Conceptual exploration of power peak shaving by smart train operation in rail freight transport

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Abstract
Powerful electric locomotives with high traction performance are foreseen to be used to boost the overall performance of freight transport. However, they would exert extra burden on the power supply system, so the power peak demand would be a bottleneck for future freight transport. To avoid large-scale modifications to the existing systems but ensure operational reliability, this study investigates the formation of power peaks and explores power peak shaving concepts to let the existing systems be more reliable and accommodate more freight traffic. Different from many previous studies which focus on energy saving, this study aims at lowering the power peak demand by “smart train operation”, i.e. altering the train speed profile without compromising running time. This study is mainly performed by simulation based on a standardized freight operation with full regenerative braking used. But this study also shows a real case study based on measurement data of power history from an onboard energy meter. The study shows the formation of power peaks in different conditions and suggests some possible measures to shave the power peak demand. The study also shows that there is a compromise between power peak shaving and energy saving, to which more attention is needed in future studies.

Keywords
Electric freight transport, power peak shaving, energy saving, smart train operation, onboard energy meter

Introduction
To increase the attractiveness and effectiveness of rail freight transport, it is important to boost the overall performance of rail freight in terms of high capacity and efficiency but low operational cost, energy usage and CO₂ emissions per ton-km. Powerful locomotives with high traction performance and upgraded infrastructures supporting large traffic volumes are being developed. However, powerful locomotives and increased traffic volumes would result in high power demand to both traction and power supply systems.

Today train operations at peak hours at some terminals are limited by the power supply of the infrastructure, so the train operators are charged according to not only the energy usage but also the power peaks. To accommodate possible power peaks and avoid challenging system reliability, sufficient redundancy of the traction and power supply systems is provided when designing new locomotives and infrastructures. For the existing systems, large modifications are therefore needed, but it is usually not economical and feasible to reduce possible power peaks. If there is no strategic preparation made in advance, the power peaks would become a bottleneck for rail freight transport in the future. This work aims at studying power peak shaving concepts to let the existing systems be more reliable and accommodate more freight traffic than today.

In the past, many studies on energy saving and improving energy efficiency have been done. The most common method is to apply energy-efficient driving strategies.¹⁻⁴ According to the strategies, speed, acceleration and coasting before stops are adjusted to let the train fulfil a target running time with the minimum energy usage. Timetable and speed profile are optimized based on given rail vehicles and particular routes. This offline pre-defined eco-driving may not work due to uncertainties regarding weather conditions, delays in the network and limitations of...
the signaling system. Some real-time eco-driving algorithms are studied to obtain the real-time energy-efficient speed profile. Longitudinal train dynamics is important for freight trains, because it studies the motion of the train as a whole and any relative motions between vehicles. When the train driving is changed, the in-train coupler force, traction force, brake force, curve resistance, propulsion resistance and gravitational component are correspondingly changed. From the hardware aspect, Automatic Train Operation (ATO) systems are used to implement eco-driving. For some newly-built infrastructure, some designs, like energy-saving slopes, can help to save energy. To reclaim kinetic energy during braking and provide extra power supply, Energy Storage Systems (ESS) have been installed either on-board the railway vehicles or wayside, e.g. electrochemical batteries, supercapacitors and flywheels. The energy stored in ESS can power the auxiliary functions as well as acceleration sometimes. However, since the installation of ESS systems needs considerable modification, it is not widely adopted for existing systems.

Inspired by the energy-efficient driving strategies, to limit power peak demand, one of the feasible solutions is to develop low-power-peak driving strategies, which do not need large modification to either the infrastructures or locomotives. Train drivers just need to “smartly” drive the freight train to efficiently use the existing systems. However, there are very few studies on low-power-peak driving strategies up to now.

This work aims at lowering the power peak demand by adjusting the train speed profile. This study is mainly performed by simulation based on a standardized freight operation. The formation of power peaks in different conditions is studied and some possible measures to shave the power peak are investigated by optimizing the train speed profile without compromising running time. The standardized freight operation is optimized according to the low-power-peak strategies. In addition, a real case of a Swedish freight train is optimized based on measurement data from an on-board energy meter. This study also looks into the trade-off between power peak shaving and energy saving. In the end, this study draws some conclusions on low-power-peak driving strategies for rail freight transport.

