The Penalty of Cyclic Queues in Operating Processes with Freight Trains at Formation Yards

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Abstract

The inside of the throughput line at formation yards is the Process of Freight Train Making (PTM). Elaborating on its characteristics and specificities one might identify a specific category of queueing systems. This category is *bulk service queues*, meaning similar customers are served in batches. For this discussion the customers are freight cars. Freight cars are set up into freight car groups i.e., batches. These freight car groups are coupled in order to form the freight trains. The freight train consists of one or more freight car groups. This is the crux of the PTM. Theoretically, this question might seem simple. One should merely define which freight car group(s) should go with which freight train. Practically, this question is not simple at all. Considering how a bulk service process operates, one might be easily convinced of it. Bulk service is characterized with *cyclic recurrence* and has a negative consequence seen in *cyclic queues*. In this paper we scrutinize the penalty of cyclic queues in operating processes with freight trains at formation yards by demonstrating the frame of reference and a set of effective strategies for planning of the process of freight train making. Adequate measures of performance in use are: gathering time, similar in meaning to waiting times, and time in cyclic queue, effectively the time in system.

**Keywords**: Railway freight operations, Freight trains, Formation yards, Cyclic queues, Bulk service.

Introduction

The inside of the operating processes with freight trains at formation yards are within the process of gathering of freight cars into freight trains. This process can be met in the literature (Raikov, 1985, 1986) (Razmov, 2004) under the name of “Process of Freight Train Making” (PTM). One should not mistake the process of freight train making for the process of making up of a freight train at the shunting zone of formation yard (PMT). The PTM is not as simple as the PMT. The PTM encompasses not only the operating processes with freight cars within formation yard but also out of the yard and
demonstrates the connections between: the total daily flow of freight cars per assignment; the waiting time per freight car on average; the dwell time per freight car on average; a maximum number of freight cars that a freight train consists of; etc.

Process of Gathering of Freight Cars into Fright Trains

Characteristics and Specialties

To begin the demonstration of the Process of Freight Train Making (PTM), one must elaborate on its characteristics and specificities which are dictated by a specific category of queueing systems. This category is bulk service queues, meaning similar customers are served in batches. In this discussion the customers are freight cars. Freight cars are set up into freight car groups i.e. batches. These freight car groups are coupled in order to form the freight trains. The freight train consists of one and more freight car groups, the crux of the PTM. Theoretically, this question might seem simple. One should merely define which freight car groups should go with which freight train. Practically, this question is not simple at all. Considering how a bulk service process operates, one might be easily convinced. Bulk service is characterized with cyclic recurrence that can be seen in cyclic queues. To verify this let us imagine that there is a scheduled freight train to depart from a given formation yard at 19:00. This freight train consists of four freight car groups which are planned to come to the same formation yard with previous freight trains, say, one to arrive at 10:00, second to arrive at 12:00, third to arrive at 15:00, and fourth to arrive at 17:00. The freight train arriving at 10:00 will set out the freight car group scheduled to be part of a freight train to depart at 19:00. The same will happen with the freight trains that arrive at 12:00 15:00 and 17:00, i.e., they will set out the freight car groups that are scheduled to be part of a freight train to depart at 19:00. Thus, we see that in order for the freight train at 19:00 to be served, there is a set of services to be fulfilled i.e. first the freight train at 10:00 is served, then a second freight train at 12:00 is served, after that the train at 15:00 and next the freight train at 17:00. However, the whole service of freight train to depart at 19:00 will be complete only when it leaves the formation yard. So, it should be clear now that none of the freight car groups are served until they all arrive, form and leave all together with the freight train they are scheduled for. In this example, the queue starts to materialize at 10:00 when the first freight car group arrives at the formation yard and does not vanish until 19:00 when the scheduled freight train left and its service is completed. During the intervening time, i.e., between 10:00 and 19:00, there is at least one group of freight cars waiting. Therefore, the queue only grows and does not shrink over a period of service. This phenomenon is a cyclic queue of bulk service.

