder cleaning is $2,100 per mile, the corresponding return on investment (ROI) is 55%. The relationship between benefit (ROI) and surfacing cycle is presented in Table 1 and Figure 1. It should be observed from both Figure 1 and Table 1 that a positive ROI is obtained for shoulder cleaning when the surfacing cycle is less than 10 years.

Tables 1 through 5 present the sensitivity of the benefits of shoulder cleaning to the following key parameters:

- Increase in surfacing cycle due to shoulder cleaning (Table 2)
- Discount rate (interest rate) (Table 3)
- Surfacing cost (Table 4)
- Cost of shoulder ballast cleaning (Table 5)

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[4] Represents a moderate density track with visible pumping or a high-density track with moderate fouling[6].

[5] This is obtained from the following equation:

$$\text{Annual Cost} = \frac{C * I}{(1+n)^n - 1}$$

where; C is the future cost of the maintenance activity
I is the discount rate
n is the surfacing cycle in years

Table 1: Surfacing Cycle vs. ROI

Surfacing Cycle (years)		ROI
Fouled Shoulders	Cleaned Shoulders	
1	1.3	77%
2	2.7	66%
3	4	55%
4	5.3	46%
5	6.7	36%
6	8	27%
7	9.3	19%
8	10.7	11%
9	12	4%
10	13.3	-3%

Table 2: Effect of Increase in Surfacing Cycle on ROI

Surfacing Cycle (years)	Increase in Surfacing Cycle			
Fouled Shoulders	25%	33%	50%	100 %
1	35%	77%	166 %	419%
2	27%	66%	147 %	372%
3	19%	55%	130 %	329%
4	12%	46%	114 %	290%
5	5%	36%	98%	255%
6	-1%	27%	84%	223%
7	-7%	19%	71%	193%
8	-13%	11%	58%	167%
9	-19%	4%	47%	142%
10	-24%	-3%	36%	120%

Table 3: Effect of Variation in Discount Rate on ROI

Surfacing Cycle (years)	Discount Rate			
Fouled Shoulders	10%	15%	20%	25%
1	77%	72%	67%	62%
2	66%	56%	47%	39%
3	55%	42%	30%	19%

4	46%	29%	14%	1%
5	36%	16%	0%	-14%
6	27%	5%	-13%	-27%
7	19%	-5%	-24%	-39%
8	11%	-14%	-34%	-49%
9	4%	-23%	-43%	-57%
10	-3%	-31%	-50%	-64%

Table 4: Effect of Variation in Surfacing Cost on ROI
Surfacing Cycle (years) Surfacing Cost

Fouled Shoulders	$5,000	$10,000	$15,000	$20,000
1	-26%	47%	121%	195%
2	-31%	38%	107%	176%
3	-35%	30%	94%	159%
4	-39%	21%	82%	143%
5	-43%	14%	70%	127%
6	-47%	6%	59%	112%
7	-50%	-1%	49%	98%
8	-54%	-7%	39%	85%
9	-57%	-14%	30%	73%
10	-60%	-19%	21%	61%

Table 5: Effect of Variation in Shoulder Cleaning Cost on ROI
Surfacing Cycle (years) Cost of Shoulder Cleaning

Fouled Shoulders	$1,500	$2,000	$2,500	$3,000
1	148%	86%	49%	24%
2	132%	74%	39%	16%
3	118%	63%	31%	9%
4	104%	53%	22%	2%
5	91%	43%	14%	-5%
6	78%	34%	7%	-11%
7	67%	25%	0%	-17%
8	56%	17%	-7%	-22%
9	45%	9%	-13%	-27%
10	35%	2%	-19%	-32%

2) Extension of Undercutting Cycle

A related effect of ballast shoulder cleaning is the extension of the undercutting cycle due to the cleaning of the ballast shoulder. This effect is related to the same mechanisms discussed in the previous section for the extension of the surfacing cycle. In this case, however, the optimum benefit is derived when shoulder cleaning is carried out mid-way between undercutting cycles.

Using the following costs and assumptions, it is possible to determine the net benefit, and associated ROI of ballast shoulder cleaning's extension of undercutting cycle.

Costs:

- Cost of Undercutting: $30,000 per mile
- Cost of Ballast Shoulder Cleaning: $2,100 per mile
- Discount Rate: 10%

Effectiveness of Shoulder Cleaning:

- Shoulder Cleaning lasts 1 undercutting cycle

Extension of Undercutting cycle by shoulder cleaning: 25%[6]

- Undercutting Cycle – Fouled Shoulders; 20 years
- Undercutting Cycle – Cleaned Shoulders; 22.50 years
- Shoulder Clean; year 10

Thus the shoulder cleaning performed in year 10, results in a postponement of the next undercutting cycle from year 20 to year 22.5.

