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A Practical Method for Assessing the Energy Consumption and CO_2 Emissions of Mass Haulers

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Abstract: Mass hauling operations play central roles in construction projects. They typically use many haulers that consume large amounts of energy and emit significant quantities of CO_2. However, practical methods for estimating the energy consumption and CO_2 emissions of such operations during the project planning stage are scarce, while most of the previous methods focus on construction stage or after the construction stages which limited the practical adoption of reduction strategy in the early planning phase. This paper presents a detailed model for estimating the energy consumption and CO_2 emissions of mass haulers that integrates the mass hauling plan with a set of predictive equations. The mass hauling plan is generated using a planning program such as DynaRoad in conjunction with data on the productivity of selected haulers and the amount of material to be hauled during cutting, filling, borrowing, and disposal operations. This plan is then used as input for estimating the energy consumption and CO_2 emissions of the selected hauling fleet. The proposed model will help planners to assess the energy and environmental performance of mass hauling plans, and to select hauler and fleet configurations that will minimize these quantities. The model was applied in a case study, demonstrating that it can reliably predict energy consumption, CO_2 emissions, and hauler productivity as functions of the hauling distance for individual haulers and entire hauling fleets.

Keywords: hauling operations; optimum schedule; energy consumption; CO_2 emission; hauler

1. Introduction

Road and highway construction are major undertakings that involve large-scale mass hauling operations. Haulers are designed to transport excavated material from cutting areas to filling areas or disposal areas during mass hauling operations. In the course of this work, they consume very large amounts of diesel fuel and emit large quantities of CO_2 [1]. Previous research on hauling operations has largely focused on cost sensitivity analysis and reducing the execution costs of mass hauling operations (i.e., maximizing "productivity per unit cost"). There has thus been relatively little work on haulers' energy consumption and CO_2 emissions, despite their potentially significant impact on the local environment and global climate [2]. Zeng et al. [3] have shown that actors and decision-makers working with energy management systems have come under pressure to address a wide range of issues including energy consumption and the mitigation of greenhouse gas (GHG) emissions. These authors also identified several regional and global environmental issues that are affected by energy activities.

Over the last ten years, advances in construction technology and practices have significantly reduced the amounts of energy used and emissions generated by construction machinery and equipment [4–6]. This is largely due to the introduction of new regulations, for instance, the ones from United States Environmental Protection Agency (EPA) that limited the permissible emissions from new engines [5,6]. Furthermore, it has been shown that good management of road construction projects is associated with low energy consumption [7]. The quantities of fuel and energy used in road construction projects are largely determined by the construction machinery and equipment that is used and the way in which it is used [8]. Accordingly, reports published by the EPA's Clean Air Act Scientific Advisory Committee in 2006 and 2008 showed that 7.5% of total CO_2 emissions are generated by off-road equipment, with construction equipment accounting for 40% of these emissions [9]. As such, there is an urgent need for ways of maximizing the efficiency of mass hauling operations and for the widespread adoption of such methods within the construction sector. Many factors acting at different stages of the construction process contribute to the sector's overall fuel consumption and emissions output, but the bulk of the emissions produced during road construction projects occur during the construction stage [10]. Mass hauling operations in road construction projects involve heavy haulers, which generally consume large quantities of energy; fuel costs account for around 30% of their total life-cycle costs [11]. More efficient allocation of haulers can significantly reduce both costs and emissions [12–14].

A few frameworks for reducing emissions from construction projects have been proposed. One, developed by Peña-Mora et al. [15], incorporates an emissions estimation model that can be used to determine which construction methods offer the best performance and lowest emissions. Lewis et al. [16] proposed a framework for estimating emissions due to excavation activities that can be used to control both costs and emissions. An analysis of emissions data conducted by Carmichael et al. [17] indicated that (under certain assumptions), procedures that minimize costs in earthmoving operations also minimize emissions. Subsequent analyses by the same authors emphasized the magnitude of the emissions generated by off-road haulers and reinforced the conclusion that designing earthmoving operations to minimize unit costs also minimizes unit emissions [18].

This paper presents a new model for estimating mass haulers' energy consumption and CO_2 emissions. The model depends on productivity rates for different hauler types, which are computed with a construction planning program using a bill of quantities for the various earthworking activities involved in road construction projects. The model's output is then used to estimate the energy consumption and CO_2 emissions of the chosen hauler fleet based on pre-determined hourly fuel consumption values for each hauler type included in the plan.

2. Literature Review

The energy consumption and emissions of mass hauling operations have been studied in some detail. However, much of this work has focused on building construction rather than road construction, even though both types of projects involve extensive earthwork activities and operations that account for a large proportion of the total energy consumption and CO_2 emissions. The Swedish Transport Administration is working towards more energy efficient and environmental friendly infrastructure projects. Among others, the selections of construction materials and methods in the planning phase are regarded as an important aspect that may significantly influence the energy consumption and CO_2 emissions in the life cycle of infrastructure project [19]. However, most current methods focus on the construction phase or after construction phase which limits the practical adoption of reduction strategies in the early planning phase [20]. Consequently, there is an urgent need for new methods that can estimate the emissions generated at road construction sites and evaluate the environmental impact of different earthwork activities in the planning phase [21–23]. A deep knowledge of the environmental effects of construction activities is required to define procedures and criteria for mitigating GHG emissions [24].

Heavy duty vehicles such as mass haulers must comply with strict emissions standards such as the United States EPA's tier standards, and European emission standards consisting of progressively stringent tiers known under stage I–IV standards, which are regulated in the European standards for non-road diesel engine [25]. Compliance can be achieved by improving construction strategies for emissions control, reducing idling times, periodically maintaining, replacing, and modifying aged fleets of construction equipment, and developing awareness of fuel consumption and fuel quality [26]. Hajji et al. [27] developed an innovative method for estimating the energy consumption of heavy-duty diesel equipment and the resulting emissions during earthwork operations. They evaluated their model by comparing its estimates to experimental data for excavators operating under different conditions. Ahn et al. [28] introduced a quantitative method for estimating emissions during earthmoving operations based on discrete-event simulations of earthwork configurations that account for the specifications of the construction machinery that is used. This approach was evaluated against a widely-used non-road method for estimating emissions. An alternative method for estimating the emissions of mass haulers is based on the concept of a "steady-state engine", which does not account for ambient conditions or the uncertainties associated with on-site construction [29]. This approach has not yet been evaluated against data from real construction projects. Marshall et al. [30] presented a method for estimating emissions due to commercial building construction that is based on an inventory of individual construction activities. During this work, they identified several factors that significantly affect the fuel consumption and emissions of non-road construction equipment, including the bid conditions, project requirements, the equipment's fuel efficiency, and the legal status of various resources. Arocho et al. [31] estimated fuel consumption and CO_2 emissions from construction machinery and equipment on the basis of the characteristics of the construction project such as its cost and the planned extent of wholly paved areas. This method can only estimate emissions from equipment used on-site, and can only be used to estimate daily or weekly emission levels for various construction activities relevant to road construction. Another emissions estimation model known as URBEMIS (Rimpo and Associates Inc. 2007, Sacramento, CA, USA) has been developed by the South Coast Air Quality Management District (South Coast AQMD 2008, Los Angeles, CA, USA) and the California Environmental Protection Agency. However, this proved incapable of accurately estimating emissions from road construction activities [32]. These models rely on assumed similarities in operating conditions between different construction projects, which introduces errors in estimates of energy consumption and emissions because the unique aspects of individual projects, such as their production rates and job cycles are not accounted for in the estimation [33]. Data on equipment productivity and site conditions have been used in conjunction with design documents for road construction projects to estimate emissions [34]. Guggemos et al. [35] presented a method and a design tool for estimating energy usage and emissions in construction projects known as the Construction Environmental Decision Support Tool, which evaluates the environmental impacts of construction projects on the basis of a life-cycle assessment (LCA). It supports both process-based LCAs, and economic input–output analysis-based LCAs; in both cases, worksheets for the construction equipment being used are required. Ercelebi et al. [36] proposed a linear programing model for efficiently managing the dispatching of hauler fleets in surface mining operations and concluded that it could reduce hauling costs, which account for "50%–60%" of the total operating cost for such operations.

