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Design of Hump Profile in Railroad Classification Yard

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Synopsis

The fundamental objective of this paper is to aggregate and establish a set of practical principles, guidelines, and procedures to clarify and improve classification yard design and to enhance the efficiency of the design process. The paper primarily addresses theoretical and technical aspects of hump yard height and grade design, placement of the switches and the retarders . It attempts to compile and document yard design procedures, based on the Theory of Energy Head and Energy Loss. This procedures are applicable to the design of new yards, rehabilitation of the existing yards of different types and sizes including manually operated as well as highly automated classification yards.

1. Introduction

The purpose of a railroad classification yard is to sort cars from inbound trains into classifications and to build outbound trains by suitably grouping specific classifications of cars.The classification process entails considerable physical movement of trains, cars, and engines between receiving tracks, classification tracks and departure tracks. Associated with this physical movement of cars are an inventory system to

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monitor the location of each car and the control of the routs and speeds of cars and engines.

The classification of cars in the hump yard is accomplished by pushing a string of cars over a hump and switching them to various classification tracks. Cars are uncoupled right after their centers of gravity pass the hump crest. From that point on, each cut of cars is a freely moving body whose energy of motion is due to the downward grade along the hump track. Essentially, each car has different rollability and thus, without controlling the car velocity at certain points along the track, collisions are inevitable. The car spacing and velocities along the route from the hump crest to the classification track are controlled by retarders. Here cuts can be single or multiple but the subsequent discussion assumes single-car cuts.

In the switching area, a minimum separation of approximately 20 m is generally required for cars being switched to different tracks. If this separation is not achieved, the switch can not be thrown for the trailing car and the car is switched to the wrong classification track. This problem of maintaining sufficient car separation, to avoid misswitching cars, is compounded by the fact that cars have widely different values of rolling resistance; consequently, the easy-rolling cars tend to overtake the hard-rolling cars. By properly monitoring the behavior of each car and decelerating the easy-rolling cars, cars can be guided through several switches to their proper classification tracks.

When a car has reached the beginning of a classification track (a tangent point) it may be required to roll as far as 1,000 m or as little as 30 m, depending on the number of cars already standing on the classification track to which it is being switched. Because of this great disparity of distances and the different rolling behavior of cars, the velocity of each car must be adjusted so that severe impacts do not occur on the classification tracks. At the same time, cars must have sufficient energy to couple with other cars already waiting on the classification tracks.

The objectives in designing a hump profile and the corresponding retarder system are:

1. The hump must be high enough to provide cars with a sufficient quantity of kinetic energy so that they can easily overcome the rolling and track resistances and roll over the assessed distance beyond the tangent point;
2. The shape of the hump profile must give cars sufficiently high speed to create and

maintain sufficient separation between consecutive cars in the switching area to permit satisfactory switching operation;

3. The impact of cars during coupling on the classification tracks should be minimal to ensure minimum car and cargo damages;
4. The probability of misswitching should be as low as possible;
5. The placement and operation of switches and retarders must ensure sufficiently high shunting speed so that a bottleneck at the hump does not occur;
6. The retardation system, including the civil engineering design and electrical systems, must cost as little as possible and be easy and inexpensive to operate and maintain.

2. Hump Height

The hump must provide a rolling car with sufficient quantity of kinetic energy necessary for executing a work to overcome all rolling and track resistances acting on the car, and for covering the requisite distance on the classification track.

The calculation of the height of the hump proceeds from the requirement that the hard-rolling car running in unfavorable weather conditions (low temperature and headwinds) will reach a reference point in a requisite distance beyond the tangent point of the most unfavorable track (track with the highest energy loss due to the track resistance).

