Regenerative Electric Braking on the Locomotives of the C., M. & St. P. Ry.

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From the standpoint of the practical operating man, the author explains the principles of regenerative electric braking on the Chicago, Milwaukee & St. Paul locomotives, and further explains the action of trains under various conditions using this feature. Specific comparisons of the operation of main-line trains by steam and electricity detail the points of advantage secured by the electrification of this mountain railway.—Editor.

The inherent working principle of direct-current regenerative electric braking is the maintenance of the voltage or electrical pressure of the regenerating machine higher than that of the distributing system to which it is connected, by an amount sufficient only to overcome the resistance of the circuit involved and to allow a flow of current which will be within the machine's safe capacity, or regulated within the limits of the duty required. Controlling the value of regenerated current in electric hoist or other stationary service is simplified where the voltage of the distributing system, the duty demanded, and the distance to the apparatus which may absorb the regenerated energy and consequently the circuit resistance are fairly constant. In railway service all these conditions vary in an irregular manner due to the movement of trains, variations of track gradient, and other conditions peculiar to train operation.

One of the important advantages of steam railway electrification, where heavy grades exist, accrues from regenerative braking in the fact that the locomotive not only holds the descending train at a uniform safe speed, but also changes the mechanical energy of gravity into electrical energy for pulling some other train; whereas in ordinary electric railway and regular steam practice this energy is dissipated in heating and wearing of wheels and brake shoes.

A simplified wiring diagram of the direct-current regenerative braking scheme used on the C., M. & St. P. electric locomotives is shown in Fig. 1. In braking operation, the exciter armatures are connected to the terminals of the traction motor fields, the line connections to the trolley being the same as for regular motor operation. If the exciter voltage is higher than the voltage drop across the motor fields, current will flow from the former through the latter, which is in addition to the current already flowing from the trolley wire during motoring. Since the traction motor armatures continue to revolve at practically the same speed as before, this exciter current is added to the motoring field-current, and the generated pressure of the traction motors will rise somewhat in proportion to the

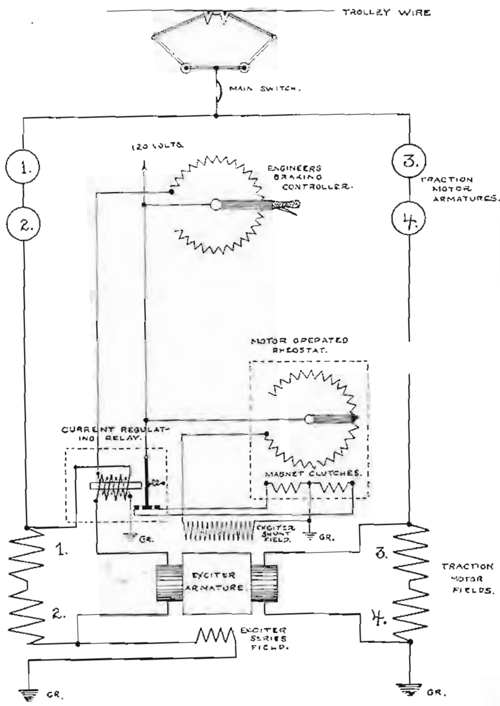

Fig. 1. Simplified Wiring Diagram of Regenerative Braking

additional excitation supplied. If enough excitation is added this pressure may be greater than that on the wire, and the current will tend to reverse its normal direction from the wire through the motors to the track, putting out mechanical energy, and flow from rail to wire requiring mechanical energy input to the motors running as generators.

On the other hand, if at the instant the regenerative braking connections are made, the exciter armature voltage is less than the voltage drop across the traction motor fields, a portion of the field current will flow through the exciter armature, which thus acts as a shunt. The traction motors, with less than their initial motoring excitation for a given speed, will necessarily have to revolve faster in order to regain their pressure balance with that on the wire. This action can only take place if the braking controller is applied when ascending a grade. If descending a grade, the train momentum may be sufficient to hold conditions fairly constant for a given excitation of the traction motor fields; otherwise their speed will decrease to the point where the generated pressure of the locomotive is less than that of the wire plus the resistance to the flow of current to a substation or another locomotive pulling a train,

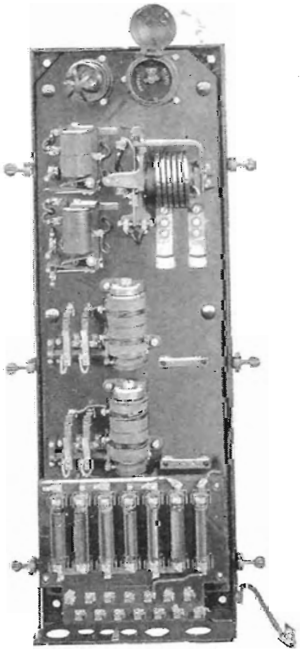

Fig. 2. Braking Current Regulating Relay

and the current will again flow in its normal motoring direction.