In the present study, it is important to identify the formation of power peaks and then investigate the possibility of power peak shaving concepts. However, since railway freight transport is widely implemented in Europe, payload, train configuration, traction effort, operational speeds, track conditions and timetabling vary in different countries and on different railway lines. It is thus impossible to conduct the study based on the numerous running cases in reality.

For a European project, it does not make sense to use any specified line or a certain train. The possible way forward is to study the power peaks based on standardized infrastructure and a synthetic freight train. For such an application, there are many train service categories defined to represent typical line speed profiles for freight train service with predefined stations and stops. The standardized profile and synthetic train can widely represent real working condition all over Europe. Since no such train or track is existing, the present study on power peak shaving concepts is conducted based on simulation.

Simulation tool
The study is performed with an in-house software STEC, developed by KTH and used in some European projects on transport energy efficiency and reduced environmental impact. The software is used to calculate the energy consumption and running times with user-defined train and track and several other parameters. The main advantages of the program are the user-friendly interface and the flexibility that allows for build-on customization. Since the software can show intermediate traction power and braking power concerning different driving styles and gradients, it is used to study the power peak shaving in this work.

To simulate different train types’ energy consumption and performance, the properties of the studied train and track are defined in the program. Train mass, adhesive mass, coefficients of running resistance, traction characteristics and limitations, braking characteristics and limitations, as well as energy information about the comfort and auxiliary systems, are necessary information. From the infrastructure aspect, line gradients and line speeds need to be entered along the line, together with information on locations of stations, as well as dwell time at each station. Information on the total track length and desired integration step length of the calculations are also necessary. The final step is to specify the braking mode, coasting and output parameters. Once a successful simulation is performed, the program shows the total travel time and details about power, energy consumption and braking. Since this work only studies freight trains, seats and comfort are not considered.
**Simulation inputs**

This study is aligned to “freight mainline” in EN 50591 “Specification and verification of energy consumption for railway rolling stock”. The freight mainline is a 300 km-long section with uphill and downhill gradients, in which three types of gradients, 0.3%, 1% and 1.5%, are included. The freight service has a maximum line speed of 100 km/h and an average stop distance (incl. signal stops) of 50 km. The line speed profile, track topography and the timetable including departure and arrival times are listed in Table 1.

The running resistance on level track is an important input for simulation, which is defined by Davis equation as

\[ R = A + B \cdot v + C \cdot v^2 \]

where \( R \) is the running resistance on level track, \( v \) the velocity, and \( A, B \) and \( C \) are coefficients (constant, linear and quadratic term, respectively) determined from theoretical considerations or measurement.

Besides the running resistance, the detailed information of the standardized train configuration and the locomotive is listed in Table 2. The train information is from EN 50591, but the locomotive is not given. To represent a typical locomotive operating on freight mainlines, the input data of the standardized locomotive are from state-of-the-art vehicles reported in the FINE1 project, which is an European project working with noise and energy of railway system. To investigate the influence of different maximum traction power, the hyperbola section with constant power is proportionally reduced from 5.5 MW, as shown in Figure 1, and used in the following study.

The driving style is not specified by EN 50591, even though it has a significant effect on energy usage. Normally, an energy-efficient driving style is used. However, this study focuses on investigating the influence of different maximum power demand, so the undefined train speed profile allows for more freedom to study the power peak shaving concept. To simplify the study, regenerative braking is fully applied and the fed energy is counted as negative without any reduction factor.

**Results and discussion**

A typical running cycle consists of three phases: acceleration, cruising and deceleration. Sometimes, coasting is applied to save energy. With help of the simulation, this section shows the relationship between running performance and power peak, and investigates the power peak shaving concepts by adjusting the train speed profile in different running conditions. This section begins with investigation of the power peaks and power peak shaving based on simplified conditions. Then the identified power peak shaving method is applied to the standardized freight