The sine component of the weight of the rolling car must execute a work equal to the resistive work done by:

a) rolling resistance of the car on the distance between the crest of hump and the reference point (100 m beyond the tangent point)

$$A_r = g \cdot M \frac{r_m \cdot l}{1000} \quad [kJ] \tag{1}$$

where

M = mass of the car in *t*,

g = gravitational acceleration in m/s^2 ($9.81 m/s^2$),

r_m = mean rolling resistance of the car in *N/kN*,

l = distance between the crest and the reference point in *m*.

b) resistance of track curves and switch curves:

$$A_c = g \cdot M \frac{\Sigma\, r_c \cdot l_c}{1000} = g \cdot M \frac{c \cdot \Sigma\alpha}{1000} \quad [kJ] \tag{2}$$

where

r_c = curve resistance in *N/kN*,

l_c = curve length in *m*,

$c \cdot \Sigma\alpha$ = relative resistive work in curves in *J/kN*.

c) resistance of strikes in the switches:

$$A_s = g \cdot M \frac{20\, n}{1000} \quad [kJ] \tag{3}$$

where

n = number of switches in the track of the car.

For execution of this work, the rolling car disposes of:

a) kinetic energy ensuing from humping speed at the crest of the hump:

$$E_o = \frac{M \cdot v_o^2 \cdot \rho}{2} \quad [kJ] \tag{4}$$

where

v_o = humping speed in *m/s*.

ρ = rotational head correction factor

b) potential energy ensuing from the elevation of the hump crest over the reference point on the classification track:

$$E_p = g \cdot M \cdot h_{hump} \quad [kJ] \tag{5}$$

where

h_{hump} = requisite height of the hump in *m*.

From the equilibrium of the requisite energy and the resistive work done:

$$E_o + E_p = A_r + A_c + A_s \tag{6}$$

after substitution of equations (1), (2), (3), (4), and (5):

$$\frac{M\cdot v_o^2\cdot\rho}{2} + g\cdot M\cdot h_{hump} = g\cdot M\frac{r_m\cdot 1}{1000} + g\cdot M\frac{c\cdot\Sigma\alpha}{1000} + g\cdot M\frac{20\,n}{1000} \qquad (7)$$

the equation for the requisite height of hump can be derived as:

$$h_{hump} = \frac{r_m\cdot 1}{1000} + \frac{c\cdot\Sigma\alpha}{1000} + \frac{20\,n}{1000} - \frac{v_o^2}{2g'} \quad [m] \qquad (8)$$

where

g' = conversion gravitational acceleration in m/s^2, keeping in view the influence of the car's rotating parts.

The first three terms of the right side of equation (8) represent the energy loss caused by rolling resistance, curve resistance, and switch resistance. The term $v_0^2/2g'$ represents the initial energy head ensuing from the humping speed.* In other words, the requisite height of hump can be defined as a total energy loss along the track between the hump crest and the reference point, reduced by the initial energy head at the crest of the hump.

3. Hump Grade Profile

Beside assigning the hump height, an appropriate grade profile must also be designed so that sufficient time separations between the consecutive cars at switches and retarders can be ensured.

Velocity of a car with a certain rollability at any place of the hump depends on the hump profile. The steeper the grade is, the higher is the car velocity at the given place of the hump. This ensues from the fact that increasing the grade of the track will increase the car energy head. Accordingly, the cars with higher energy head traverse the switching area with a higher velocity and consequently, a higher humping speed can be reached.

* For explanation of the Theory of Energy Head and Energy Loss see [8].

