# The Carbon Footprint of Vibratory and Impact Rolling: A Sustainable Option for Bulk Earthworks on Infrastructure Projects

**Derek Avalle, Burt Look, and Brendan Scott**

**Abstract** Vibratory and impact rollers achieve deeper lift compaction than static rollers. Ground improvement with impact rollers occurs through rolling dynamic compaction, enabling compaction to significant depths, generally more than 1 m. This provides the opportunity to place thick layers, potentially with a larger maximum particle size than conventional smooth drum rollers, while achieving engineering standards of density and stiffness. The overall consequence of this is that the earthworks exercise becomes a far more sustainable activity. Deeper lift compaction beyond traditional thin compacted layers using conventional heavy vibratory rollers has been achievable for some time, but to lesser depths than is possible with impact rollers. The compaction of deeper lifts at faster operating speeds, albeit, typically with a greater number of passes, requires a fresh look at specifications for infrastructure earthworks. The paper explores the green credentials of deep lift compaction, by comparing earthworks plant, productivity and fuel usage for compaction using conventional circular drum rollers with thin layers, and deeper lift compaction using vibratory and polygonal impact rollers. Quality control to greater depths can be a limiting factor. Testing protocols often require modification to accommodate the changes in layer thicknesses and material specifications.

**Keywords** Impact roller · Vibratory roller · Deep lift compaction · Sustainability

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## 1 Background

In today's world of increasing demand for sustainable practices, it is imperative to select equipment that not only consumes less fuel but also reduces carbon emissions, as well as to apply specifications that acknowledge the attributes of current models and types of compaction equipment. Rollers have different rates of fuel efficiency and compaction production capacity. For example, vibratory rollers are known to consume more fuel compared to static rollers due to their high-frequency vibrations. However, a greater depth of influence is possible with vibratory rollers than with static rollers.

Factors such as operator expertise, maintenance routines, material types and terrain conditions can influence the level of fuel efficiency achieved by a compaction roller. Therefore, in order to identify the ideal roller, one should strike the best balance between performance capabilities and economical use of fuel resources. By making this informed choice, construction companies stand not only to save on operational costs but also contribute towards environmental conservation efforts at large.

The type of compaction equipment and number of passes also play a crucial role in determining fuel efficiency. Using fewer passes with a heavier roller can result in less fuel consumption compared to multiple passes with lighter rollers.

Fuel consumption is usually measured in litres used per hour (L/h). Direct comparison is difficult as this varies with the ground conditions, type of work, the type and brand of equipment, age and maintenance of equipment and operator skill, amongst others. There is also both work and idle time as well weather conditions. Therefore, using fuel consumption as a metric is somewhat complex. Equipment manufacturers cite comparisons between models or type of work rather than absolute numbers. Comparison of actual fuel consumption between manufacturers with their various size and types of equipment cannot be made on a like-for-like basis across different manufacturers.

The weight of rollers is a crucial factor to consider when it comes to fuel efficiency. Heavier rollers require fewer passes, which means they consume less fuel compared to lighter ones that need more passes for the same level of compaction. Therefore, heavier rollers may result in significant cost savings over time, although a higher investment and mobilisation cost. The choice of machine will depend on the ground conditions at the site. Figure 1 provides an example of drum rollers and typical material types.

For variable fill, smooth drum rollers tend to bridge "rocky" high spots without compacting the low spots. Thus, pad foot or tamping rollers tend to be used in such materials with the smooth drum roller as a finishing roller for the final surface.

Non-circular or polygonal impact rollers, as illustrated in Fig. 2, offer the major advantage of compaction to greater depths [3, 13]. These units operate at a much higher speed, generally 10–14 km/h, and deliver compaction to significant depths of 2–3 m or more, with a combination of potential and kinetic energy, providing the capacity to compact loose layer thicknesses up to 1.5 m [12].