The effects of idling times on fuel consumption during construction operations have been estimated by simulating discrete events and used to evaluate technical plans with respect to efficiency of resource utilization and emissions [37]. Information on the relationship between idling time and hourly fuel consumption can be applied across a fleet of construction machines in various ways, leading to a range of concepts for identifying optimal production cycles that minimize unit costs and emissions [11]. Variation in engine power and activity has been identified as a major source of variation in fuel consumption and emissions [38]. In addition, a "fuel-based emission inventory" method has been presented and used to estimate the effects of construction machines' engine characteristics on fuel consumption and emission rates over specific duty cycles in an extensive study of non-road equipment based on "Fuel-based emission rates" [39]. This method has been evaluated against fuel consumption data for agricultural non-road and off-highway equipment from the U.S. Federal Highway Administration (FHWA) [40]. Finally, Lucas et al. [41] utilized life cycle analysis to estimate the fuel consumption and CO_2 emissions due to infrastructure construction.

Hauler speed is another key determinant of fuel consumption. One study concluded that haulers should be limited to 55 miles per hour (mph) under all road conditions to minimize fuel consumption [42]. This analysis suggested that raising the speed limit by 15% increased fuel consumption to the same extent as increasing the grade of the terrain by 10%. The characteristics of the terrain (including its relief and curves) also strongly affect fuel consumption and trip times for haulers in mining and construction projects [43]. Because topography and the gradient of the road have very significant effects on fuel consumption, many efforts to minimize fuel usage use information about the terrain to be traversed [44]. If a site has many steeply sloped areas, haulers' travel times will not necessarily be minimized by taking the shortest or most direct route between two points [45]. Travel time strongly affects hauling performance in large projects with complex haulage routes that require careful scheduling of hauler time cycles.

Haulers' CO_2 emissions depend strongly on their properties (for example, their payloads), which vary widely. Therefore, a practical method for estimating hauler emissions should have clear definitions of different hauler types because it is impossible to accurately estimate emissions using a "one-size-fits-all policy" [46]. A recent study showed that heavy haulers' fuel consumption is 10% greater than that of comparable passenger vehicles due to the effect of the payload [47]. It has also been argued that the fuel consumption of heavy haulers increases with the load factor [48]. This conclusion was based on a study that used the haulers' load capacity and operational characteristics such as hauler speed and production rate as input parameters to determine the haulers' cycle times. However, the analysis was based exclusively on data for haulers dealing with a single soil type and thus neglected the influence of soil properties such as the soil moisture content and water saturation. In contrast, the model presented herein estimates the hourly fuel consumption of machinery and equipment in an ideal frame based on information supplied by the manufacturer, using an estimated load factor that depends on the swell factor of the excavated material. Therefore, the load factor depends directly on the properties of the material being hauled.

Previous research has focused on estimating the energy usage and emissions of construction equipment during post-project evaluation [31,38]. In contrast, this paper describes an approach that uses construction planning tools supported by a new algorithm to predict haulers' energy consumption and CO_2 emissions during the planning phase of a project. A detailed model for predicting the energy consumption and CO_2 emissions of haulers during the earthmoving operations of a road construction project is developed, implemented, and evaluated. Predictions are made on the basis of the hauling distance, productivity rate, and cycle time for each hauler, which are based on an optimized hauling schedule.

3. Model Structure

Haulers are designed to transport excavated material from cutting areas to filling areas or disposal areas during earthwork operations and road construction activities. The types and models of haulers used in a given road construction project will depend on the site conditions. This paper proposes a model for predicting the energy consumption and CO_2 emissions of mass haulers based on information available during the project planning phase, namely a hauler database and a bill of quantities for earthwork operations. The model can account for the existence of multiple loading and dumping areas within the construction project, as well as different facilities and areas relating to earthwork operations such as crushing plants, disposal areas, borrow pits, and so on. In brief, the modeling approach involves first specifying an optimized schedule for the mass hauling operations based on the project data and hauler database (Figure 1), and then utilizing a new algorithm to estimate the haulers' energy usage and hauler CO_2 emissions by considering the optimized schedule and information from the hauler database. The modeling process can be divided into three stages.