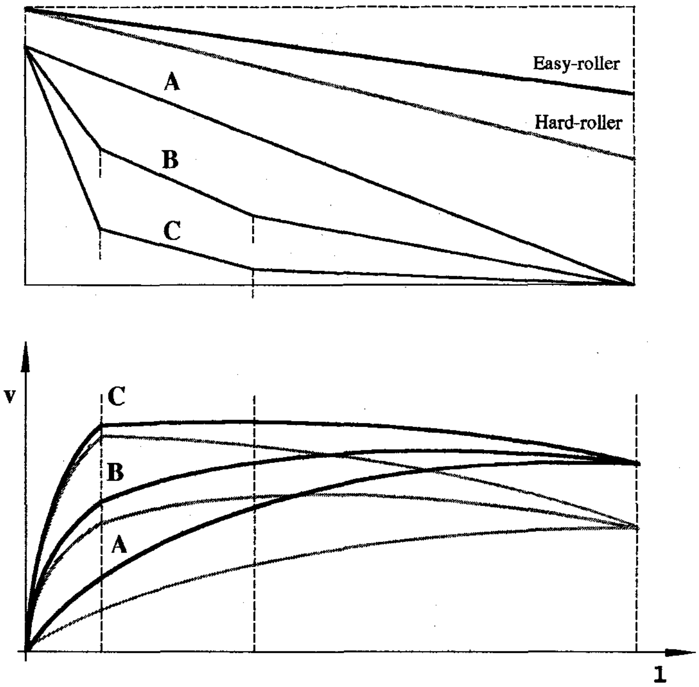

Figure 1: Car velocity as a function of the hump profile

Figure 1 shows the courses of car velocities for different setups of the hump profile with the same hump height and the same rollabilities for easy-rolling and hard-rolling cars respectively. From the picture it is evident that the difference of velocities of cars with different rolling characteristics is smaller, when the initial grade of track is greater. This conclusion ensues from the fact that the greater the gradient, the smaller the influence of car resistance on it's energy head.

In Figure 2, the energy heads of an easy-rolling and a hard-rolling car in the first track section of the hump profile are shown. If, according to this picture, this difference of the energy heads is:

$$\Delta h = h_E - h_H = \frac{v_E^2 - v_H^2}{2g'} \quad [m] \tag{9}$$

then the difference between the velocities of the easy-rolling and the hard-rolling cars is:

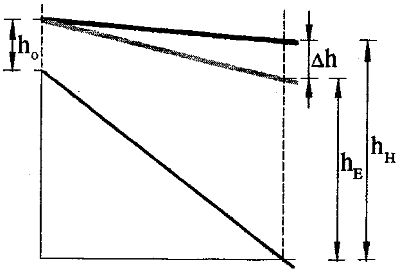

Figure 2: Energy head on the first grade

$$v_E - v_H = \frac{2g' \cdot \Delta h}{v_E + v_H} \qquad (10)$$

The greater is the grade in the first section of the track, the greater is the sum of velocities $v_E + v_H$, and as the difference of the head energies Δh is independent of the grade, the smaller is the difference of velocities $v_E - v_H$.

The same conclusion ensues also from the equation for computing the velocity v_2 of a car rolling down the grade on a given distance l when the initial velocity v_1 is known:

$$v_2 = \sqrt{v_1^2 + \frac{2g' l(s-r)}{1000}} \quad [m/s] \qquad (11)$$

It is evident, that with increasing gradient s the influence of the car resistance r on the velocity v_2 decreases.

If, at an increasing gradient, the velocity difference between the easy-rolling and the hard-rolling cars decreases, then also the difference of rolling times of these cars from the crest of the hump to the reference point and thus the danger of catching up the consecutive cars within the switching area will decrease.

With regard to these theoretical conclusions, the vertical grade profile can be designed. The basic principle is to select a sequence of grades in such a manner that:

1. Cars do not violate the maximum speed limits for switches and curves;
2. Cars maintain sufficient spacing at switches and retarders;
3. Cars do not catch up to other cars prior to the tangent point;
4. The speed requirements at the reference point, such as the tangent point, are met;
5. Cars do not violate the minimum speed limit set up by the designer.