| Location | Distance (km) | Height (m) | Speed limit (m) | Arrival (hh:mm:ss) | Stop (hh:mm:ss) | Departure (hh:mm:ss) |
|----------|---------------|-----------|----------------|-------------------|----------------|---------------------|
| A        | 0             | 0         | 40             | 00:03:00          | 00:00:00       |                     |
|          | 1             | 0         | 60             |                   |                |                     |
|          | 18            | 0         | 60             |                   |                |                     |
| B        | 20            | 0         | 40             | 00:24:00          | 00:02:00       | 0:26:00             |
|          | 21            | 0         | 90             |                   |                |                     |
|          | 50            | 0         | 100            |                   |                |                     |
|          | 78.5          | 0         | 60             |                   |                |                     |
| Signal s1| 80            | 0         | 60             | 01:12:00          | 00:01:00       | 01:13:00            |
|          | 81            | 0         | 100            |                   |                |                     |
|          | 98.5          | 0         | 60             |                   |                |                     |
| C        | 100           | 0         | 100            | 01:30:15          | 00:05:00       | 01:35:15            |
|          | 102           | 0         | 100            |                   |                |                     |
|          | 132           | 90        | 90             |                   |                |                     |
|          | 142           | 190       | 75             |                   |                |                     |
|          | 152           | 340       | 100            |                   |                |                     |
|          | 160           | 340       | 75             |                   |                |                     |
|          | 170           | 190       | 90             |                   |                |                     |
|          | 180           | 90        | 100            |                   |                |                     |
|          | 198           | 0         | 100            |                   |                |                     |
| D        | 200           | 0         | 100            | 02:55:00          | 00:05:00       | 03:00:00            |
|          | 287           | 0         | 80             |                   |                |                     |
| Signal s2| 290           | 0         | 80             | 04:03:00          | 00:13:00       | 04:16:00            |
|          | 292           | 0         | 80             |                   |                |                     |
|          | 297           | 0         | 40             |                   |                |                     |
|          | 299           | 0         | 25             |                   |                |                     |
| E        | 300           | 0         | 40             | 04:29:00          | 00:03:00       |                     |
service listed in Table 1 and a Swedish freight service in use.

Identification of power peaks

High traction power is needed when a train is accelerating or overcoming an uphill gradient, so most of the traction energy consecutively becomes kinetic energy or potential energy. For the cruising and coasting phase, the traction power demand is low due to low running resistance or even becomes minus because of regenerative braking. This section focuses on the acceleration phase on level track and cruising phase with an uphill gradient.

Level-track section. The simplest working condition is a train running on a level track with only running resistance considered (neglecting the resistances caused by curvatures and tunnels). The train increases its speed from standstill or a low speed to a high speed. When the train is accelerating and approaching the top speed, high power is needed to overcome the running resistance and accelerate the train.

### Table 2. Information on train and locomotive of the freight mainline.14,15

| Wagon – Tank car (Zans) |  |
|------------------------|--|
| Number of wagons       | 18 |
| Tare mass of the train (without locomotive) | 423 ton |
| Relative load          | 50% |
| Gross mass of the train (without locomotive) | 1026 ton |
| Length of the train (without locomotive)    | 306 m |
| Factor for rotating masses | 1.04 |
| Specific running resistance, constant term | 10.3 N/ton |
| Specific running resistance, linear term    | 0.0 N/(km/h) |
| Absolute running resistance, quadratic term | 3.76 N/(km/h)^2 |
| Available braking effort, service brake (without locomotive) | 800 kN |

| Locomotive |  |
|------------|--|
| Specific running resistance, constant term (A) | 24000 N |
| Specific running resistance, linear term (B) | 256 N/(km/h) |
| Absolute running resistance, quadratic term (C) | 2.6 N/(km/h)^2 |
| Design mass in working order according to EN 15663 | 80 ton |
| Rotating masses (of tare mass) | 4.2% |
| Maximum velocity | 120 km/h |
| Maximum traction force | 300 kN |
| Maximum traction power | 5.5 MW |
| Begin of maximum power hyperbola traction | 66 km/h |
| Begin of power reduction traction | 120 km/h |
| Maximum ED-brake force | 240 kN |
| Begin of maximum power hyperbola ED-brake | 30 km/h |
| Begin of power reduction ED-Brake | 120 km/h |
| Maximum total brake force | 240 kN |

![Figure 1. Traction diagrams with different maximum constant power.](image)
The influence of different maximum traction power on the acceleration performance is shown in Figure 2(a) and (b), in which the train is running in a 10 km-long level-track section and accelerating from zero to different top speeds. In the level-track section, the power peak appears when the train is approaching the top speeds in all cases. We can see the train acceleration distances to different top speeds with the same maximum traction power of 5.5 MW and with the power peak limited to 3.0 MW. The curvatures of the speed profile in acceleration are the same and directly related to the maximum traction power, but the higher the target speed the longer is the acceleration distance. After reaching the top speeds, the traction powers to maintain the constant speeds are not the same due to different running resistances at different speeds. If the maximum traction power is reduced, the acceleration becomes slower and it takes a longer acceleration distance to reach the same target speed.