When the current has been reversed for braking, the exciter armature will carry the sum of the traction motor field and armature currents. Since the tractive effort is proportional to their sum, it may be seen that the power of the locomotive in holding the descending train may be regulated by increasing or decreasing the exciter voltage. The engineer has control over the excitation of this machine by means of the controller which

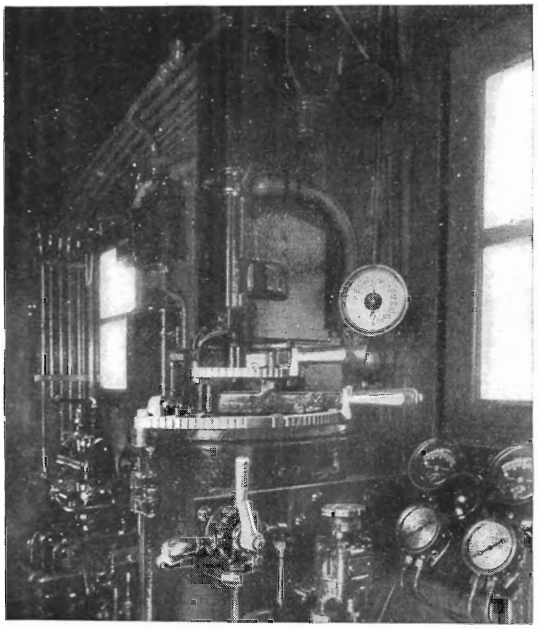

Fig. 3. Braking Controller

changes the setting of the braking current limit relay.

This relay (Fig. 2) operates at a definite spring tension setting which is opposed in its action on the relay armature by flux set up in the relay magnetic circuit by a series coil carrying the sum of the field and armature currents of one pair of traction motors and by a shunt coil supplied with variable voltage from the braking controller (Fig. 3). The relay armature carries two contacts similar in effect to a single-pole, double-throw switch each side of which is wired to a clutch magnet on the motor-operated rheostat (Fig. 4). This regulates the current in the exciter shunt field and consequently the exciter armature voltage. The small motor of this rheostat runs continuously while the regenerative braking controller is "on," and by means of magnetic clutches, may cause the motor operating through gearing to turn the rheostat arm in either direction of rotation, thus increasing or decreasing the resistance (and current) in the exciter field, depending on which clutch is energized by the separate contacts on the braking current limit relay.

The spring on this relay normally pulls the armature over to make contact for the magnet clutch that will cut resistance out of the exciter field circuit. This condition, when braking is started, will then cause an increase in the exciter armature current flowing in the series coil of the regulating relay. When this current reaches a value sufficient to create enough flux to pull the armature away from the contact made by the spring, the motor-operated rheostat will come to rest. If the current increases further, the relay armature will be pulled over to the other contact, which will cause its magnet-clutch to cut resistance in the exciter field circuit and lower the current, so that a constant regulating action is obtained.