The usual approach to this problem is to select a sequence of grades and for preassigned hump height, to set up the hump profile, starting with the steepest grade after the hump crest and following by successively less steep grades into the bowl. The first of them is the accelerating grade placed immediately after the crest vertical curve with a considerably falling gradient of 30 - 50 ‰ (in the hump yards where the horizontal track formation allows it, even 60 ‰), so that the sufficient separation between the consecutive cars can be created. The height of this grade should be approximately half of the total hump height. The accelerating grade is followed by one or two inter-grades with descending gradients of 12 - 20 ‰. The switching area lies in gradient of 1 - 1.5 ‰ (for automated hump yards the maximum gradient of 1.2 ‰ is recommended). Classification tracks may in two thirds of their length have the falling gradient of 1 - 1.5 ‰.

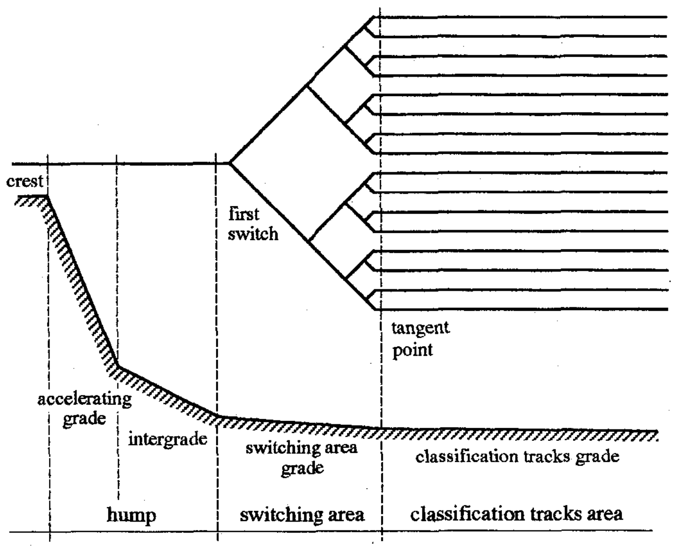

Figure 3: Horizontal and vertical layouts of the hump yard

The above mentioned method of setting up a hump profile based on an empiric experience of the designer is correct and generally used. However, it has some disadvantages which may, in some cases, cause a situation when some initial conditions required for a new or a rehabilitated hump yard will not be met.

The main disadvantage consists in the impracticability of assigning a correct value of the car's mean rolling resistance. Cars roll down the hump yard with a varying velocity which depends on the height and the grade profile of the hump. This velocity largely influences the magnitude of the air resistance which is a component of the rolling resistance. In the computation of rolling resistance for assigning the hump height, however, the variable velocity is substituted by its mean value which becomes a source of an inaccuracy. The divergence of the mean velocity from the real velocity appears as a squared divergence of the mean rolling resistance from its real value. In practice, this may result in the situation when the real run out of a car is considerably different from the required.

The more accurate calculation of hump profile consists in prior assigning the velocities which the hard-rolling car under unfavorable conditions should reach in some crucial points of the hump yard. These crucial points are:

- Crest of the hump,
- First switch in the switching area,
- First switch of the bundle of rails (second switch),
- Tangent point.

Assigning velocities in the crucial points gives the preliminary information of the car's rolling along the hump track and then enables the more accurate computation of rolling resistance in a single sections of the track.

The car velocity at the hump crest is given as the humping velocity. The calculation of the velocity of the hard-rolling car in the switching area follows the requirement of ensuring sufficient spacing between consecutive cars necessary for safely throwing the switches. The separation is sufficient if it holds:

$$\frac{l_{car}}{v_o} - \Delta t = \frac{l_{is} + b}{v_H} \qquad (12)$$

where

l_{car} = mean car length in *m*,

v_o = humping speed in *m/s*,

Δt = time separation between easy and hard-rolling cars at the reference switch in *s*,

l_{is} = length of the switch insulated section in *m,*

b = mean car wheel base in *m,*

v_H = mean velocity of the hard-rolling car at the switch in *m/s.*

The term l_{car}/v_O is the initial separation time between two consecutive cars at the crest of the hump. The term $(l_{is}+b)/v_H$ represents the occupation time of the insulated section of the switch by the hard-rolling car.