Freight trains are much heavier than passenger trains. The impact of train weight with ±10% deviations on the gross mass of the standardized train is studied. Figure 2(c) and (d) show that for the same maximum traction power and speed, the heavier the train the longer the acceleration distance is. At the cruising phase, since the running resistance is related to train mass, the heavier train needs a slightly higher power to maintain the constant speed. When the maximum traction power is lower, the impact of the gross mass on the acceleration distance is amplified, i.e. long acceleration distance is needed.

For the level-track section, the power peak can be reduced by lowering the acceleration when the train is approaching the top speed, but the acceleration phase needs a long distance and time. Because the top speed is not related to the amplitude of the power peak, slightly increasing target speed but keeping acceleration low can be used to lower the power peak. When the power peak is significantly reduced, the train may fail to reach the target speed, because running resistance increases with speed. When the traction power is reduced, the acceleration phase becomes very sensitive to the train weight.

**Uphill track section.** The track is not always levelled, so the freight train has to go uphill and downhill. For downhill gradients, the train can use its potential energy to minimize the traction power demand. However, for uphill gradients, the train has to overcome running resistances and gravity. Since freight trains are heavy, a continuous and large power supply is needed, especially for long and steep uphill sections. The simplified condition here is a train entering an uphill section with a constant gradient at a certain initial speed. Within the section, a certain traction power is kept from start to end.

The impact of the maximum traction power and initial speed on the speed is shown in Figure 3(a) and (b). The most challenging working condition is to

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Comparison of speed profiles and traction powers as a function of location: (a) Speed profiles with different top speeds and maximum traction power; (b) Speed profiles with different gross weights; (c) Traction powers with different top speeds and maximum traction power; (d) Traction powers with different gross weights.
negotiate a 1.5% uphill gradient with an initial speed of 100 km/h. It compares the speed profiles with different maximum traction powers at a 1.5% uphill section. When the traction power is not sufficient, the train gradually slows down to a speed where the tractive force becomes large enough to overcome the running resistance and gravity. For all the cases, the train speeds are lowered to a certain value which is decided by the maximum power supplied. The higher the power supply the higher the convergent speed is. With the same initial speed, a low traction power results in a significant and fast speed drop. To maintain a constant speed, the train speed is lowered before entering the steep uphill section. If a constant speed is needed, the line speed is carefully designed. For the cases with the same maximum traction power, as shown in Figure 3(b), although a high initial speed experiences a larger speed drop, the average speed within this uphill section is still faster than directly lowering the line speed.

Gross weight is also important in the uphill section. Figure 3(c) shows the influence of ±10% deviations of the train gross weight for different maximum traction power. With the same traction power, the heavy train decreases its speed more and faster than the light train. With reduced traction power, the speed drop is not as much as the case with high traction power.

However, when a train accelerating on an uphill gradient is not discussed, because the train has to overcome gravity and speed up the train. There is little room to play with to limit the power demand.

In the uphill track section, the maximum traction power, running resistance, gradient and train weight determine the speed the freight train can maintain. When the gradient is small and the traction power is sufficient, the train can keep running at high speed. If the train is heavy or the traction power is insufficient, the train speed constantly drops down until reaching a balanced speed.

Power peak shaving. The freight train generates high power peaks during acceleration or overcoming uphill gradients. For the acceleration phase on the level track, it is possible to lower the power peak by limiting the acceleration. But low acceleration results in a long acceleration distance and a long time to reach the top speed. A heavy train can further prolong the accelerating distance and running time. For a heavy train running in a long and steep uphill track section, for power peak shaving it is a better measure to slow down the train by gravity than to maintain a constant low speed. However, too low power supply makes the train fail to overcome the uphill gradient. Since the power peak shaving always makes the train

**Figure 3.** Comparison of speed profiles: (a) the same initial speed but different maximum power; (b) different initial speed but the same maximum power 5.5 MW; (c) the same initial speed but different maximum power and gross weights.
driving gentle and smooth, the train longitudinal dynamics is not needed to be discussed.