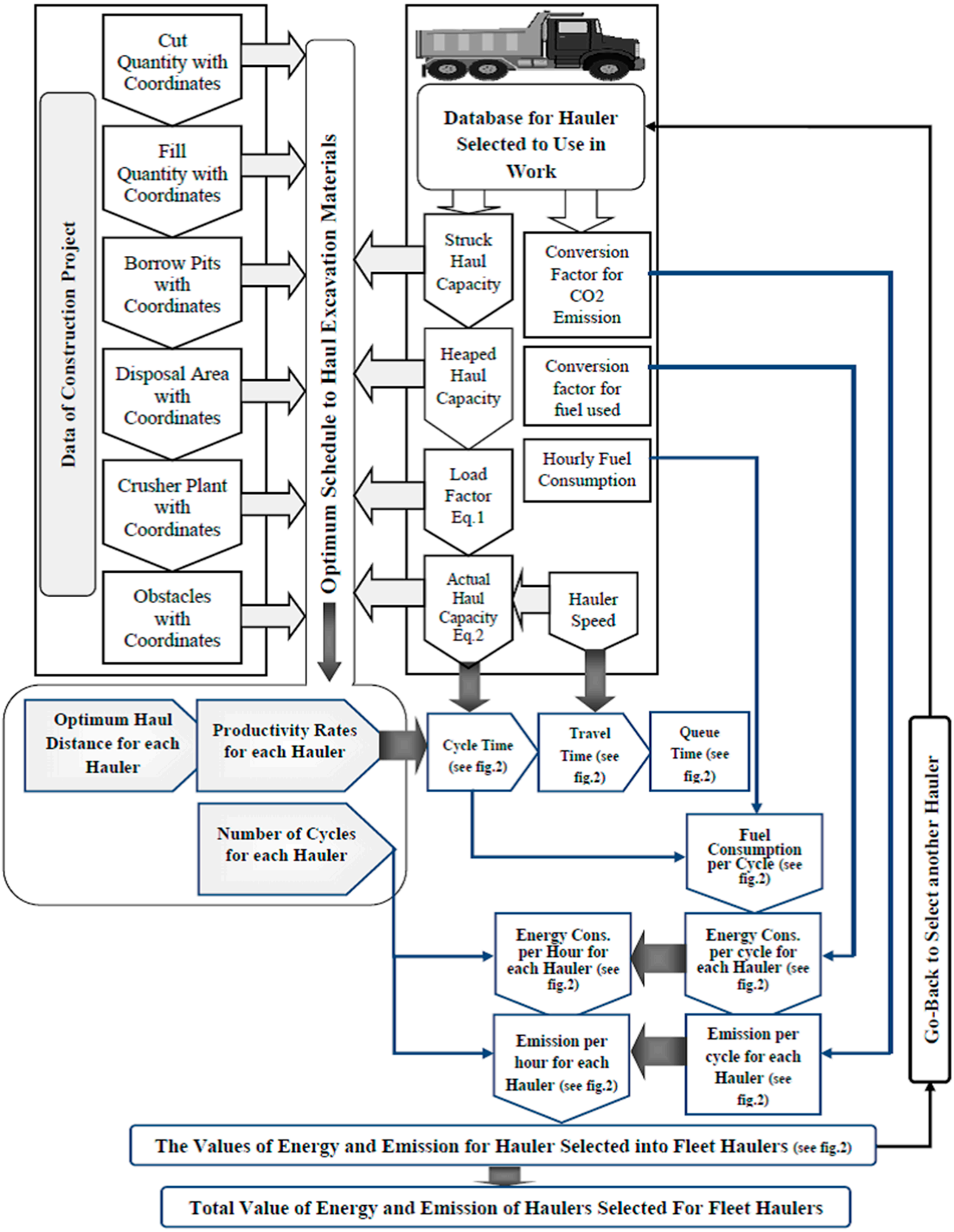

Figure 1. Structure of the model for estimating the energy usage and CO_2 emissions of haulers used in earthwork operations. Eq.: Equation; fig.: Figure.

3.1. Collecting Input Data

The first step in the modeling process is to compile the project data, i.e., the bill of quantities for mass hauling operations in the construction project relating to cutting and filling areas, including the locations of borrow pits, disposal areas, crusher plants, and obstacles such as facilities, constructions and intersections of routes used for earthmoving or other purposes. These factors are used to estimate the shortest and longest possible hauling distances for each hauler and load, which are then used to determine an overall optimum hauling distance (Figure 1). In addition, the swelling factor (*swell*) of the excavated material is used to calculate a load factor (L_f) for the hauler (Equation (1)), which is used to compute the actual hauling capacity of each hauler in the second step.

$$L_f\% = \frac{(100\%)}{(100\% + swell\ \%)} \tag{1}$$

where *swell* = swelling factor (%).

In addition, it is necessary to compile the hauler database, which records information on the struck and heaped capacity, maximum speed, load factor, and hourly fuel consumption for each hauler selected for inclusion in the assessment (Figure 1). These data are complemented with the estimated actual hauling capacity of each hauler (H_{cact} (LCM/cycle)) (i.e., LCM = Loose Cubic Meters), which is computed from their heaped capacity and the load factor using Equation (2):

$$H_{cact} = H_c * L_f \tag{2}$$

where H_c = Heaped haul capacity, and L_f = Load factor (%).

3.2. Generating a Schedule

The second step in the modeling process involves generating an optimum schedule using input data from the first stage. The optimum schedule is a plan designed mainly on the basis of the planners' perspective and experiences, with the aim of maximizing the utilization of each hauler while ensuring that the requisite amounts of material are moved to and from each location. The hauler data are vital in the generation of the optimum plan because the final outputs of this stage are presented in terms of optimal haul distances, productivity [34], and cycle numbers (Figure 1), all of which depend on the hauler data (i.e., capacity, speed, load factor, fuel type, and hourly fuel consumption) [48]. An average hauler speed (S_t (km/h)) is defined on the basis of the conditions and surface characteristics of the construction site, the terrain, the routes the haulers will travel, and the path conditions [44].

3.3. Assessing Energy Consumption and CO_2 Emissions

The third stage of the modeling process involves using a new algorithm to assess each hauler's energy consumption and CO_2 emissions (see Figure 2), based on previously obtained results and data (i.e., haul distance, productivity rate, number of cycles, actual haul capacity, speed, hourly fuel consumption, conversion factors for energy and emission). To begin with, it is necessary to compute a cycle time (C_t (h/cycle)) for each hauler that depends on the actual haul capacity (H_{cact} (LCM/cycle)) and the production rate (P_r (LCM/h)), as shown in Equation (3):

$$C_t = \left(\frac{H_{cact}}{P_r}\right) \tag{3}$$

where H_{cact} = Actual haul capacity, and P_r = Production rate.

It is also necessary to calculate the travel time (T_t) for each hauler, i.e., the time required to haul and return, H_d (km/cycle); see Equation (4). This quantity is used to compute the estimated queue time (Q_t) for each hauler in each cycle, which depends on the cycle time and travel time (Figure 2) as well as the loading time (L_t) and dumping time (D_t) which depend on the properties of the hauler and loading server [49] (Equation (5)).

$$T_t = 2 * \left(\frac{H_d}{S_t}\right) \tag{4}$$

where S_t = Hauler speed, and H_d = Haul distance.

$$Q_t = [C_t - (L_t + D_t + T_t)] \tag{5}$$

where C_t = Cycle time, L_t = Loading time, D_t = Dumping time, and T_t = Travel time.

The hauler fuel consumption per cycle (F_c (L/cycle)) is computed from the hauler's hourly fuel consumption (F_h (L/h)), which can be obtained from the hauler database, and the cycle time for the hauler in question (Equation (6)).

$$F_c = F_h * C_t \tag{6}$$

where F_h = Hourly fuel consumption, and C_t = Cycle time.

The energy consumption for each hauler per cycle (E_c (MJ/cycle)) can be calculated using the hauler's fuel consumption per cycle, which is obtained as described above (Figure 2) and the energy conversion factor (E_f (MJ/L)) for the fuel type that the hauler uses, as shown in Equation (7).

$$E_c = F_c * E_f \tag{7}$$

where F_c = Fuel consumption per cycle, and E_f = Energy conversion factor.