The equivalent present worth of the twenty-year cycle is $4,459 per mile (i.e., the equivalent present worth of a $30,000 undercutting every 20 years). The equivalent present worth of the twenty-two and half-year cycle is $3,514 per mile. Hence the net benefit is $945 per mile. Noting that shoulder cleaning occurs in year 10, the equivalent present worth of the shoulder cleaning is $810. The corresponding return on investment (ROI) is 17%. The sensitivity of ROI to undercutting cycle is illustrated in Table 6 and Figure 2. Also, the sensitivity of ROI to undercutting cost is shown in Table 7.

Table 6: Undercutting Cycle (years) vs. ROI

Fouled Shoulders	Cleaned Shoulders	ROI
10	11.3	0%
15	16.9	14%

[6] Since it is halfway through the cycle, the benefit will be applied only to the second half of the cycle.

20	22.5	17%
25	28.1	12%

Table 7: Effect of Variation in Undercutting Cost on ROI

Undercutting Cost	ROI
$20,000	-22%
$30,000	17%
$40,000	56%

It should be noted here that these two benefits of cleaned shoulders, associated with increasing surfacing cycles and increased undercutting cycles, while complementary; are not necessarily additive. This is because a frequent undercutting cycle will improve the overall surfacing cycle; independent of ballast shoulder cleaning. Thus the combined benefit is less than the sum of the two individual effects.

3) Elimination of the need for additional shoulder ballast

As noted earlier, another effect of ballast shoulder fouling is the reduction in lateral ballast resistance[7]. This, in turn, results in an increase in the quantity of ballast required to maintain the ballast section's lateral strength. The following analysis is based on the economics of shoulder ballast cleaning as compared to the increased ballast shoulder requirements. The cost of the additional ballast needed to maintain the same level of lateral resistance as a clean shoulder is calculated as follows:

<u>Costs</u>:

- Ballast Cost per Ton: $14
-

<u>Track Parameters</u>

- Shoulder width: 12 inches
- Depth of ballast: 12 inches

To compensate for a loss of ballast shoulder lateral resistance of 30%[4], an additional 176 cubic yards of ballast is required per mile. For ballast with a density of 1 ton per cubic yard, a total of 176 tons of ballast is required. Thus the cost of additional ballast is $2,464 per mile (Note: this cost does not include the cost of installing the ballast in track).

[7] There is also a change in the required ballast slope associated with the fouled shoulder, however there is an overlap with the loss of lateral resistance, and as such it will not be considered here.

Noting that the cost of shoulder ballast cleaning is $2,100 per mile, the corresponding return on investment (ROI) for shoulder ballast cleaning is 17%. The following table shows the relationship for the ROI of shoulder cleaning as a function of ballast shoulder width. It should also noted that the ROI increases as the cost of ballast increases.

Table 8: Ballast Shoulder Width vs. ROI

Shoulder Width (inches)	ROI
12	17%
15	46%
18	76%

Combining the above benefits for ballast shoulder cleaning, produces a range of total benefit (ROI) that can approach (and even exceed) 100% depending on track conditions. While; this benefit varies significantly as a function of track conditions and maintenance practices, in general, for mainline track conditions, it can be seen that ballast shoulder cleaning does pay for itself in terms of reduced maintenance costs and improved performance.

References:

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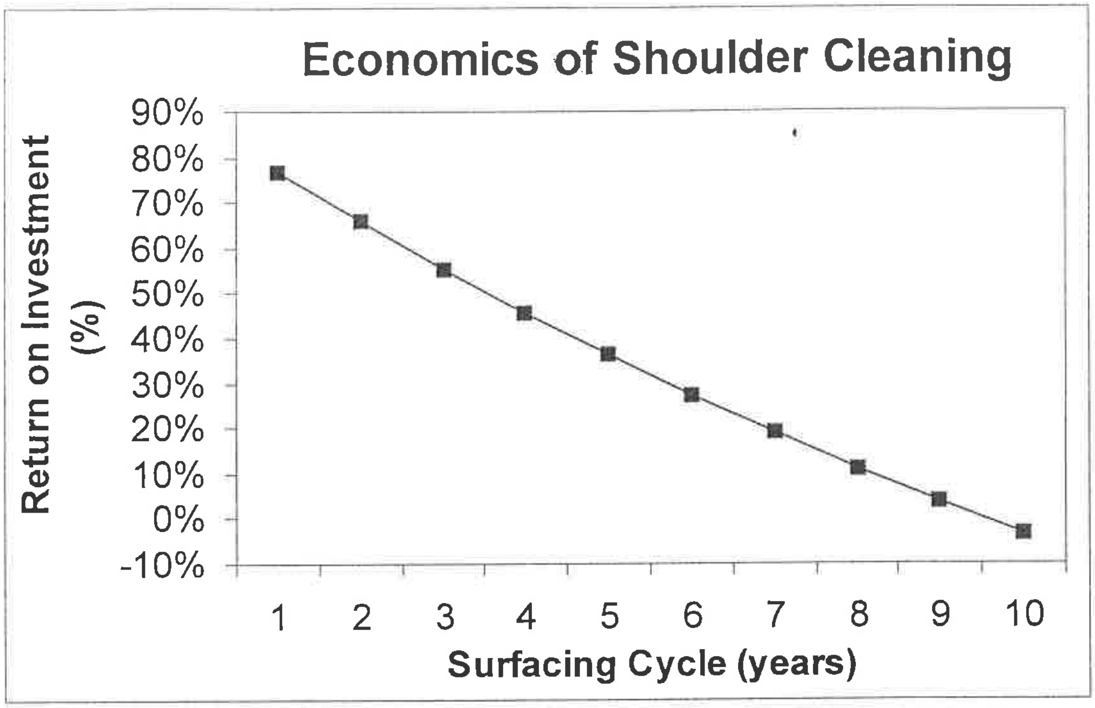
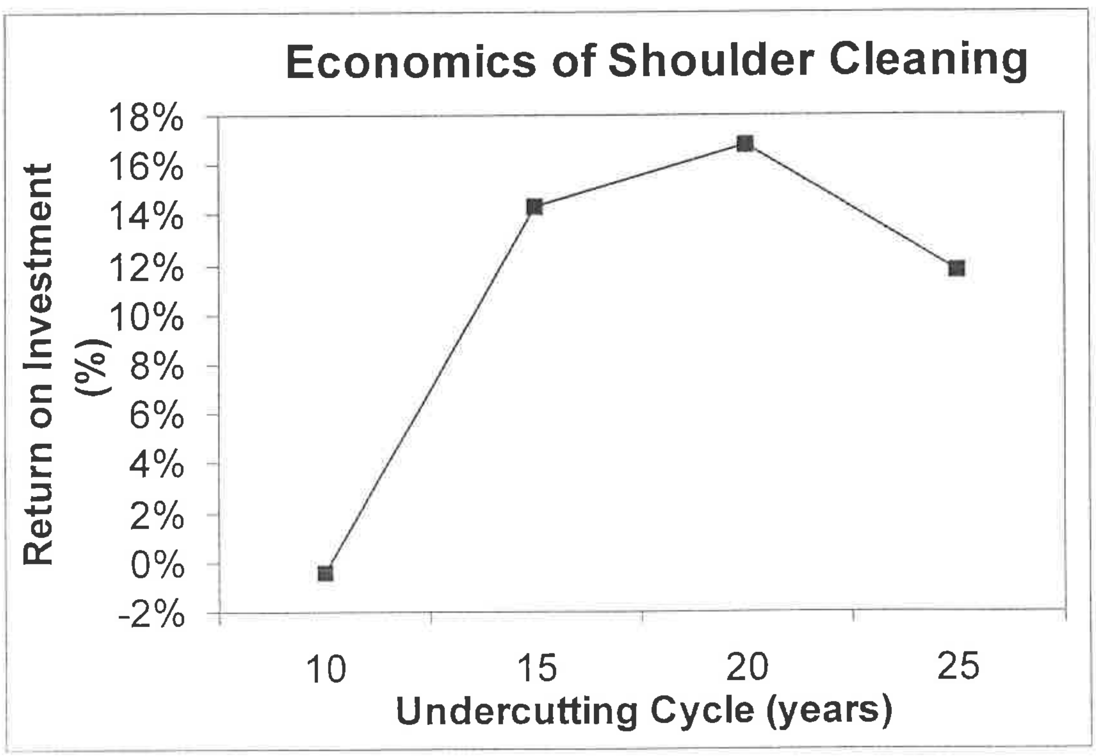


Economics of Shoulder Cleaning
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-10%
Return on Investment (%)
1
2
3
4
5
6
7
8
9
10
Surfacing Cycle (years)



Economics of Shoulder Cleaning
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
-2%
Return on Investment (%)
10
15
20
25
Undercutting Cycle (years)