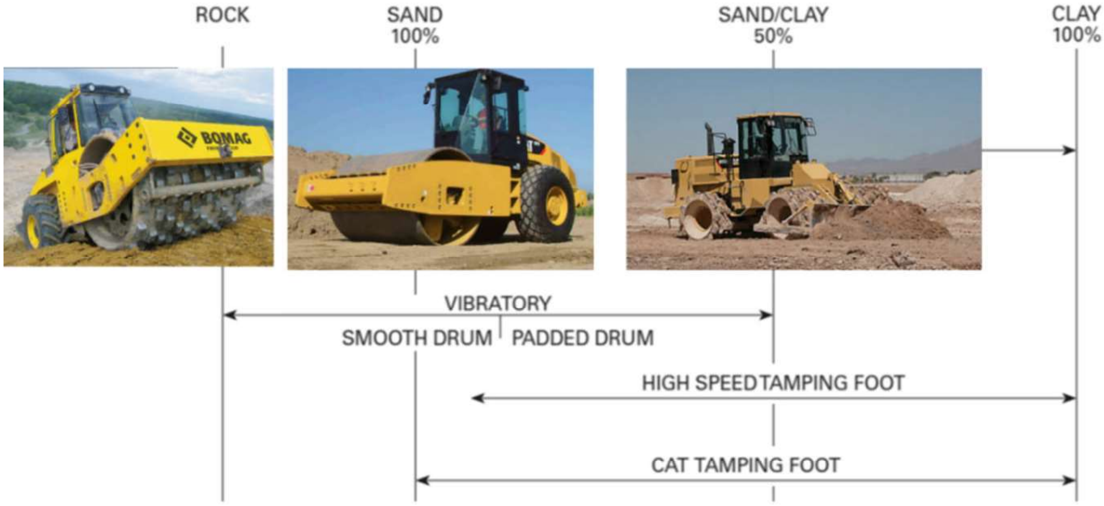


**Fig. 1** Soil compaction equipment is required to match soil type (adapted with photos from [2])

**Fig. 2** From left to right, examples of 3-, 4- and 5-sided impact rollers. (Photos 1 and 3 from Landpac [5]. Photo 2 from broonsimpactrollers.com.)

Although an impact roller can compact to greater depths, a larger number of passes is typically required compared with drum rollers, for example, 20–30 passes for impact rollers compared with 6–8 passes for drum rollers. The efficiency gain from increased compaction depth for an impact roller is partially offset by increased fuel consumption; there are, however, further benefits arising from efficiency gains and quicker completion of compaction works, such as saving on support plant costs and fuel, and personnel. It is important to remember that factors such as operator expertise, maintenance routines, terrain conditions and type of roller used, all play a role in determining fuel efficiency levels. Additionally, the time saving facilitated by increasing the compacted layer thickness may in itself be a governing factor.

It should be noted that self-propelled drum rollers are rated on their overall weight, not the actual mass on the line of the drum. Impact rollers, however, are rated on the mass of their polygonal modules themselves, or on the energy delivered to the ground. This highlights a further variable in the selection of the most appropriate compaction machines for any particular project.

Roller speed would be a poor indicator of productivity, as slower drum roller speeds often produce compaction to greater depths, while impact rollers need to maintain their higher speed to maximise the dynamic effects. For example, a vibratory roller at 5 km/h has a deeper zone of influence compared to operating at 10 km/h in non-vibratory mode. In the case of impact rollers which operate at about 10–14 km/

h, the deeper compaction depth is contingent on maintaining the optimal operating speed.

Note that the focus of this paper is for large earthworks and mining projects. In urban environments, close to existing buildings, infrastructure and utilities, smaller compaction (<6 tonne) and non-vibratory equipment is usually required.

## 2 Selecting Appropriate Compaction Equipment

The complexity of the decision-making process with regard to compaction should not be under-estimated. The number of variables is substantial, and no two sites or projects will be exactly the same. Conventional standard specifications, however, do not necessarily account for such variability.

The size of the project and the ground conditions typically determine the type of compaction equipment used. On small or urban jobs, light-weight compaction equipment applies, while on large earthworks projects, large dozer compactors may be used to both push and compact the soils simultaneously. The Caterpillar Performance Handbook [2] is one of the few manufacturer documents that provide easily accessible fuel consumption data.

### 2.1 Fuel Consumption

The fuel consumption for various selected equipment is shown in Table 1, in various applications and application descriptions are given in Table 2.

Dozer/compactors have the advantage of a wider range of soil types and dozing and compacting. However, despite its large weight such equipment has a reduced lift thickness compared to vibratory rollers which have excitation (amplitude and vibration) to affect granular soils to a greater depth. Table 2 shows that the dozer/

**Table 1** Fuel consumption for various equipment [2]

| Model | Operating mass (tonne) | Fuel consumption (L/h) | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| 815 K—dozer/ compactor | 22.4 | 26.0–30.0 | 36.0–42.0 | 44.0–47.0 |
| 825 K—dozer/ compactor | 35.5 | 37.8–43.8 | 53.7–67.3 | 63.7–69.7 |
| CS 54—vibratory compactor | 10.6 | 5.7–9.5 | 9.5–13.2 | 13.2–17.0 |
| CS76B—vibratory compactor | 17.6 | 11.4–13.3 | 13.3–17.0 | 17.0–26.5 |

**Table 2** Typical application description (adapted [2])

| Model type | Typical application description (relative to work application) | | |
|---|---|---|---|
| | Low | Medium | High |
| Dozer/compactor | Light work. Dozing loose fill. Considerable idling/ travel/no load | Production dozing, loose soils. Normal compaction | Heavy production. Push-loading. Heavy landfill compactor work |
| Vibratory compactor | Machine has support equipment dozing and spreading, while compactor travels on the flat | Compaction of spread material. Assists dozing/spreading, possibly on slopes | Possibly only machine for operation, doze and spread, with multiple passes, work on slopes |

compactor would operate at 250% added fuel as compared with an equivalent mass compactor. However, this would be blind to the additional operating cost of the additional support equipment for a compactor only, such as a grader/tractor dozer equipment which would typically operate at a fuel usage of 15–25 L/h. The ratioed fuel cost would then be only about 110%, and with an additional operator cost.