**Power peak shaving and running time**

The maximum traction power can be minimized by a moderate acceleration in the level-track section or a speed slow-down in the uphill section. However, both measures lead to a longer running time in the corresponding section and result in train delay if there is no compensation made in other sections. To make “smart train operation” possible, this section studies the relationship between power peak shaving and time loss.

**Time loss at level-track section.** In the level-track section, a limited power supply results in moderate acceleration which causes long accelerating distance and running time. Since the train reaches the top speed at different running times and distances, there is no direct way to compare the time losses of different traction powers. For comparison, the train here accelerates from zero speed to top speed within a 10 km-long section and the running time is taken as an indicator. Since the running distances for the different cases are the same, so the running time can reflect the impact of the accelerations.

Figure 4(a) shows the running time of the cases with different top speeds and maximum powers. For all three target speeds, the power peak reduction increases the running time. For the same traction power, lowering the target speed prolongs the running time. The lower the maximum power the longer is the running time. However, when the top speed is slightly increased, it is possible to shave the power peak and keep the running time unchanged within the section. For example, the train with a maximum power of 3.5 MW and a top speed of 105 km/h has almost the same running time as the train with a maximum power of 5.5 MW and a top speed of 100 km/h.

For power peak shaving during acceleration on level track, the simple solution is to reduce acceleration when approaching the target speed. If the target speed is kept unchanged, the time loss caused by low acceleration must be compensated at other parts where the power demand is not high, e.g. by reducing coasting distance or applying hard braking. However, if the target speed can be slightly increased, it is possible to shave the power peak without any time loss.

**Time loss at uphill section.** In the uphill track section, high traction power is needed for overcoming gravity. If the maximum traction power is lowered, the train speed would correspondingly decrease to reach a balancing speed, which is dependent on initial speed, gradient, train weight and traction power. Now the train with limited power supply can lower its speed to the balanced speed before entering this section, so the train can maintain a constant speed within the section. Nowadays it is used to let the train follow a low line speed limit, but the low line speed leads to a long running time without the power peak being much shaved. On the other hand, it is not needed for the train to maintain a constant speed in the uphill section, so the kinetic energy of the train can be used to shave power peak and to reduce the time loss. The time losses at different power peak shavings for different initial speeds are studied here.

To make the time losses for different cases comparable, the running time within a 10 km-long section with a constant uphill gradient is taken as an indicator. The running distances are thus kept the same for different cases, so the running times can reflect the influences of different measures. Figure 4(b) examines the running time as a function of maximum traction power at different initial speeds. For the same initial speed, shaving the power peak prolongs the running time. For the same permissible traction power, a low initial speed results in a long running time. However, if it is permissible to adjust the initial speed, it is possible to keep the running time unchanged when reducing the power peak. For example, if the initial speed is increased from 75 km/h to 100 km/h, the maximum power of the train can be reduced from 4.5 MW to 4.0 MW without any time loss. By comparing Figure 4(a) and (b), we can see that shaving a power peak at the uphill section leads to more time loss than in the level-track section.

![Figure 4. Running time as a function of maximum power: (a) acceleration phase plus cruising on level track; (b) uphill section with constant gradient.](image-url)
For power peak shaving at the uphill section, the solution is to allow the speed to slow down within this section. But if the initial speed is kept unchanged, the time loss caused by power peak shaving must be compensated at other sections where the power demand is not so high. If the initial speed can be slightly increased, it is possible to shave the power peak without any time loss within the section. However, it is more difficult to shave the power peak in the uphill section than in the level-track section.

**Time saving at other sections.** Power peak shaving at the acceleration phase or uphill sections prolongs the running time. From the previous results, we see that if the top speed at the level-track and the initial speed at the uphill section are slightly raised, the time loss can be compensated within the section, so there is no amendment to the train speed profile in other sections needed. However, if it is not allowed to adjust the speed, to keep the timetable unchanged, it is needed to save the running time at other sections where the power demand is not high.

A solution is to shorten or remove the coasting distance so that the average running speed during the cruising and coasting phase gets increased. Figure 5(a) and (b) compares the running time for different top speeds and coasting distances in a 20 km-long level-track section. For the same top speed, a shorter coasting distance reduces the running time, but the time saving is not significant. If the top speed can be increased, more considerable time saving can be expected.