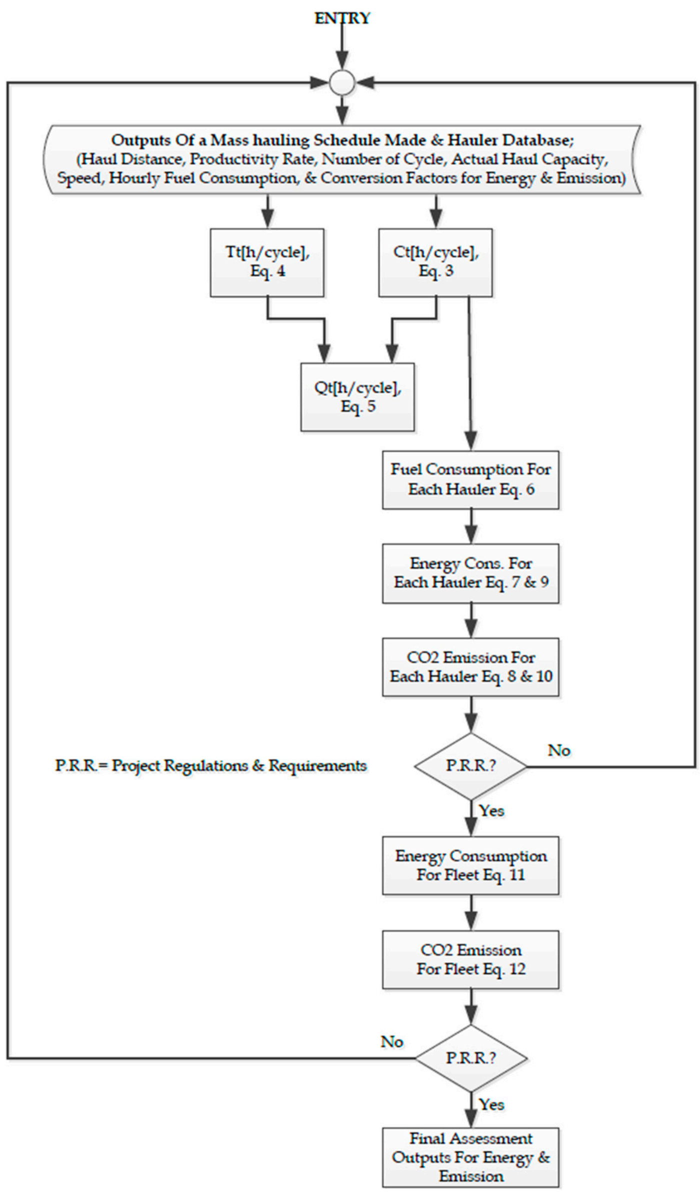

Figure 2. Flowchart for estimating energy consumption and emissions.

Similarly (Figure 2), each hauler's CO_2 emissions per cycle (CO_{2E} (kg/cycle)) can be calculated from its fuel consumption per cycle and the conversion factors for CO_2 emission (C_f (kg/L)) (Equation (8)).

$$CO_{2E} = F_c * C_f \tag{8}$$

where F_c = Fuel consumption per cycle, and C_f = CO_2 emissions conversion factor.

The estimated energy consumption (E_{ch} (MJ/h)) and CO_2 emissions per hour (CO_{2Eh} (kg/h)) of hauler work on earthwork activities can be estimated from the number of cycles (N_c (cycle/h)) per hour for each hauler based on the optimum hauling schedule (Equations (9) and (10)).

$$E_{ch} = E_c * N_c \tag{9}$$

where E_c = Energy consumption per cycle, and N_c = Number of cycles per hour.

$$CO_{2Eh} = CO_{2E} * N_c \tag{10}$$

where CO_{2E} = CO_2 emission per cycle, and N_c = Number of cycles per hour.

Having performed all of these calculations, their results can be compared to the regulations and requirements that apply to the project (Figure 2) in order to determine which (if any) of the initially considered haulers should be selected. If none of the haulers satisfy all of the criteria, one can resume the process from the end of the first stage (the creation of the optimum schedule) and examine alternative haulers. Once a hauler that satisfies the project's energy consumption and CO_2 emission requirements has been identified (Figure 2) each of the other haulers called for by the optimum schedule is evaluated similarly until all of the hauling requirements have been met.

Once the energy consumption and CO_2 emissions of each individual hauler have been predicted, they can be combined to obtain total energy consumption (E_{cht}) and CO_2 emission (CO_{2Eht}) values for the full set of haulers that will constitute the hauling fleet for the project. These quantities will depend on the number of each hauler type required under the optimum plan (Figure 2) and are computed using Equations (11) and (12). These whole-fleet values can once again be compared to the project requirements to determine whether the proposed plan can be accepted (Figure 2).

$$E_{cht} = \sum_{i=1}^{n} E_{ch} \tag{11}$$

where n = number of haulers; i = 1, 2, 3, . . . , n.

$$CO_{2Eht} = \sum_{i=1}^{n} CO_{2Eh} \tag{12}$$

where n = number of haulers; i = 1, 2, 3, . . . , n.

4. Application of the Proposed Model in a Case Study

To evaluate its performance, the proposed model was tested in a case study. Figure 3 presents an integrated definition for function modeling (IDEFO) representation of a streamlined process for estimating energy consumption and emissions in earthwork operations. The generic procedure for applying the detailed model will be outlined below, along with a brief discussion of the project that was selected to test and demonstrate the model.

Data were collected from a new road construction project (väg 870) in Kiruna Municipality, northern Sweden. The case study data were obtained from the project documentation and consisted of the project tender, which provides exact bills of quantities for earthwork activities and operations in addition to information on the size and location of borrow pits, disposal areas, and other relevant project-related information. The planned road had two lanes with a maximum design speed of 80 km/h and a width of 7.5–9 m. It was designed to bear heavy traffic to and from a facility operated by the company LKAB (Kiruna, Sweden) and also to serve tourists and public traffic to and from Nikkaluokta (Gällivare, Sweden).

The bill of quantities for the project's earthwork operations included the sizes and coordinates of the land-cut, land-fill, disposal area, and borrow pits, as well as the total length of the planned road and details of the associated facilities, annexes, and intersections through the project paths (Figure 3). The hauler database contains information on three Caterpillar truck models (770G, 773E, and 775G) that was obtained from the Caterpillar handbook, including the trucks' model numbers, speeds, loading and dumping times, haul capacity, hourly fuel consumption, and hourly operating costs [50]. All trucks were assigned the same loading time (4 min) and dumping time (2 min) despite their different haul capacities [49]. The heaped capacity is basically the struck capacity plus a heaped load (i.e., the volume of material carrying above the body sides) [51]. Hence, use the heaped capacity as a designed capacity for trucks. Moreover, the trucks were assumed to travel at a constant 50 km/h and brake effects were neglected. It was further assumed that all of the haulers worked with a single server (excavator), whose energy consumption and emissions were not included in those of the fleet. The swell factor of the excavated material was assumed to be 30%, giving a load factor of 0.769. The energy conversion factor and CO_2 emission conversion factor for diesel engines were set to E_f = 36.0 MJ/L [52] and C_f = 2.614 kg/L, respectively [53].

Two computer programs were used to create a detailed model in the case study: DynaRoad is 'Project management software for heavy civil engineering projects. It is used for planning and optimizing the mass-haul of an earthworks project based on the location of materials. It helps in creating a construction schedule and monitoring the progress of the project' [54]. It was used to draw up the optimal schedule for earthwork operations [55,56], and Matlab was used to solve the necessary equations and determine the relationships between the model's parameters (Figure 3) so as to estimate the energy consumption and emissions.