Parameters and Coefficients

Undoubtedly, the process of freight train making (PTM) is a complex one. Its quality level can be seen in a set of qualitative and quantitative measures that are its main parameters. These are, as follows:

- Total arrival rate of freight cars

\[ \lambda_{cars} = \sum_{i=1}^{n} \lambda_{cars,i} \]  

where, \( i = 1, 2, \ldots, n \) is a number of assignments;
• Total arrival rate of freight car groups

\[ \lambda_{\text{groups}} = \sum_{i=1}^{n} \lambda_{\text{groups},i} \]  

(2)

where, \( i = 1, 2, \ldots, n \) is a number of assignments;

• Headways – \( I_{\text{groups},i} \) – inter-arrival times between the freight cars groups for the \( i \)-th assignment;

• Total number of freight cars

\[ N_{\text{cars}} = \sum_{i=1}^{n} N_{\text{cars},i} \]  

(3)

where, \( i = 1, 2, \ldots, n \) is a number of assignments;

• Total number of freight car groups

\[ N_{\text{groups}} = \sum_{i=1}^{n} N_{\text{groups},i} \]  

(4)

where, \( i = 1, 2, \ldots, n \) is a number of assignments;

• A number of freight cars that a freight car group consists of, on average – \( m_{\text{gr}} \);

• A number of freight cars that a freight train consists of, on average - \( m_{\text{cars}} \);

• A number of freight car groups that a freight train consists of, on average - \( m_{\text{groups}} \);

• Period of gathering per assignment

\[ T_k = \sum_{k=1}^{n} T_{g,k} , \]  

(5)

where, \( k = 1, 2, \ldots, n \) is a number of freight trains per one and the same assignment;

\( T_{g,k} \) is the period of gathering for the \( k \)-th freight train from the same assignment;

• Setup time – \( t_{\text{service},k} \) - the time required for service of the \( k \)-th freight train, after having all freight car groups for the \( k \)-th freight train arrived in the formation yard;

• Envisaged time – \( t_{\text{envisaged},k} \) – the time to elapse from the moment the \( k \)-th freight train completes the service to the moment the same freight train leaves the formation yard;

To resume an illustration, let us suppose that the arrival pattern of the freight car groups for a given assignment is a constant rate. So then, the parameter of the process of gathering, say, \( B_{\text{gathering}} \), which demonstrates how many hours the freight cars stand under gathering into freight trains per one and the same assignment, might be computed as an area of triangle, as follows:

\[ B_{\text{gathering}} = \frac{m_{\text{cars}}^{\text{cart}} \cdot T_k}{2} = \frac{m_{\text{cars}}^{\text{cart}} \cdot \sum_{k=1}^{n} T_{g,k}}{2} \]  

(6)
One might recognize that the fraction \( \frac{\sum_{k=1}^{m} T_{g,k}}{2} \) takes an all-important portion. This fraction is the coefficient of gathering of freight cars into freight trains \( (c_{\text{gathering}}) \). Further, let us suppose that the process of gathering is permanent i.e., without interruptions, and the freight trains’ departures coincide exactly with when the queues dissipate. There are two important properties that become clear, as follows:

- the period of gathering per assignment is equal to 24 hours;
- the PTM submits to a cyclic recurrence;

Following the first property, by substituting \( T_{g} = 24 \) hours, the equation for \( B_{\text{gathering}} \) takes form, as follows:

\[
B_{\text{gathering}} = \frac{m_{\text{cars}} c \cdot 24}{2} = 12 \cdot m_{\text{cars}} c
\]  

(7)

One should realize that in this particular case the coefficient of gathering comes up to 12 (twelve). In theory, this value is a basis and indicates the regularity of the arrival pattern that has been assumed to begin the illustration. In practice, the arrival pattern is not regular, and the coefficient of gathering incurs different values than 12 (twelve).