Both reducing coasting distance and increasing top running speed can help saving running time. For the level-track section, it is sufficient to apply only one method to compensate for the time loss. For the uphill section, the time loss is significant, so both measures need to be implemented. When the running distance is long, increasing top speed can save more time. For the downhill section, since the power demand is low, reducing coasting distance or increasing top running speed also works.

Applying hard braking later than usual can also save running time, but it can only save a little time. Figure 5(c) shows that although the braking force is doubled, only a bit of time can be saved. In addition, too hard braking causes much wear on braking wheels and pads, and wastes much energy. Therefore, it is not suggested to apply hard and late braking in the braking phase for time-saving purpose.

We can see that within the 20 km-long section, compared with the normal running time with 6 km-long coasting, removing coasting can help to save 6% of travelling time, while increasing the top speed and applying hard braking in addition can achieve about 10% and 11.5% of time-saving, respectively. Based on the discussion above, if the top running speed is not adjustable, a small amount of time can be saved by reducing coasting. If a large amount of time needs to be compensated, a slight speed increase in the cruising phase should be considered. Hard and late braking is not suggested, which cannot save much time but cause some problems related to the longitudinal dynamics.

**Optimisation of standardized operation**

Power peak shaving by smart train operation is applied to the synthetic freight train running on the 300 km-long track defined in EN 50591, cf. Table 1. The freight train also runs according to the timetable listed in Table 1, but with different driving strategies applied to lower the power peaks. Figure 6 compares two train speed profiles and the corresponding power demands with and without power peak shaving applied. The entire running is divided into six sections (S1–S6), as shown in Figure 6(a) and the power peak is shaved as much as possible in each section. For the running case without power peak shaving, to save energy, the maximum running speed is kept low to minimize the running resistance. To make the different cases comparable, coasting and regenerative braking are assumed to be fully used without any other losses in both cases.
For the five level-track sections (S1–S3 and S5–S6), as shown in Figure 6(a), the power peaks occur in the acceleration phase. A gentle acceleration can significantly reduce the power peaks. The timetable is not set tight and some time margin is included in the timetable, so the train does not need to closely follow the line speed limit. For the hilly track section (S4), the power peaks occur at acceleration and gradient negotiation. For the reference case with a high power peak, the running speed is minimized to the lowest line speed limit within this section to avoid unnecessary retardation and at the downhill section, the train speed is increased to 81 km/h with help of gravity to fulfil the timetable. To shave power peak, train slow-down by gravity is used, in which the kinetic energy stored by the train is gradually released and turned to potential energy, so the traction power is not at high demand and the average running speed is not much reduced. To compensate for the time loss in the acceleration phase and low operational speed at uphill, the train’s running speed is increased in the level-track and downhill sections.

Regarding energy usage, it is not easy to compare the energy usages of different cases, because the combinations of coasting, friction braking and regenerative braking are different. Here a fully-coasting strategy is assumed and applied. The braking is only applied at the end to stop the freight train, full regenerative braking with 100% efficiency is applied at low speeds or when the downhill gradient is large. The net energy usages with and without power peak shaving applied are listed in Table 3, c.f. Figure 6. The most energy-efficient driving style is to reduce the time in the acceleration phase and to keep the speed at the cruising phase low and smooth. The long acceleration phase due to reduced power peak increases the total energy usage, because it is necessary to increase the top speed at the cruising phase (which leads to high running resistance). We can deduce that the efficiency of regenerative braking is not 100% in reality, so higher energy loss would be expected, which means that there is a trade-off between power peak shaving and eco-driving.

Swedish case study

To reflect train operations, a Swedish case study is performed to shave the power peaks of a freight operation where the power supply at the infrastructure is weak. It is based on measurement data in which power history and other key information of a hauling service is recorded by an energy meter onboard. For this Swedish case study, an optimized train speed profile is suggested through simulation.

The freight train service studied here operates in Northern Sweden with a total running distance of 241 km (between Hälnäs and Piteå). The power supply is 15 kV, 162/3 Hz and booster transformers are used, which have high impedance and low power transfer capacity. The train runs according to the scheduled timetable. Figure 7(a) and (b) shows the track height above the sea level and the line speed, respectively. The locomotives are Siemens Class 243 locomotives and equipped with an onboard energy meter that records energy usage and reclaimed energy with a certain sampling rate. The total train weight is 2070 t.