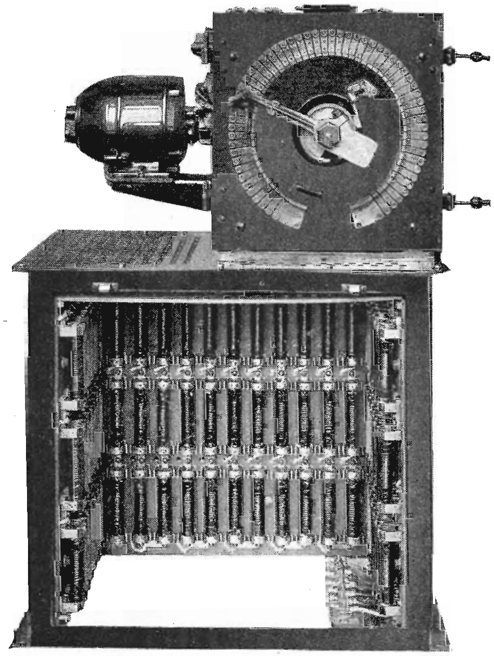

Fig. 4. Motor-operated Rheostat

The shunt coil on the regulating relay is supplied by current, varying in value, from the braking controller, which is in effect a hand-operated rheostat. This shunt coil adds its magnetic flux to that of the series coil and therefore assists in overcoming the opposing spring tension. On the first position of the controller the current in the shunt coil is at a maximum, and therefore the relay will act at low values of current in the series coil. As the controller is advanced by the engineer this shunt coil current is lessened and the relay setting is increased until a position is reached where the shunt coil is de-energized and regulation is dependent wholly on the series coil. Further movement of the control reverses the current through the shunt coil causing its flux to oppose that of the series coil and increase the current at which the relay will balance. The shunt coil is gradually increased in strength in this direction until the same maximum is obtained as was used on the first notch, and this gives the maximum allowable regenerative braking effort of the locomotive. For ordinary changes of grade, speed and distance from substations, this action is fast enough to maintain uniform braking tractive effort. Moreover the exciter, being driven by a series motor, varies its speed and voltage with the trolley pressure, thereby requiring a minimum amount of work by the exciter field rheostat.

However, when a locomotive is generating power and the trolley voltage is suddenly decreased by another locomotive in the near vicinity starting a train, or ceasing regeneration, or is increased by another locomotive starting regeneration, it is evident that the pressure balance is likely to be upset on the locomotive in question, and more current may flow through the motors than is within their capacity if such an unbalancing is not quickly compensated for by the control apparatus. This condition is taken care of by the series field on the exciter which carries the line current and opposes in its effect the separate excitation of the shunt field. Therefore, any increase in this current will decrease the exciter voltage and traction motor field current, thus imposing a limit within safety. Or if the trolley voltage increases the generated current will decrease and the exciter voltage will rise, thus tending to hold the tractive effort constant. This protection from sudden voltage changes is further helped by the damping effort of the reactance of this circuit, and by the fact that the total locomotive voltage is made up of the two components, viz., the traction motor armature plus that of the exciter. This inherent regulation at low current values is also essential for protection from swings in line current when regenerating on light grades with long freight trains, in the prevention of cumulative train-slack surges. It also renders it possible to operate under conditions of grade such as tipping over the summit of a hill or level breaks in the regularity of the descending gradient, so that the locomotive can automatically change from motoring to braking with no change in its motor connections and no perceptible action on the train slack.

The motors are protected under exceptional conditions when regenerating, such as grounding of the trolley wire or opening of the substation circuit breakers, by over-load and over-voltage relays, respectively. A ground on the wire would cause a very large current to flow through the motors on a regenerating locomotive near at hand, and the overload relay should therefore act quickly to disconnect them from the line and kill their field excitation. If the circuit breakers at the substation are opened for any reason, or the wire or pantograph should break so that no path is left for the generated current, the voltage of the traction motors would rise excessively. This excess pressure is relieved by the over-voltage relay, which disconnects the motors from the line and kills their excitation. If the exciter motor should fail, the voltage of the control generator which is directly connected thereto will drop, thereby allowing the contactors to open and deaden all circuits. Three instances under extraordinary conditions may be cited to illustrate the working of the regulation equipment in actual operation.

When a passenger train was descending a grade and a freight train was ascending, the power was taken off the wire at the substations because of some wire trouble. The passenger locomotive on the down grade, generating power, pulled the freight up to the station where a meeting had been arranged, with nothing being noticed out of the ordinary on either locomotive until the latter arrived first at the switch and shut off power. There being then nothing to absorb the regenerated energy of the passenger train, the over-voltage relay acted, which was the first indication to show the engineer that anything out of the ordinary was taking place.

In another case a locomotive at a siding had a partly broken pantograph. This caused an arc from the roof of the locomotive to parts of the collector, which was still in contact with the wire. The engineer, for reasons of safety, had the power taken off at the substations so that he could untangle the damaged pantograph and disconnect it from the locomotive. The substation men acted quickly, but still the arc persisted for quite awhile as the engineer waited. Later, it developed that another locomotive descending the grade when the power was cut off had continued to generate current sending it into this arc at the damaged pantograph several miles away, without any indications of difficulty, this condition persisting until the engineer headed into a switch and shut off his controllers.