When the vibratory mode is used for the round rollers the fuel consumption is high, although the depth of compaction increases. The fuel consumption with reduced dynamic energy would be approximately 90% as compared with say 2 mm amplitude dynamic energy at the initial passes. As the compaction improves, the operator would reduce the vibration mode, thus reducing the fuel consumption. Under favourable conditions, a vibrating roller may produce compaction equivalent to that of a static roller 2–4 times as heavy [9]. This dynamic/static force ratio was also found in Look [8] for compacted residual soils from weathered interbedded sandstone/sandstone material. In materials derived from weathered basalt or sandstone the ratio was 150% and 120%, respectively. Thus, the type of material affects such values.

The layer thickness, the machine speed and number of passes affect the production efficiency. The dozer compactor is used for both pushing and compacting while any compactor has to be supplemented with a dozer or grader equipment.

The comparative fuel usage for drum and impact rollers varies around 15–20 L/h for a standard 15-tonne drum roller, while most impact rollers consume in the range 25–35 L/h. The impact roller consumes significantly more fuel compared to its standard counterpart. However, deeper lifts are able to be compacted, thus a reduced compaction time is involved.

An impact roller typically delivers around two impacts per second, which is equivalent to 120 impacts per minute. However, this may vary depending on the speed of the tractor, the shape and size of the module, and the ground conditions. In comparison, a vibratory drum roller operating at a frequency of 33 Hz will impart 1,980 impacts per minute. Vibratory rollers may have 2 mm amplitude as compared to 150–200 mm drop of an impact roller. The impact roller delivers at a high impact/ low frequency compared to a standard vibratory roller which is low impact/high frequency.

## 2.2 Depth of Influence

Typically, the required level of compaction varies at different depths and in different applications. The production rates vary depending on the size of the equipment and the desired compaction level (Table 3). The thickness is based on what is ideally achievable with modern equipment and will vary with material type (e.g., clay material having reduced thickness). A standard specification may limit compaction depths to 300 mm maximum, as greater depths are difficult to quality control with traditional testing equipment and procedures, which does not account for equipment that can achieve specification for deeper lifts and higher production rates.

The depth of compaction is greater for impact rollers because they impart higher stresses than conventional rollers. The high stress increases the penetration of the drum into the soil thereby increasing the depth of influence. The increased depth of influence is also due to wave propagation during the impact. An impact roller can be expected to deliver a production rate of around 1,000–2,000 cubic metres per hour of compacted material 1 m deep with 15–20 passes, compared with the numbers in Table 3.

Briaud and Saez [1] show the change in stress with depth and the depth of influence with modulus (Fig. 3). The octagonal drum coverage approximates a cylindrical drum. The triangular drum has an influence depth of 200% to 160% that of a cylindrical drum at a modulus of 30 MPa and 50 MPa, respectively.

Scott et al. [11] conducted research on a field-based study comparing before and after compaction test results using a 4-sided impact roller to compact 1.5 m of homogeneous fill material. Various in-situ testing methods and instrumentation were used to measure the ground response and take surface settlement measurements. The results support the findings of Briaud and Saez [11] who examined the depth of influence from theoretical studies for various shaped rollers. The corroboration of the results from the theoretical and field studies provides credence to the extended influence depth. However, these studies also show a significant number of passes is required to obtain the desired compaction or modulus.

Table 4 provides a comparison with the traditionally accepted 300 mm maximum compacted lift thickness for general fill, which would be reduced for clay material.

Using the manufacturer's compaction equipment specification, a thickness of 450 mm is typically sighted. This value is not applied due to constraints in current density testing which is limited in depth. Thus, the 300 mm depth for large earthworks

**Table 3** Productivity with compaction level and maximum thickness [8]

| Size of drum roller | Production ($m^3$/hr) for various relative compaction (%) and maximum compaction thickness (mm) | | |
|---|---|---|---|
| | 90–95% ≥600 mm | 95–98% 450–600 mm | ≥98% <450 mm |
| Medium–heavy (10–15 t) | 900 | 450 | 250 |
| Heavy > 15 t | 1,500 | 1,000 | 450 |