The road construction data were entered into an Excel file, taking care to ensure consistency of units, in order to avoid errors during processing with DynaRoad in the first stage of the model building process [57]. The bill of quantities was then imported into DynaRoad along with the hauler database to enable the generation of a schedule based on the project's activities, including all necessary resource adjustments. Data from the DynaRoad resource report and optimum schedule such as the haul distance, productivity rate, and number of rotations were exported into an Excel file containing data from the hauler database including information on the haulers' actual haul capacity, speed, hourly fuel consumption, and conversion factors for energy and emissions. Matlab is then used to solve Equations (1)–(12) with the data from the Excel file. The resulting output can be tuned by the planner so that only the parameters of interest are displayed. In addition, the planner can go back to earlier stages of the modeling process in order to ensure that the solutions obtained comply with the applicable project regulations. For example, the estimated energy consumption and CO_2 emissions for either individual hauler types or the fleet as a whole can be compared to the relevant environmental regulations and limitations in order to determine whether the evaluated configuration should be accepted or whether it is necessary to go back to the hauler database and evaluate alternative options (Figure 3).

The planner can also vary the swell factor to determine how modifying the load factor affects the actual haul capacity, production rate, and cycle time, and thus the haulers' queue times, which are computed during the third stage of the modeling process. Because the queue time strongly affects energy consumption and emissions (i.e., long queue times imply significant idle time; see queue time in Figures 1 and 2) [37], the selection of haulers might need to be modified. The final outputs of the modeling process include estimates of the hourly energy consumption and CO_2 emissions for individual haulers and the fleet as a whole, enabling meaningful evaluation of the environmental impact of the planned earthwork operations.

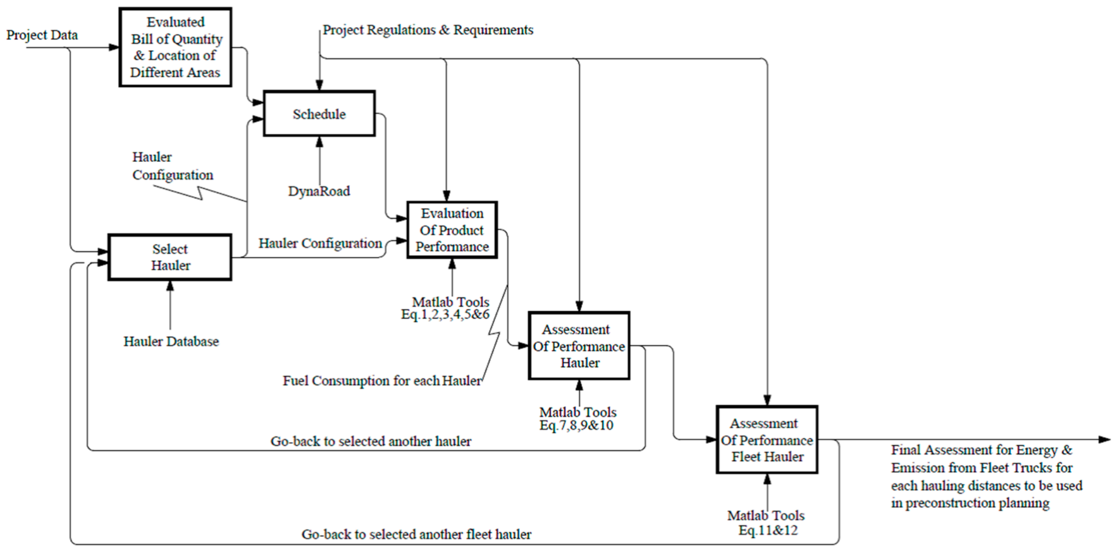

Figure 3. Integrated definition for function modeling (IDEFO) representation of a simplified process for estimating the energy consumption and CO_2 emissions of haulers for earthmoving operations in road construction.

The most important model outputs are the optimum haul distance, productivity rate, number of cycles, cycle time, queue time, fuel consumption based on cycle time, energy consumption per cycle and per hour, CO_2 emissions per cycle and per hour, and the total hourly energy consumption and CO_2 emissions for the selected hauler fleet. It should be noted that all of these values are estimated for each hauler and each haul distance. The maneuver time for each hauler is included in their loading times, and the reserve time is included in the queue time (see Table A1 in Appendix A).

5. Results and Discussion

Table A1 (Appendix A) shows the model's predictions of the productivity, number of cycles, cycle time, queue time, energy consumption, and CO_2 emissions for the three hauler models considered in the case study, over hauling distances ranging from 50 m to 23,000 m. These quantities were computed using Equations (1)–(8) and the case study data. The results of the DynaRoad computations were verified to represent a mass optimized schedule [54,56,57] by performing a resource adjustment to achieve a zero surplus and zero deficit for the utilized resources based on the report on the hauling resources. The model's output provided detail on several path-moving scenarios for haulers and included quantities relevant to planners during the preconstruction phase and construction managers during the construction phase. For example, it includes cycle times for each hauler model over a wide range of haulage distances, giving construction managers a clear understanding of the expected timing of earthwork activities that could be used for work monitoring during the execution phase to rapidly identify unexpected deviations from the schedule. The cycle time is also useful to planners because it directly affects the cost of hauling operations [14]. Consequently, it is important to consider when comparing different hauling options.

The model's most important outputs are the predicted energy consumption and CO_2 emissions of the haulers, which the planners and estimators need to know during the planning phase in order to devise a work plan that will satisfy the relevant environmental regulations. The model provides detailed information on the energy usage and cycle times of each hauler for a wide range of haulage distances. It therefore gives planners a clear overview of the energy consumption and environmental consequences of earth moving operations, allowing them to readily determine which individual haulers and fleet structures are most efficient or best able to satisfy the relevant environmental criteria.

The data presented in Table A1 to show the relationships among energy consumption, CO_2 emissions, and haulage distance. The energy consumption and emissions of each hauler are also influenced by their actual haul capacity and the work plan, which was determined during the planning stage [14]. However, for a given set of work conditions and paths, the main determinant of the energy consumption and CO_2 emissions is the haulers' actual haul capacity (Figure 4a,b). In this case, the three haulers energy consumption and emissions were very understandable and expected behaviors for hauling distances of less than 1 km based on engine power for each hauler (i.e., energy consumption and emissions for hauler; 775G > 773E > 770G), and this idea for relationship between engine power and consumption/emission was shown by Caterpillar Performance Handbook [50].