As an experiment, the braking controller of a locomotive descending a grade was set on the first step and the pantograph lowered from the wire, thus breaking connection with all outside sources of power. The locomotive then furnished its own energy for operating the motor-generators and air compressors, and the train was brought down the grade with the air brakes. In this case the exciter (on the motor-generator) and the locomotive were running when the pantographs were lowered from the wire. The exciters then furnished current for the traction motor fields, and the traction motors furnished current to drive the exciter. The speed of the motor-generator varied as the train speed, and the engineer controlled both by means of the train brakes.

The regenerative braking apparatus has no part in the regular motoring operation of the locomotive. Any failure in this apparatus itself leaves the locomotive ready to operate at full speed to its destination, the train being controlled with the air brakes on descending grades. On passenger locomotives the exciter is used for charging the train lighting batteries when it is not being used for braking. This requires only an additional switch for changing its connections. The exciter, which is driven by the motor-generator that drives the blower for ventilating the traction motors, requires little extra space.

In the parallel running position of the motoring controller, eight 1500-volt motors are connected to the line in four groups of two in series, and a practicable range of braking speed from 16 to 25 m.p.h. is available. In the series running position of the controller the eight motors are connected in two groups of four motors each and braking may be done at half speed.

Train handling during regenerative braking requires no more skill and practice by the engineer than that required in ordinary air-brake practice. Since all of the electric braking effort is exerted at the locomotive driving wheels the conditions obtain as if the locomotive air-brakes only were applied, leaving the train brakes running free, and quick slow-downs are not possible.

Therefore, long trains with several inches of free slack at each car coupler may suffer severe shocks on the head cars if the brakes are suddenly applied on the locomotive. For example, a freight train of 100 cars may have 70 ft. of "slack," and if this were all

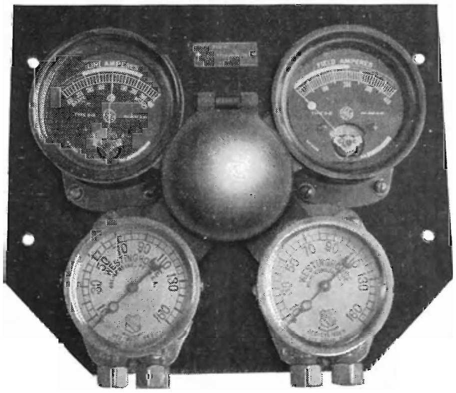

Fig. 5. Ammeters Showing Degree of Regenerative Braking

"bunched" with the train at standstill, in starting up the locomotive would move 70 ft. before the last car in the train would be affected at all. If the train is running with all the slack stretched out and braking is suddenly applied on the locomotive, the cars tend to eliminate the free play in the coupling devices by bunching up hard against the locomotive, sometimes resulting in damage to equipment or telescoping weak cars which happen to be in the forward part of the train. However, if the braking is gradually applied on the locomotive this cumulative surge of train slack is avoidable and no severe shock will take place. Or if in descending a grade air-brakes are applied to the whole train, locomotive and cars, and then released gradually on the cars only, the slack will run in easily, the shock being "damped" by the slow release of the brakes. The locomotive will then hold the train after it has bunched and all brakes on the cars have been released. To accomplish this latter result "retainers" are utilized on the cars. These are small cocks which when "turned up" will hold about 15 lbs. per sq. in. pressure in the car air-brake cylinders, which leaks off very gradually, following a full application and "release" of the train-brakes from the locomotive.

Under ordinary airbrake operating conditions it is necessary to have retainers turned up on every car of a loaded train descending a long heavy grade in order to provide means of charging the brake pipe, without entirely releasing the shoes from the wheels and thus allowing the speed to get beyond control before the brakes can be applied again.

With this system of electric braking it is not possible to slow down to standstill, since at a certain low speed limit for a given value of field current, the voltage generated by the traction motors will be less than that on the trolley wire and motoring will take place. Moreover, since it is necessary to make motoring connections to the line before regenerating can be started, a certain amount of train slack will be pulled out first, to be compressed again when electric braking takes place. However, practical operation has shown that this action can be readily minimized and entirely neglected as far as effect on equipment is concerned.