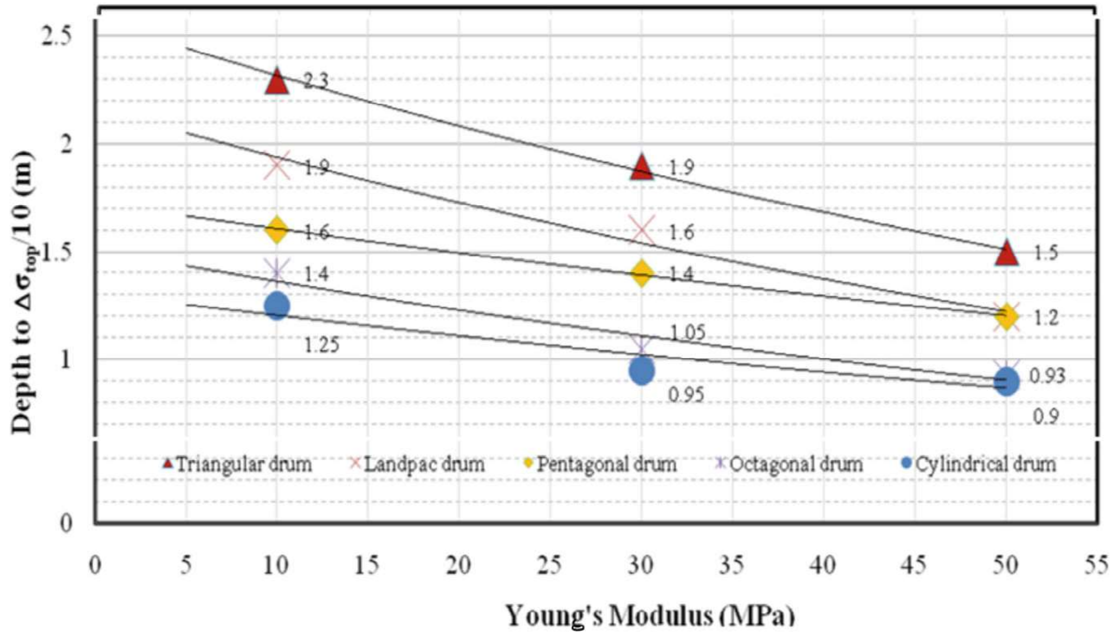


**Fig. 3** Depth of influence with modulus (Kim [4], here from Briaud and Saez [1])

**Table 4** Relative change with different rollers. Assumes similar weight and fill material with a compacted modulus E = 50 MPa. Compaction depth is material- and equipment-specific

| Type of heavy roller | Relative change | | |
|---|---|---|---|
| | Effective compaction depth | Fuel usage | Σ benefit (%) |
| Non vibratory (traditional) | Typically, 300 mm maximum | 13 L/h | 100 |
| Non vibratory (manufacturer) | Typically, 450 mm maximum (150%) | 13 L/h (100%) | 150 |
| Vibratory | Typically, 600 mm (200%) | 15 L/h (115%) | 175 |
| Impact roller | Typically, 1200 mm (or more) (400%) | 25–35 L/h (230%) | 175 |

projects represents the historical association of the 1960s rather than the modern advanced compaction equipment and testing technology to compact to deeper lifts [6, 7]. Testing methods also need to be designed to suit the layer thickness and equipment used [10].

The effective compaction depth is offset by the larger fuel consumption due to the larger number of passes required to achieve an acceptable level of compaction. Table 4 also highlights that without the constraints of the depth of testing, a 50% environmental benefit is possible with modern compaction equipment but is not being realised.

Vibratory and impact rollers theoretically provide environmental and operational cost benefits. As mentioned in earlier sections, actual results are difficult to obtain for direct comparisons to be made. Both a pad foot or impact roller would require a smooth drum roller to produce a smooth finishing surface if a pavement layer or running surface is required. The fuel usage for the finishing surface roller also needs to be factored in, as well as other support plant (grader and watercart, for example), which are not shown in Table 4.

## 3 Conclusions

Choosing the right type of compaction roller is essential for any construction project that aims at achieving optimal performance levels whilst minimizing environmental impact and operational costs. Therefore, energy-efficient compaction rollers that save on operational costs and also contribute towards environmental conservation efforts are desirable. In rural, mining and landfill applications vibratory and impact rollers provide significant benefits with deep lift compaction.

The deeper compaction depths possible with vibratory and impact rollers are partially offset with additional fuel consumption, but still an overall gain to using a typical 300 mm maximum lift thickness. This benefit is unlikely to be realised as even modern-day compaction equipment, vibratory and non-vibratory, are not being optimally used due to testing depth constraints in specifications.

Overall, the 400% depth gain offered by deep lift impact roller compaction is offset by increased fuel, but with optimal usage a 175% environmental gain is possible; however, testing methods and depths constrain such benefits from being realised.

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