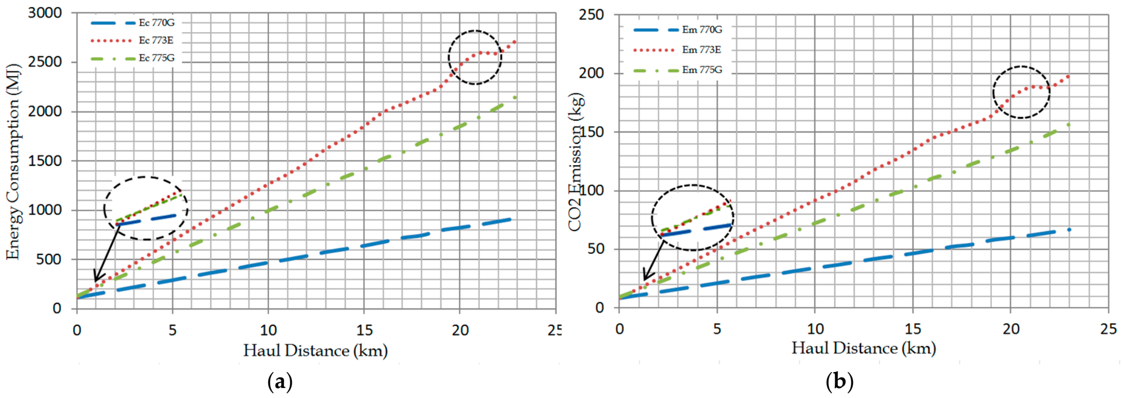

Figure 4. (**a**) Energy consumption; and (**b**) CO_2 emissions as functions of the haul distance for the three hauler models considered in the case study.

The actual haul capacity, horsepower and hourly fuel consumption of hauler 773E were lower compared to hauler 775G. However, hauler 773E had higher energy consumed and CO_2 emissions than hauler 775G even though this is not what would be expected given the difference in their haul capacities [48]. As shown in Table A1, the production rates for hauler 773E were substantially lower (Figure 4a,b) than those for hauler 770G (i.e., it has a lower haul capacity) when the haulage distance exceeded one kilometer. In addition, hauler 773E had a longer cycle time than the other haulers. These contrasting trends in the productivity rate and cycle time for hauler 773E are due to the nature of its optimum work plan for mass haulers, which involves using paths and routes with multiple intersections linking several different construction facilities [45]. This reduced its productivity rates and increased its cycle time, leading to high energy and emissions, as well as higher queue times than were predicted for the other haulers. These outcomes are also reflected in the three haulers' energy and emission curves (Figure 4a,b), which show that the energy consumption and emissions for hauler 773E increased sharply between haulage distances of 19–21 km but then decreased a little between 21 and 22 km before resuming steady growth.

The relationship between the haulers' productivity rates and haul distances also highlighted the divergence of 773E: its productivity falls below that of hauler 770G at haul distances above 3 km (Figure 5), suggesting that obstacles on the route selected for 773E affected its energy consumption and CO_2 emissions.

The hourly energy consumption and CO_2 emissions for each hauler were estimated using Equations (9) and (10) (Table A1) and compared to the project's environmental regulations to select a suitable hauler fleet composition. Hourly energy consumption and CO_2 emissions for the fleet (all three haulers) were also computed with Equations (11) and (12), and used in the final assessment to determine whether the plan could be expected to satisfy the environmental regulations and conditions for the project (Table 1).

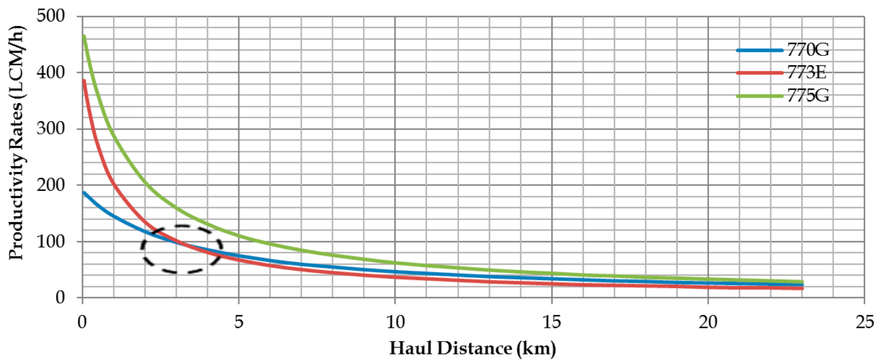

Figure 5. The relationships between the productivity rates of the three haulers and the haul distance.

Table 1. Hourly energy consumption and emissions for each individual hauler model and the whole fleet considered in the case study.

Item	Caterpillar			Fleet
	770G	773E	775G	
Energy consumption (MJ/h)	1153.799	1729.803	1943.995	4827.597
CO_2 emission (kg/h)	83.73	125.69	141.12	350.63

The final estimate of the fleet's energy consumption was then used to identify an optimal hauling distance for the fleet's operations (Figure 6) given a targeted productivity rate and level of energy consumption.

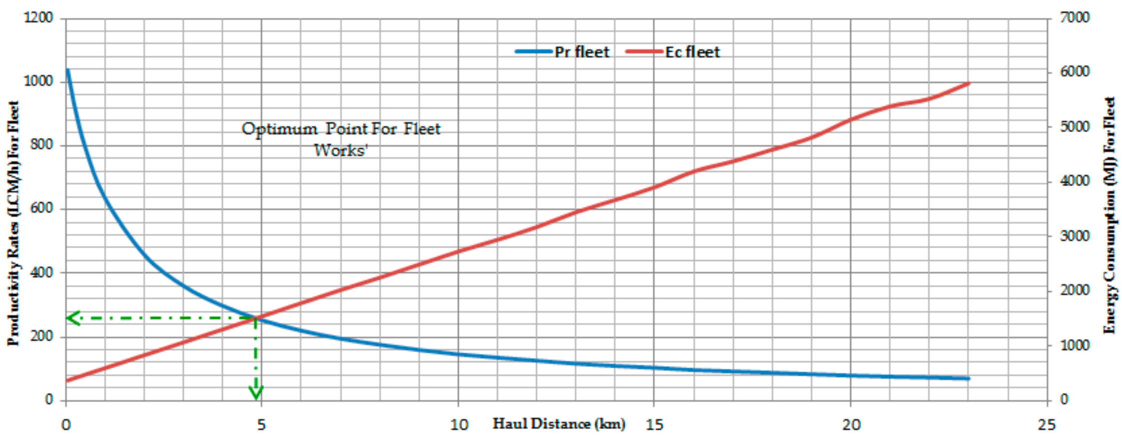

Figure 6. Identifying an optimum fleet work plan that achieves acceptable productivity and energy consumption.

These results allow the planner to estimate the fleet's energy consumption and CO_2 emissions due to a given work duty, over a working day (involving multiple duties), over a working week, or over the complete duration of the project (assuming constant conditions and specifications; see example 1 below).

The modeling approach was used to predict the hourly energy consumption and CO_2 emissions for three hauler models that were hauling material over a distance of 4 km in the case study discussed in Section 4. There were three particular quantities of interest:

(1) The total energy consumption for each hauler per day if a working shift lasts for 8 h and there are two such shifts per work day.
(2) The total CO_2 emissions for each hauler per day under the above conditions.
(3) The fleet's total daily energy consumption and CO_2 emissions under the above conditions.

Table 2 lists the energy consumption per cycle for each hauler under these conditions and the number of cycles for a haul distance of 4 km, the values represent the outputs of the proposed model based on a mass-haul optimization [55,56].

Table 2. The energy consumption, CO_2 emissions, and number of cycles for the three haulers considered in the case study given a haul distance of 4 km.