Following the second property, one may easily identify the cyclic queues within the PTM. Let us be reminded that every queue starts to materialize when the first group of freight cars arrives at the formation yard and dissipates only when the freight train entire leaves the formation yard. Therefore, the cyclic length for the \( k \)-th freight train, say, \( T_{c,k} \), encompasses the time from the moment at which the first group of freight cars for the \( k \)-th scheduled freight train arrives to the moment at which the same freight train leaves the formation yard. Simply, in formula, this is:

\[
T_{c,k} = T_{g,k} + t_{\text{service},k} + t_{\text{enviaged},k}
\]  

(8)

Consequently, one might identify a parameter of the \( k \)-th cyclic queue, say, \( B_{\text{cyclic-queue}}^{k} \), which demonstrates how many hours the freight cars stand in the \( k \)-th cyclic queue. The formula is, as follows:

\[
B_{\text{cyclic-queue}}^{k} = \frac{m_{\text{cars}} c \cdot T_{c,k}}{2}
\]  

(9)

In this case the all-important fraction is: \( \frac{T_{c,k}}{2} \), and is to be the coefficient of the \( k \)-th cyclic queue \( (c_{\text{cyclic-queue}}^{k}) \). Considering that there might have a number of freight trains to be made per assignment, respectively there might have a number of cyclic queues to occur, so then the coefficient of the cyclic queues per assignment entire will take the following fraction:

\[
\frac{\sum_{k=1}^{m} T_{c,k}}{2}
\]

The coefficient of gathering and the coefficient of cyclic queue are of prime importance because of their great significance in minimizing the average gathering time and the average time in cyclic queue per freight car. Therefore, improvements of the process of freight train making can be achieved through reductions in the values of coefficient of
gathering and coefficient of cyclic queue, and hence, decreasing in the parameter of process of gathering and the parameter of cyclic queue.

1 Gathering Time and Time in Cyclic Queue

The measures that evaluate the setup-quality level of the process of freight train making (PTM) at a given formation yard are: the gathering time per freight car on average and the time in cyclic queue per freight car.

The gathering time per freight car, say, \( t_g \), is analogous, to some extent, to the waiting time per freight car on average and per the i-th assignment is computed by the following formula:

\[
\frac{B_{\text{gathering},i}}{N_{\text{cars},i}}
\]

After elementary mathematical transformations, by substituting \( B_{\text{gathering},i} \) with its equal the equation of the gathering time per freight car per assignment takes form, as follows:

\[
t_{g,i} = \frac{c_{\text{gathering},i} \cdot m_{\text{cars}}}{N_{\text{cars},i}}
\]

, where
- \( c_{\text{gathering},i} \) – coefficient of gathering per the i-th assignment;
- \( m_{\text{cars}} \) – a number of freight cars, on average that a freight train consists of;
- \( N_{\text{cars},i} \) – a total number of freight cars per the i-th assignment;

Following the same logic, the time in cyclic queue per freight car, say, \( t_c \), is analogous, to some extent, to the time in formation yard. Its computation is similar and is, as follows:

\[
t_{c,k} = \frac{c_{\text{cyclic-queue},k} \cdot m_{\text{cars}}}{N_{\text{cars},k}}
\]

, where
- \( c_{\text{cyclic-queue},k} \) – coefficient of cyclic queue per the k-th cyclic queue;
- \( m_{\text{cars}} \) – a number of freight cars, on average that a freight train consists of;
- \( N_{\text{cars},k} \) – a total number of freight cars per the k-th cyclic queue;

1 Interruptions

The interruptions in the process of freight train making (PTM) are mostly caused by the irregularity in customers’ demand. Therefore, theoretically, the PTM can be defined as a non-permanent. Thus, the coefficient of gathering preempts different values. Let us look at a single assignment, so then in the case of interruptions the coefficient of gathering,
c_{\text{gathering}} will not preempt the value from the fraction: \[
\frac{\sum_{k=1}^{m} T_{g,k}}{2}, \text{ where } T_g = \sum_{k=1}^{m} T_{g,k}.
\] The coefficient of gathering will be, say, \(c_{\text{gathering}}^i\), and will preempt value, which is less than the demonstrated fraction. The difference, i.e. \(c_{\text{gathering}}^i - c_{\text{gathering}}\), between the two values is to indicate the time for the occurred interruptions. This time, say, \(t_{\text{interruptions}}\), demonstrates the headways between two successive freight trains to be formed at formation yard per one and the same assignment. In formula, this is:

\[
c_{\text{gathering}}^i = \frac{T_g - t_{\text{interruptions}}}{2} \quad (13)
\]