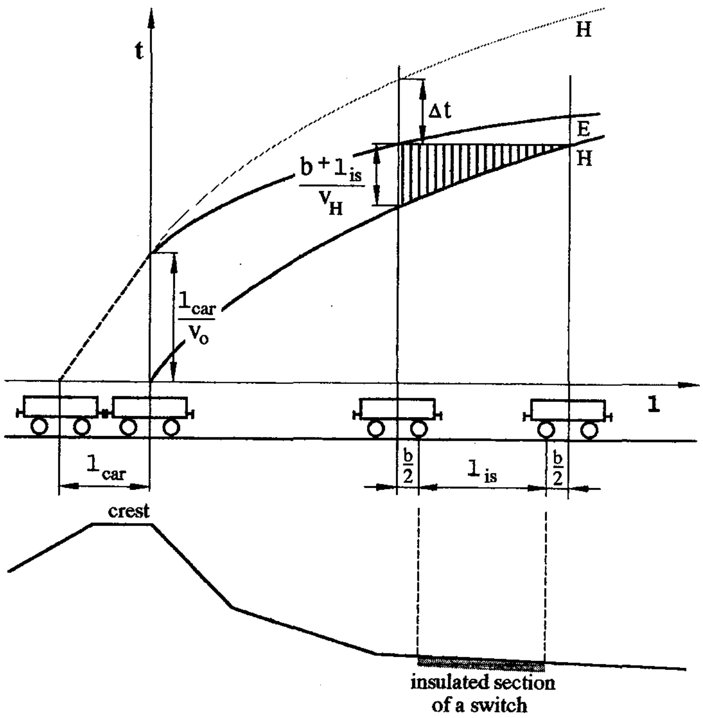

Figure 4: Spacing between cars in the switching area

From the equation (12) the requisite velocity of the hard-rolling car at the switch can be derived as:

$$v_H = \frac{l_{is} + b}{\frac{l_{car}}{v_o} - \Delta t} \quad [m/s] \tag{13}$$

The humping speed v_0 is selected according to the required capacity of the hump yard. The time spacing between the consecutive cars Δt depends on the distance from the hump crest and should be assigned empirically for each hump yard.

The velocity of the hard-rolling car at the beginning of the classification track for a requisite run out beyond the tangent point can be determined from the track grade and the lay out conditions behind the last switch. Supposing that no switches are placed in the classification track, the track lies in a single gradient, and the velocity of the car at the reference point reaches zero, then the velocity at the beginning of the classification track can be derived from the Law of Conservation of Energy modified into the form:

$$\frac{v_H^2}{2\,g'} + \frac{s \cdot l}{1000} = \frac{r_H \cdot l}{1000} + \frac{c \cdot \Sigma\alpha}{1000} \tag{14}$$

From this equation the velocity of a hard-rolling car at the beginning of the classification track is:

$$v_H = \sqrt{\frac{2g'}{1000}\,[\,l_t(r_H - s) + c\cdot\Sigma\alpha\,]} \qquad [m/s] \tag{15}$$

where

g' = conversion gravitational acceleration in *m/s²*,

l_t = length of the track between the last switch and the reference point (the requisite run out of the car) in *m,*

r_H = mean resistance of the hard-rolling car in *N/kN,*

s = gradient of the classification track in *‰,*

c = a resistive constant expressing a resistive work of curve,

$\Sigma\alpha$ = sum of the central angles between the last switch and the reference point in grades.

With regard to above mentioned principles, the computation of the hump profile is as follows:

1. By the equations (13) and (15), the requisite velocities of the hard-rolling car in the crucial points of the hump are calculated.