Item	Caterpillar		
	770G	**773E**	**775G**
E_c (MJ/cycle)	256.399	576.601	474.145
CO_{2E} (kg/cycle)	18.62	41.87	34.43
N_c (cycle/h)	4.5	3.0	4.1
Haul distance (km)	4	4	4

Solution:

where N_h = Number of work hours per duty, and N_d = Number of work duty per day

(a) *According to the data in Table 2:*

$$E_{ch}\,(\text{MJ/cycle}) = E_c * N_c \qquad (for\ one\ hour)$$
$$E_{cduty}\,(\text{MJ/duty}) = E_c * N_c * N_h \qquad (for\ one\ duty)$$
$$E_{cday}\,(\text{MJ/day}) = E_c * N_c * N_h * N_d \qquad (for\ one\ day)$$
$$E_{cday}\,(\text{MJ/day}) = 256.399 * 4.5 * 8 * 2 = 18460.73 \qquad (for\ 770G)$$
$$E_{cday}\,(\text{MJ/day}) = 576.601 * 3.0 * 8 * 2 = 27676.48 \qquad (for\ 773E)$$
$$E_{cday}\,(\text{MJ/day}) = 474.145 * 4.1 * 8 * 2 = 31103.91 \qquad (for\ 775G)$$

(b) *According to Table 2 data:*

$$CO_{2Eh}\,(\text{kg/h}) = CO_{2E} * N_c \qquad (for\ one\ hour)$$
$$CO_{2Eduty}\,(\text{kg/duty}) = CO_{2E} * N_c * N_h \qquad (for\ one\ duty)$$
$$CO_{2Eday}\,(\text{kg/day}) = CO_{2E} * N_c * N_h * N_d \qquad (for\ one\ day)$$
$$CO_{2Eday}\,(\text{kg/day}) = 18.62 * 4.5 * 8 * 2 = 1340.46 \quad (for\ 770G)$$
$$CO_{2Eday}\,(\text{kg/day}) = 41.87 * 3.0 * 8 * 2 = 2009.65 \quad (for\ 773E)$$
$$CO_{2Eday}\,(\text{kg/day}) = 34.43 * 4.1 * 8 * 2 = 2258.5 \quad (for\ 775G)$$

(c) *Total daily fleet energy consumption and emissions:*

$$E_{cfleet}\,(\text{MJ/day}) = 18460.73 + 27676.48 + 31103.91 = 77241.12 \quad (for\ three\ haulers)$$
$$CO_{2Efleet}\,(\text{kg/day}) = 1340.46 + 2009.65 + 2258.5 = 5608.61 \qquad (for\ three\ haulers)$$

Table 3 shows the hourly, duty, and daily energy consumption and CO_2 emissions for each hauler and fleet of haulers were estimated using equations in above.

The main limitation of the model presented is the assumption that all haulers in the fleet serve a single excavator. This could be addressed by extending the model to allow for multiple excavators and loaders. It would also be beneficial to evaluate the model's performance by comparing its predictions to those of non-road and off-road models. In addition, the model could be refined to enable more systematic evaluation of hauling fleet compositions in order to minimize energy consumption and emissions. Finally, it would be useful to incorporate additional predictive factors into the model, such as the age of the hauler's engine, hauler speed, idle time, and loading and dumping times.

Table 3. The energy consumption and CO_2 emissions for the three haulers based on the work hour, duty, and day.

Item	Caterpillar			
	770G	**773E**	**775G**	**Fleet of Three Haulers**
E_c (MJ/h)	1153.79	1729.78	1943.99	4827.57
E_c (MJ/duty)	9230.37	13,838.24	15,551.96	38,620.56
E_c (MJ/day)	18,460.73	27,676.48	31,103.91	77,241.12
CO_{2E} (kg/h)	83.79	125.60	141.16	350.54
CO_{2E} (kg/duty)	670.23	1004.825	1129.25	2804.31
CO_{2E} (kg/day)	1340.46	2009.65	2258.5	5608.61

6. Conclusions

This paper presents a detailed model for estimating the embodied energy and CO_2 emissions due to mass hauling operations in road construction. The model used a mass optimized construction plan in the case study together with a developed algorithm and manufacturers' hauler data to estimate quantities relevant to planners, such as the haul distance, productivity rate, and number of cycles. These data can be combined and sorted into groups for later use when planning similar earth-moving operations.

The literature review revealed several factors that influence energy consumption and emissions due to earthwork operations, including hauler-related variables and site conditions. The model takes these factors into account and can predict the energy consumption and CO_2 emissions for each hauler in a work plan or a whole fleet of haulers during pre-construction planning. This allows planners of hauling operations to comply with environmental legislation and minimize the environmental impact. Because predictions can be obtained for multiple hauler types, the model can be used to optimize the composition of a hauling fleet for a given project schedule in order to minimize energy consumption and CO_2 emissions. Moreover, its output is readily visualized in a way that makes it straightforward to evaluate the predicted energy consumption (MJ/cycle or hour) and CO_2 emissions (kg/cycle or hour). The model was applied in a case study on a real-world construction project, demonstrating its ability to predict haulers' fuel consumption, emissions, and productivity. Overall, the results presented herein demonstrate that the new modeling approach is powerful and flexible, and should be useful to planners needing to predict the emissions and energy consumption of mass haulers in future road construction projects.

The model presented here will be extended to include other pollutant sources, such as carbon monoxide, hydrocarbons and nitrogen oxides. The comparison of the present model with other methods in terms of the degree of improvement will be a key research area in the future investigation.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

Table A1. The model's output for the three haulers included in the case study.