On the one hand the interruptions reduce the parameter of the process of gathering, \(B_{\text{gathering}}\), and hence further reduce the gathering time per freight car, \(t_{g,i}\), on the other hand, however, one should not forget that interruptions would cause formation yard to stand idle and it may have a negative effect on its utilization in general.

1 Setouts

Setouts are the freight car groups that are left at a formation yard because the scheduled freight train, in practice, has become too long or too heavy. In other words, because of technical restrictions, grade, infrastructure limits and safety reasons every freight train is generally assigned a maximum tonnage and/or length. E.g., if the maximum tonnage is exceeded, the locomotive(s) may not have enough power to pull the freight train and it will stall, meaning stop and be unable to continue. The effect of excess tonnage may also be inability to keep up with the flow of traffic, resulting in delays to other freight trains and/or the train with excess tonnage. If the maximum length is exceeded and the train does not fit within the technical and infrastructure limits it may derail or at the least will not fit in tracks used to allow passage of other trains. Consequently, in the practical process of freight train making, there are setouts. Put another way, there are groups of freight cars that cannot be transported and must be left at formation yards. From the purely theoretical viewpoint, this property of the PTM forces the cyclic length to approach infinity and the cyclic queue turns into perpetual queue.

1 Frame of Reference

The production level of a formation yard is identified with the penalty of cyclic queues. The basic concept here is that the gathering time per freight car on average and the time in cyclic queue per freight car must be minimized subject to the optimum values of the period of gathering and cyclic length. Implementing such a concept into practice is a task of great difficulty because cyclic queues in operating processes with freight trains, as a matter of principle, are one of the components of a trade-off. By way of illustration, the operating cost for shunting at formation yards depends on the number of freight cars in a group, independently of the freight carried. The larger the freight car group, the lower is the operating cost per single freight car, because this reduces a set of operations e.g., yard-engine movements, coupling and uncoupling of freight cars, switches work etc., and hence the operating times. If, however, the larger freight car groups arrive in the beginning of the cyclic queue and are scheduled to wait the smaller freight car groups to arrive in order to form a freight
train and complete the service, regardless of operating cost, this particular process aggravates and incurs bigger waiting costs per single freight car because there are more freight cars waiting.

In the above example illustrates a matter of concern. The cyclic queues in the formation yards vary depending on the clients’ demand, over a planning horizon. This horizon might be week, two weeks, month or three months etc. So, if the concept is to minimize the gathering time and the time in cyclic queue and hence reducing cost, both operating cost and waiting cost over the entire planning horizon, one should also tend to minimize the cost per a single freight car over a single period of gathering and cyclic length. Therefore, the concern involves two interdependent viewpoints as follows:

- the first viewpoint is that the waiting time per single freight car increases, and hence the waiting cost per single freight car is on the increase as well, as the period of gathering and cyclic length increases. Therefore, the longer the time between the arrivals of freight car groups for one and the same scheduled freight train, the longer a single freight car must wait.
- the second viewpoint comes from the previous one and is that the operating times per a single freight car decrease, and hence the operating cost per single freight car is on the decrease as well, as the period of gathering and cyclic length increases. Therefore, the longer the time between the arrivals of freight car groups for one and the same scheduled freight train, the less frequently the operating cost is incurred.

Yet, speaking in easily understood terms, it is clear now that in the guise of cyclic queue at formation yards over a planning horizon, the issue is brought to balancing the trade-off between the operating costs and waiting costs per a single freight car subject to their common minimization.