2. Mean velocities and mean rolling resistances in the track sections between the crucial points are calculated.
3. Points of change of gradient are assigned, being placed as near as possible in front of the first switch of the switching area, in front of the first switch of the bundle of rails and after the last switch before the classification track.
4. The gradients of the track sections between the selected points of change of gradient are calculated as:

$$s = r_H + \frac{1000}{l_s}\left(\frac{v_{H2}^2 - v_{H1}^2}{2g'} + \frac{20\,n + c \cdot \Sigma\alpha}{1000}\right) \quad [‰] \tag{16}$$

where

r_H = mean rolling resistance of the hard-rolling car in the reference track section in *N/kN*,

l_s = length of the track section between two neighbor points of change of gradient in *m*,

v_{H1} = velocity of a hard-rolling car at the beginning of the track section in *m/s*,

v_{H2} = velocity of a hard-rolling car at the end of the track section in *m/s*,

n = number of switches in the track section,

$\Sigma\alpha$ = sum of central angles of the track curves and the curved branches of the switches lying in the reference track section in grades.

This more precise method of computation merges the computation of the hump height with the computation of the hump grade profile and enables the calculation to be closer to the optimum variant of the hump profile design.

4. Location of the First Switch

Location of the first switch is an important factor of designing a hump system. The determining factors for the location of the first switch are the desired hump velocity and the hump grade. For a given desired hump velocity and a hump grade, there is an optimum location for the first switch in terms of obtaining the maximum headway separation at that point. Locating the first switch either too close or too far from the hump crest will restrict the hump speed. Also, for a given location of the first switch, any increase in hump velocity requires that the hump grade be made steeper for cars to clear the first switch, or if the first switch location is moved away from the optimum location - either toward or away from the hump crest - the hump grade has to be steepened to achieve a desired hump velocity.

The location of the first switch must be chosen in such a way that at an unfavorable succession of cars (a hard-rolling car followed by an easy-rolling car) the minimum headway separation between the cars must be preserved to allow the cars to be switched to different tracks. The location of the first switch is computed according to Figure 4. The mean velocity of the hard-rolling car in the middle of the switch insulated section can be determined by equation (13). This velocity corresponds to the energy head which the hard-rolling car has in the middle of the insulated section ($h_H = v_H^2/2g'$).

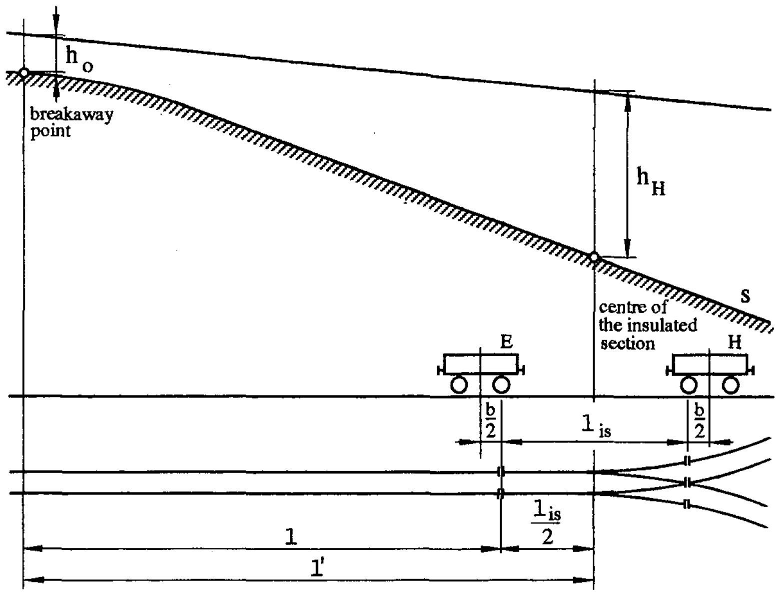

Figure 5: Location of the first switch

The mean energy head consists of the energy head at the breakaway point h_o corresponding to the humping velocity v_o, and the energy head corresponding to the work done by forces acting on the car during its travelling along the distance between the breakaway point and the center of the insulated section.

$$h_H = h_o + \frac{l'(s - r_H)}{1000} \quad [m] \tag{17}$$

where

h_o = car energy head at the crest of the hump in *m*,

l' = distance between the breakaway point and the center of the insulating section of the first switch in *m*,

s = gradient of the track in ‰,

r_H = mean rolling resistance of the hard-rolling car in *N/kN*.