With one locomotive in a train tipping over the summit of grade it is only necessary to keep the motoring controller "on" and advance the braking controller gradually as the descent is started. Each car will bring its own slack in gradually and no surges will be experienced. For each train of a certain weight on a given grade, there exist definite speed limits within which the locomotive can be controlled perfectly, as evidenced by the ammeters before the engineer (Fig. 5). All that is necessary to be done is to manipulate the braking controller according to changes in gradient or track conditions so that this limit is not exceeded, and so that the locomotive does not slow down to the point where motoring action will take place. If the speed increases for any reason above that value which will require more tractive effort than the safe current in the motors determines, the train air-brakes may be applied sufficiently for control, and regenerative braking continued at the same time with no interruption.

The same method also applies to passenger and freight service when braking on gradients of about 1 per cent or less. When regenerative braking at half speed on light grades, it is sometimes necessary to first bunch and hold the train slack with the driver brake until regeneration can be started.

However, a slightly different procedure in starting is required when descending heavy grades with long freight trains and a stop has been made. In this case, with all the train on the grade, the engineer releases brakes and allows the train to drift up to a speed of about 20 m.p.h., and then applies the train brakes with the retainers turned up on about one-half of the cars on the head end of the train. Only a light application is made, sufficient to hold the speed momentarily while braking is started. The locomotive driver brakes are kept released and the motoring controller is advanced to the running position and the braking controller brought up slowly until the ammeters indicate reversal of current, when the train brakes are released. The engineer then holds the speed about constant by bringing on the braking controller as the retainers "leak off." Since the freight locomotive tractive effort rapidly diminishes at speeds much above the normal running value, very little slack is stretched in the train by this procedure and no shocks are perceptible.

Under most conditions of freight train movement a helper locomotive is used, both in ascending and descending heavy grades, in order to take full advantage of regenerative braking. Following the air brake test at the summit of the grade, the head man starts the train out just as if on the level. When the main controller has been set on parallel for full speed, or series for half speed, the braking controller is advanced notch by notch. As the speed comes up the line ammeter needle goes back to zero in the middle of the scale and gradually advances over the braking scale as the regenerated (reversed) current increases. The leading locomotive bunches the train slack back against the helper in the middle of the train, who then sets his controllers and holds back the train just enough to allow complete control by the man on the head end. In making a stop the head man eases off the braking controller and the line ammeter gradually returns from braking current toward zero. When the current has been decreased sufficiently, he sets his automatic air brakes and throws off both controllers. As soon as the brakes slow down the train the helper's braking current falls off, and the controllers are shut off before the line ammeter needle passes the zero point and motoring begins.

Likewise with a helper, if a stop is made on a gradient of more than 1 per cent, regenerative braking is started under a slightly different procedure than when tipping over the summit. In this case the head man releases brakes and allows the train to drift up to about 20 miles per hour. He then applies the train brakes sufficiently to hold this speed for a moment while operating the controllers. As soon as they are set and the line ammeter begins to show braking current the brakes are released. The helper also starts to operate his controllers for regenerative braking as soon as the train brakes are first applied.

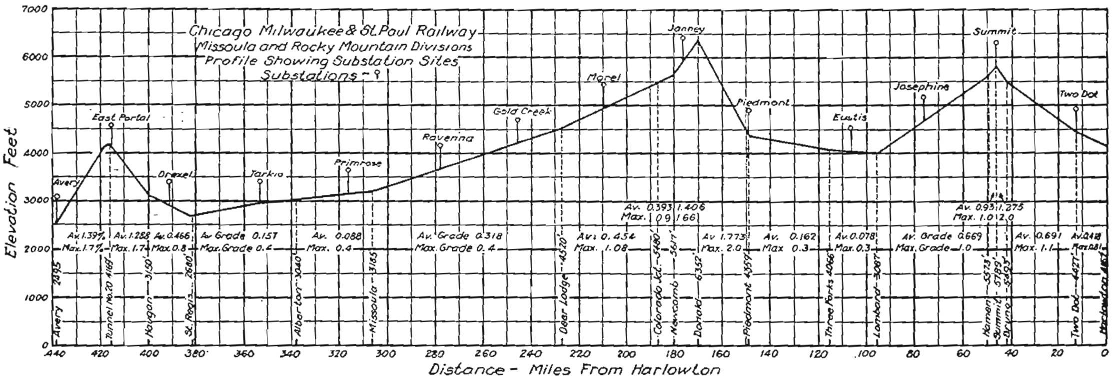

Fig. 6. Profile of Electrified Section C., M. & St. P. Rwy.