Terms	Productivity Rate (LCM/h)			Number of Cycles (Cycle/h)			Cycle Time (h/Cycle)			Queue Time (h/Cycle)		
Haul Distance (m)	770G	773E	775G	770G	773E	775G	770G	773E	775G	770G	773E	775G
50	187.1	386.1	464.8	9.85	14.3	14.52	0.1015	0.0699	0.0688	Nil	Nil	Nil
100	184.3	368.1	450.4	9.7	13.63	14.08	0.1031	0.0733	0.0710	Nil	Nil	Nil
250	176.7	324.0	411.2	9.3	12.0	12.850	0.1075	0.0833	0.0778	Nil	Nil	Nil
500	164.3	270.0	360.0	8.65	10.0	11.250	0.1156	0.1	0.0889	Nil	Nil	Nil
1000	145.3	202.5	288.0	7.65	7.5	9.0	0.1308	0.1333	0.1111	Nil	Nil	Nil
2000	117.8	135.0	205.6	6.2	5.0	6.42	0.1613	0.20	0.1556	Nil	0.0200	Nil
3000	98.8	101.7	160.0	5.20	3.77	5.0	0.1923	0.2655	0.200	Nil	0.0455	Nil
4000	85.5	81.0	131.2	4.5	3.0	4.1	0.2222	0.3333	0.2439	Nil	0.0733	Nil
5000	75.0	67.5	110.4	3.95	2.5	3.45	0.2533	0.4000	0.2899	Nil	0.1000	Nil
6000	66.5	57.6	96.0	3.5	2.13	3.0	0.2857	0.4688	0.3333	Nil	0.1288	Nil
7000	59.8	50.4	84.8	3.15	1.87	2.65	0.3177	0.5357	0.3774	Nil	0.1557	Nil
8000	55.1	45.0	76.0	2.9	1.67	2.38	0.3448	0.6000	0.4211	Nil	0.1800	0.0011
9000	50.3	40.5	68.8	2.65	1.5	2.15	0.3777	0.6667	0.4651	Nil	0.2067	0.0051
10,000	46.6	36.9	62.4	2.45	1.37	1.95	0.4077	0.7317	0.5128	Nil	0.2317	0.0128
11,000	43.7	34.2	57.6	2.3	1.27	1.8	0.4348	0.7895	0.5556	Nil	0.2495	0.0156
12,000	40.8	31.5	53.6	2.15	1.17	1.67	0.4657	0.8571	0.5970	Nil	0.2771	0.0170
13,000	38.0	28.8	49.6	2.0	1.07	1.55	0.5	0.9375	0.6452	Nil	0.3175	0.0252
14,000	36.1	27.0	46.4	1.9	1.0	1.45	0.5263	1.0000	0.6897	Nil	0.3400	0.0297
15,000	34.2	25.2	44.0	1.8	0.93	1.38	0.5556	1.0714	0.7273	Nil	0.3714	0.0273
16,000	32.3	23.4	40.8	1.7	0.87	1.2800	0.5882	1.1538	0.7843	Nil	0.4138	0.0443
17,000	30.4	22.5	39.2	1.6	0.83	1.23	0.625	1.2	0.8163	Nil	0.4200	0.0363
18,000	29.4	21.6	36.8	1.55	0.8	1.15	0.6463	1.2500	0.8696	Nil	0.4300	0.0496
19,000	27.5	20.7	35.2	1.45	0.77	1.1	0.6909	1.3043	0.9091	Nil	0.4443	0.0491
20,000	26.6	18.9	33.6	1.4	0.7	1.05	0.7143	1.4286	0.9524	Nil	0.5286	0.0524
21,000	25.7	18.0	32.0	1.35	0.67	1.0	0.7393	1.5	1.0	Nil	0.5600	0.0600
22,000	24.7	18.0	30.4	1.3	0.67	0.95	0.7692	1.5	1.0526	Nil	0.5200	0.0726
23,000	23.8	17.1	28.8	1.25	0.63	0.9	0.7983	1.5789	1.1111	Nil	0.5589	0.0911
Terms	**Energy Consumption (MJ/Cycle)**			**Energy Consumption (MJ/h)**			**CO_2 Emission (Kg/Cycle)**			**CO_2 Emission (Kg/h)**		
Haul Distance (m)	**770G**	**773E**	**775G**	**770G**	**773E**	**775G**	**770G**	**773E**	**775G**	**770G**	**773E**	**775G**
50	117.1692	120.9636	133.8372	1154.11662	1729.7795	1943.3161	8.5077	8.7834	9.7181	83.80084	125.6026	141.1068
100	118.9483	126.8802	138.1172	1153.7987	1729.3771	1944.6907	8.6370	9.2129	10.0288	83.7789	125.5718	141.2055
250	124.0632	144.1512	151.2828	1153.7878	1729.81440	1943.9840	9.0085	10.467	10.985	83.7790	125.604	141.157
500	133.4268	172.98	172.8	1134.1278	1729.8000	1944.0000	9.6883	12.560	12.547	82.350	125.6	141.15
1000	150.8753	230.64012	216.0000	1154.1959	1729.8009	1944.0000	10.9552	16.7470	15.6840	83.80728	125.6025	141.156
2000	186.0966	345.9600	302.5681	1153.7989	1729.8000	1942.4873	13.5127	25.1205	21.9698	83.77874	125.6025	141.0461
3000	221.8860	459.2160	388.8000	1153.8072	1731.2443	1944.0000	16.111	33.346	28.231	83.777	125.71	141.15
4000	256.3999	576.6012	474.1452	1153.7996	1729.8036	1943.9953	18.6175	41.8676	34.4283	83.7787	125.602	141.156
5000	292.2959	691.9200	563.4781	1154.5687	1729.8000	1943.9995	21.2239	50.2411	40.9148	83.83440	125.6027	141.1560
6000	329.6570	810.8438	648.0000	1153.7996	1727.0974	1944.0000	23.9368	58.8763	47.052	83.7788	125.4065	141.156
7000	366.5920	926.6785	733.5850	1154.7647	1732.8888	1944.0001	26.6187	67.2872	53.2664	83.84890	125.8270	141.1559
8000	397.86192	1037.880	818.52624	1153.7996	1733.2596	1948.0925	28.8892	75.3616	59.4341	83.77868	125.8538	141.4531
9000	435.8304	1153.1988	904.1868	1154.95056	1729.79820	1944.0016	31.6460	83.7351	65.6540	83.8619	125.6026	141.1561
10,000	470.4336	1265.7074	996.9232	1152.5623	1734.019	1944.0002	34.1587	91.9044	72.3877	83.68881	125.9090	141.1560
11,000	501.6521	1365.6316	1080	1153.7998	1734.3521	1944.0000	36.4255	99.1600	78.4200	83.77865	125.9332	141.156
12,000	537.3090	1482.6856	1160.5972	1155.21435	1734.7421	1938.1973	39.0146	107.6595	84.272	83.88139	125.9616	140.7342
13,000	576.9	1621.6877	1254.1932	1153.8000	1735.2058	1943.9995	41.8893	117.753	91.068	83.7786	125.9957	141.1554
14,000	607.26312	1729.800	1340.6897	1153.7999	1729.8000	1944.0000	44.0941	125.6027	97.3490	83.77879	125.6027	141.15605
15,000	641.00016	1853.3570	1413.8183	1153.8003	1723.6221	1951.0692	46.5437	134.5743	102.6589	83.77866	125.15409	141.66928
16,000	678.7044	1995.9228	1524.7044	1153.7975	1736.4528	1951.6216	49.2816	144.926	110.711	83.7787	126.085	141.710
17,000	721.125	2075.76	1586.9387	1153.8000	1722.8808	1951.9346	52.3617	150.7232	115.2294	83.77872	125.1002	141.7321
18,000	745.6644	2162.25	1690.434	1155.7798	1729.8000	1943.9991	54.1427	157.003	122.744	83.92118	125.6024	141.1556
19,000	797.1710	2256.2608	1767.2728	1155.8980	1737.3208	1944.0000	57.8835	163.8296	128.3236	83.931075	126.14879	141.15596
20,000	824.1430	2471.1430	1851.4285	1153.8001	1729.8001	1943.9999	59.8419	179.4324	134.4343	83.77866	125.6026	141.1560
21,000	853.0056	2594.700	1944.000	1151.5576	1738.4490	1944.0000	61.9376	188.404	141.156	83.6157	126.230	141.156
22,000	887.5404	2594.700	2046.316	1153.8025	1738.4490	1943.9998	64.4452	188.404	148.585	83.7787	126.230	141.155
23,000	921.1007	2731.2631	2160.000	1151.3759	1720.6958	1944.0000	66.8822	198.3201	156.840	83.60275	124.9416	141.156

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