From equation (17) the distance of the center of the switch insulated section of the first switch from the breakaway point is:

$$l' = \frac{1000(h_H - h_o)}{s - r_H} \quad [m] \tag{18}$$

The distance of the beginning of the switch insulated section from the breakaway point then is:

$$l = \frac{1000(h_H - h_o)}{s - r_H} - \frac{l_{is}}{2} \quad [m] \tag{19}$$

This distance is measured from the breakaway point which, however, does not represent a place with a fixed position. The location of the breakaway point varies according to the rolling resistance of the reference car. From this point of view it is more convenient to define the location of the first switch as a distance from crest of the hump rather than from the breakaway point.

The distance of the beginning of the switch insulated section of the first switch from the crest of the hump then is:

$$l = \frac{1000(h_H - h_o)}{s - r_H} + \frac{R \cdot s}{2000} - \frac{l_{is}}{2} \quad [m] \tag{20}$$

5. Location of the Retarders

Retarders are required so that a degree of control over cars during the course of their rolling can be exerted. Various requirements must be satisfied in designing a retarder placement. A retarder system must be able to accomplish its purpose, which is to sufficiently control the speed of cars rolling down the hump yard at a reasonable misswitching rate and without damaging cargo and cars. At the same time the retardation system, including the civil engineering design and electrical systems must cost as little as possible and be easy and inexpensive to operate and maintain.

The retarders must be placed into the hump profile in such a manner that cars have sufficient separation at switches and retarders downstream within the given speed limits. Retarder placement can be done by studying velocity and distance profiles of a special sequence: a hard-rolling car followed by an easy-rolling car which in turn is followed by another hard-rolling car. This represents the worst case as far as closing up the headway is concerned.

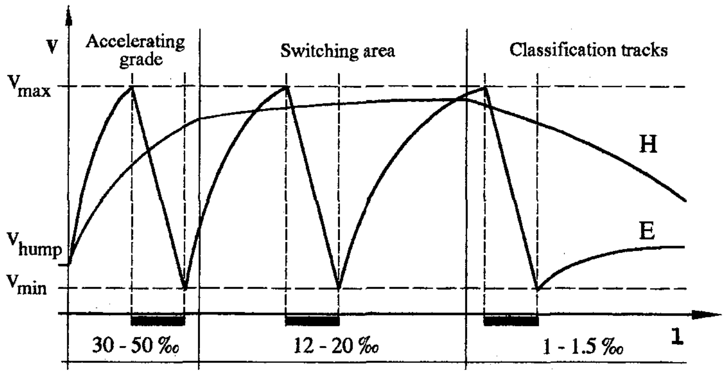

Figure 6: Velocity based placement of the retarders

If the easy-rolling car is allowed to roll freely, it will tend to catch up with the hard-rolling car within a short distance. The first retarder should be placed before the headway is first indicated to be getting smaller than the desired value. The velocity of the easy-rolling car at the exit point of the retarder should be reduced below that of the hard-rolling car through retarder action. The necessary size and location of the second, third, etc., retarder can similarly be established through further computation of distance and velocity profiles. In the following, retarder configurations of the conventional clasp-type retarders will be discussed.

Basically the clasp-type retarders can be placed in one or more of the following track segments:

1. Segment: the retarders are placed into the accelerating grade between the hump crest and the first switch (master retarder),
2. Segment: the retarders are placed into the switching area (inter-grade) on the lead track of each track group (group retarder),
3. Segment: the retarders are placed at the tangent point of each classification track (tangent point retarder).