A profile of the present electrified section in Fig. 6 shows the three mountain ranges crossed by the railway. The Belt mountains are approached from Harlowton, going westward, by 35.7 miles of an easy up-grade, ranging to 0.6 per cent, as far as Lennep. Here the grade increases to about 1 per cent for 5.0 miles, until about two miles from the summit where a sharp grade of a little over 2 per cent is encountered going into Loweth. From this point to Lombard, 49.4 miles, is a descending grade of about 1 per cent. From Lombard to Piedmont, 53.6 miles, is practically all water grade and no regeneration is practicable. With the exception of the short stretch of 2 per cent grade mentioned above between Bruno and Loweth, one electric locomotive will pull 2500 tons trailing load from Harlowton to Piedmont. And since the train friction is an aid to the locomotive, helping to retard the train during regenerative braking, trains of almost any size can be taken care of between these stations. It is customary for west bound full tonnage freight trains to "double the hill," from Bruno to Loweth on the 2 per cent grade. This means leaving half the train on the siding and pulling the rest up to the summit and then going down to get the other half. This is such a short grade that little time is lost in this way. East-bound freights on this grade having more tonnage than one locomotive will hold with electric braking, make free use of the air brakes.

From Piedmont to Donald is 20.9 miles, with a 2 per cent grade over the Rocky Mountains and Continental Divide, and two locomotives are customarily used on west-bound full tonnage trains averaging about 2500 tons each. East-bound trains of 2300 tons have been successfully brought down this grade with one locomotive regenerative braking, without using air-brakes and with about the same current in the motors that would be required for 1250 tons ascending the grade. However, some of this train was empty cars which have a high friction factor. With full loaded cars about 1750 tons trailing regenerative braking on this grade at 17–20 m.p.h. will require about the same current in the motors that 1250 tons loaded cars will in ascending at 15 m.p.h.

From Donald to Butte, 18.1 miles, is nearly all 1.6 per cent grade, and 1650 tons trailing east bound trains may be handled by one locomotive and 2500 west bound regenerative braking, although it is customary to keep the helper in the train which was used up the eastern side of the grade between Piedmont and Donald. Ordinarily east-bound trains are made up to 3000 tons at Butte for two locomotives.

Butte to St. Regis, 195.7 miles, is all descending grade with several short stretches of 1 per cent just west of Colorado Junction and 0.4 per cent to 0.6 per cent for long stretches. Almost any train which will hold together is hauled by one locomotive. Train length is usually limited by strength of draft rigging and safe operation of the air brakes, which get rather "ticklish" tending to "dynamite," or going into emergency application, and sticking on and generally refusing to operate according to rules and theory when more than 100 cars are hauled in a train.

From St. Regis to East Portal, 33.0 miles, the average west bound gradient is about 1.7 per cent ascending, over the Bitter Root Mountains, and from East Portal to Avery, 24.3 miles, about 1.7 per cent descending. Train loading generally corresponding to that on the west slope of the Rocky Mountains between Donald and Butte is followed here.

With steam operation the freight men met their hardest work on the severe grades, both when ascending and descending, but the passenger trains were always supplied with helpers under such conditions and were not hard to handle. Now the electrics go from one end of the section to the other and without having to stop for brake troubles and for coal and water, the schedules have been improved, and the maximum running speeds reduced.

The run up the slight grade from St. Regis to Butte under a fast schedule under steam passenger operation was a losing game when late, and speeds as high as 65 m.p.h. often had to be used. Now the electrics make the time easily and do not exceed 45 m.p.h.

The writer has ridden on a large oil burning steam engine pulling ten steel passenger cars from St. Regis to Deer Lodge 154.6 miles, when both injectors were used wide open to supply the boiler with water, the oil firing valve feeding all the fuel possible and the throttle wide open—and we made up just 10 minutes of lost time. No coal-burning engine could have even touched this performance, but the electrics exceed it so much every day that among the men fast runs or record hauls have ceased to be a subject of common conversation.

All the practical doubters who would not at first believe that an electric locomotive could control more tonnage at a safe speed on a descending grade than it could haul ascending, have vanished. There are no cases of overheated wheels. Passenger trains which required almost a complete set of new brake shoes after crossing the mountains and arriving at Deer Lodge, now go through with almost no shoe changing at all throughout the whole mountain section, and these savings are the practical results of regenerative electric braking.