1 Strategies

But still the question exists of how the process of freight train making must be organized in order for a given formation yard to operate efficiently. It is well-known that the efficient operating processes might be approached by reducing the variability in fulfillment of every single operation over the throughput line through the subsequent technological systems of formation yard. This is a fundamental and initial element of the effective strategy for the process of freight train making (PTM). One must tend to specify exact operating times, and must tend to approach stable service pattern. Even if, however, the service rate is perfectly stable, the random fluctuations in arrival rate of freight car groups cause awkward situations and PTM deteriorates. Consequently, the second fundamental element of the effective strategy for the PTM that one must consider is a tendency toward a stable arrival pattern. So combined, arrival pattern and service pattern determine the foundation of a stable process of freight trains making.

As the concept of providing a rail freight service of good quality stands, it is unfortunately not mostly of how the freight car groups would actually arrive. It is mostly of how the freight car groups would actually depart from the formation yard in order to meet the appointed time for delivery. Even after all freight car groups for a given scheduled freight train have arrived, the whole train composition is forced to wait in order to meet a specific customer requirement, which is the appointed time for delivery. From Railway Operator point of view, this phenomenon has a negative effect seen in augmenting of the envisaged time at cyclic queue length, \( t_{\text{envisaged,k}} \), and the cyclic queue becomes longer. This generates idle times seen in either freight and/or freight cars stand waiting. Furthermore, it takes yard tracks and leads to a functional
yard capacity limitation. In the most cases, the waiting costs accumulate because of the freight train compositions stand waiting for the purpose of meeting a specific customer requirement for which the railway freight operator is not compensated. In such situations, the provided rail freight service is costly to railway freight operator and the customer(s) alike. Therefore, this strategy for PTM should be focused on minimizing cyclic queue length through reductions in envisaged times.

Furthermore, as seen above, the setouts, meaning left groups of freight cars at a formation yards, force the cyclic length to approach infinity and the queue phenomenon, from cyclic queue turns into perpetual queue. The perpetual queue is the worst type of queue. Roughly speaking, the mere existence of perpetual queues at formation yard is an indication that the planning of the process of freight train making is made without regard to the maximum freight train tonnage and length and/or the customers’ time requirement. One should never forget that the freight customer certainly would not wait in a perpetual queue. The customer will try to find a way out by choosing another transportation operator and/or mode. This indicates loss of businesses, and hence accumulation of opportunity costs. So by all means, preventing setouts during the PTM, and therefore, eliminating perpetual queues, is an imperative more than merely effective strategy.

Another potential problem with excessive cyclic queue length is that of the formation yard stands idle. Reasons for such an awkward situation might be poor scheduling, and/or excessive headways between arriving freight car groups, and/or improper schedules that promote irregularity, or merely that the formation yard capacity exceeds the customers’ demand and hence the yard is not fed enough traffic to operate at its maximum capacity and efficiency. The strategy must concentrate on reductions in irregularity with the purpose of decreasing the headways between arriving freight car groups for one and the same scheduled freight train. In the foregoing example, when the formation yard is not fed enough traffic, definitely, new business must be procured. How the freight cars’ groups arrive in order to form one and the same scheduled freight train over time is undoubtedly a crucial issue for the efficiency of the process of gathering. But, the arrivals of the freight cars’ groups are not the only elements of importance. Another crucial element of an effective process of gathering is the number of freight cars that freight car groups consist of. Furthermore, this is also important for reducing the waiting cost per single freight car during the gathering process. Therefore, if in the beginning of the gathering process bigger freight car groups arrive, and in the end of the gathering process smaller freight car groups arrive, the economy and efficiency of the entire process of freight train making is reduced. On the other hand, if in the beginning of the gathering process smaller freight car groups arrive, and in the end of the gathering process bigger freight car groups arrive, the entire process of freight train making ameliorates. Consequently, the effective strategy is that the process of freight train making must be organized in bigger freight car groups arriving on small headways.

**Inference**

In this paper we have scrutinized the penalty of cyclic queues in operating processes with freight trains at formation yards by demonstrating the frame of reference and a set of effective strategies for planning of the process of freight train making (PTM). PTM without regard to the penalty of cyclic queue in operating processes with freight trains at formation yards can aggravate their effective utilization and performance.
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