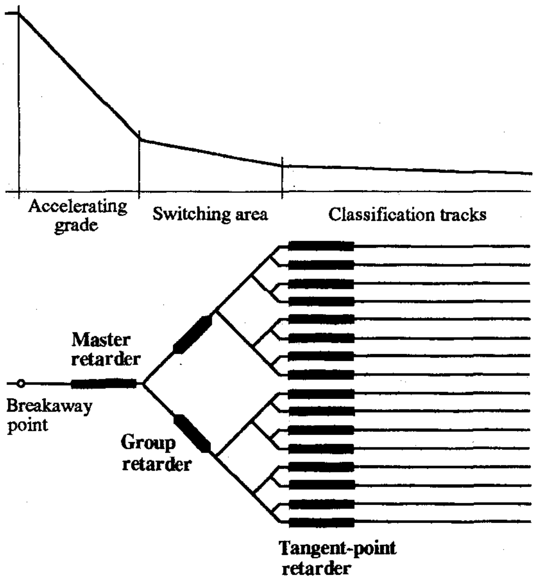

Figure 7: Placement of the retarders into the hump track formation

Theoretically all combinations of the above retarder locations are possible. They are:

1. Master retarder only;
2. Group retarders only;
3. Tangent point retarders only;
4. Master retarder and group retarders;
5. Master retarder and tangent-point retarders;
6. Group retarders and tangent-point retarders;
7. Master retarder, group retarders and tangent-point retarders.

The selection of the retarder combination is usually done, based on the performance and the cost of the retardation system. Usually, as the number of retarders along the track increases, the performance of the system improves, but the cost also increases. It also must be noted, that the performance and the cost of retardation systems are very much influenced by the number of classification tracks. The number of classification tracks influences the cost of the system proportionally because the total number of retarder segments required increases with increasing number of classification tracks. At the same time, the distance between the hump crest and the tangent-point also generally increases, which may require more and longer retarder sections to obtain the same performance characteristics.

Retarder configurations which are recommended from the cost and the effectiveness point of view are the single-control-point systems (master retarder only, group retarders only and tangent-point retarders only) for small yards, the two-control-point systems (master retarder and group retarders, master retarder and tangent-point retarders) for intermediate size yards, and the three-control-point system (master retarder, group retarders and tangent-point retarders) for large yards.

The type of clasp retarders used also becomes an important part of the retarder configuration selection. In small yards the retarder types normally installed would be the less expensive weight-responsive hydraulic retarders, while in large yards heavy-duty retarders would normally be installed.

The selection of the retarder configuration, type of retarders as well as the number of retarding units of each retarder segment can be done with regard to the velocity head of cars to be dissipated. The selected configuration of retarders must have enough capacity to dissipate the total velocity head of the most easy-rolling car being sent to the classification track with the most favorable resistance situation under the most favorable weather conditions. If these requirements are met, then it holds:

$$\Sigma h_R > h_H \tag{21}$$

where

Σh_R = sum of retardation capacities of all retarders lying in one track, expressed as an energy head to be dissipated, in *m*,

h_H = total velocity head of the most easy-rolling car in *m*.

6. Conclusion

1. The requisite height of hump can be defined as a total energy loss along the track between the hump crest and the reference point reduced by the initial energy head.
2. The higher the gradient in pre-switching areas, the smaller the velocity difference between the easy-rolling and the hard-rolling cars, and the lower the possibility of catching up the consecutive cuts within the switching area.
3. For any combination of hump profile and desired humping velocity an optimum location of the first switch in terms of obtaining the maximum head way separation between the consecutive cars can be determined.
4. The selection of retarder configuration, type of retarders as well as number of retarding units should be made with regards to cut's velocity head to be dissipated.

Most of the computations are based on the presumption that all forces acting on a moving cut can be considered as relative forces calculated per a unit of car's weight and can thus be expressed in N/kN or in ‰.

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