With the onboard energy meter, the energy usage in every 300 sec is recorded, as measurement shown in Figure 7(d). Due to the low sampling rate, the average power and speed in every 300 sec are not accurate enough for a detailed study. A simulation is, therefore, performed to numerically interpolate the speed and approximate more detailed results of the freight operation, see Figure 7(c). The interpolation is performed to keep the energy usages from both simulation and measurement close to each other in the 300 sec. A comparison between the measurement and energy usage in every 300 sec is shown in Figure 7(d).

The optimized train speed profile and corresponding traction power are shown in Figure 8. The entire service is 241 km long and consists of eight subsections. Power-peak-shaving measures are applied to shave the power peaks concerning the scheduled
timetable, speed limit and track gradient. For example, in S4 in Figure 8, the traction power and speed are much lowered in the two long uphill sections, which causes significant time loss. In order to compensate the corresponding time loss, the running speed is increased in the downhill sections, even running a little bit overspeed. The maximum amplitude of the power peaks can be lowered from 5.2 MW to 3 MW. The power peak during acceleration is shaved by limiting the traction power and prolonging the acceleration. However, for the peaks at the long and steep uphill gradients, it is unfavourable to lower the train speed ahead of the uphill gradient and then run at a constant speed to lower the power peak. Instead, it is better to gradually lower train speed by gravity, during which the kinetic energy stored by the train is turned into potential energy to minimize power demand. If the timetable is tight or the power shaving demand is high, the significant time loss would make

| Track section | Running time (s) | Max. power (MW) | Max. speed (MW) | Net energy (kWh) |
|---------------|-----------------|----------------|----------------|-----------------|
| Track section 1 | 1440            | 5.5            | 55             | 280             |
| Track section 2 | 2760            | 5.5            | 85             | 1085            |
| Track section 3 | 1035            | 5.5            | 89             | 345             |
| Track section 4\(^b\) | 4785          | 5.5            | 80             | 1736            |
| Track section 5 | 3780            | 5.5            | 91             | 152             |
| Track section 6 | 780             | 5.5            | 57             | 136             |

\(^a\)Only very slightly higher than the 5.5 MW cases.

\(^b\)Full regenerative braking applied.
the timetable much changed. Therefore, a slight speed increase at the places where the power demand is not high can help to shave power peak and keep the timetable unchanged. By applying the “smart” train operation, the maximum power demand can be reduced by almost 50% with the timetable unchanged.

The real train service and simulated train service use different braking strategies, so their energy usages are not comparable and not discussed here. In addition, this study is performed based on one of many possible approximations which can be estimated from the inaccurate measurement data with a sampling rate of 300 sec, so the transport service of the train may be different from the simulated train service studied here. More comprehensive studies will be performed when more accurate measurement data are available in the future.

Conclusions and future work

It can be foreseen that future rail freight transport has increased traffic volume, operational speed and train payload, which would exert extra burden on the power supply system and traction system. To relieve this concern, this study proposes to use “smart train operation” to shave power peaks by adjusting the train speed profile with the timetable unchanged. Although the main part of the study is based on simulation, to reflect the train operation in reality, the speed profile of a Swedish freight transport service is optimised with help of the energy data recorded by onboard energy meter.

The study shows that during acceleration or overcoming an uphill gradient, the freight train generates high power peaks, which challenge the capacity of power supply system. For the acceleration phase on level track, the power peaks do not last for a long time and can be reduced by limiting the acceleration. The corresponding time loss is small and can be compensated by reducing coasting distance or slightly increasing the running speed. However, for the long and steep uphill section, the high power is quite demanding and lasts for a long time. Lowering the train speed can effectively shave the maximum power demand, but the time loss is considerable and cannot be easily compensated. Therefore, to keep the timetable unchanged, the train has to increase the running speed at sections where the power demand is not high and reduce coasting distance. It is unfavourable to lower the train speed to a constant speed ahead of the uphill gradient to lower the power peak. Instead, it is better to gradually lower train speed by gravity, during which the kinetic energy stored by the train is turned to potential energy to minimize power demand. For a given line speed profile there is a trade-off between power peak shaving and energy saving, because the most energy-saving driving and the lowest power peak driving do not occur at the same time. However, the energy loss by power peak shaving can be minimized if a proper driving style is developed.

This work only conceptually explores power peak shaving by smart train operation. More comprehensive studies will be performed when more accurate measurement data are available in the future. Generic algorithms which can help to identify a power-shaving driving style for any specific freight transport service will be studied.

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