Offroad Air Suspension Wheels Rolling Resistances

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Introduction

The Air Suspension Wheel (ASW) is a wheel having rigid rim and hub eccentrically interconnected with air-cylinders (shocks). Unlike customary wheels, it may be driven or towed with 30% reduced resistance against rolling. For large construction/mining/agricultural vehicles, that can result in 15% fuel savings and 15% reduction in greenhouse gas emissions and pollution. The ASW Rolling Resistance (RR) is compared to common rigid and inflated tire wheels RR on pavements and off-roads. The shock adds negative rolling resistance (called Rolling Assistance, RA) to the rolling, which assists driving. By its elastic coupling and torque limiting capacity, it extends vehicle life time and reduces maintenance need by as much as 20%.

Summary

Following standard engineering practices used to assess construction vehicle rolling resistances [1], the rolling resistance of ASWs with shocks is found to be in the low range of 25-2100 lbs/ton-gravity-wheel-load (or 1.25-10.5% equivalent grade) within the wide range of concrete pavement and the very muddy, rotted, soft earth off-road (soil). That may save 13.5% on-road and 15% off-road truck fuel. The rolling resistances in lbs/ton and in slope-% (equivalent grade, GR) are illustrated in Fig. 1.

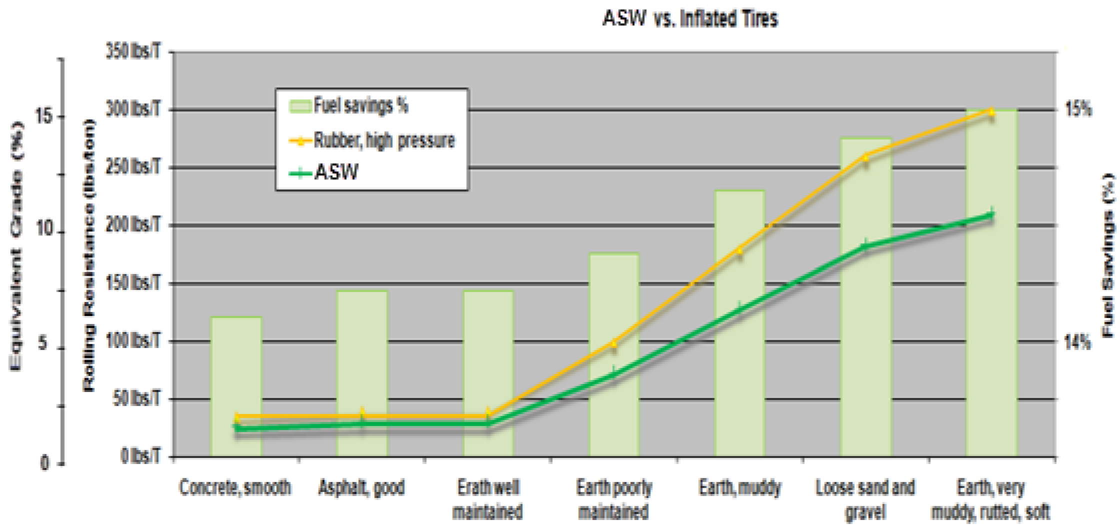

Fig. 1 Common construction truck rolling resistances compared and fuel savings thereof shown

The Rolling Resistance of a Wheel

A wheel of radius r_0, rolling with velocity v, which corresponds to angular velocity of ω, may be modeled as shown in Fig. 2, where $\omega = 2\pi/T$, $\pi \approx 3.14$ and T is the wheel-turning period.

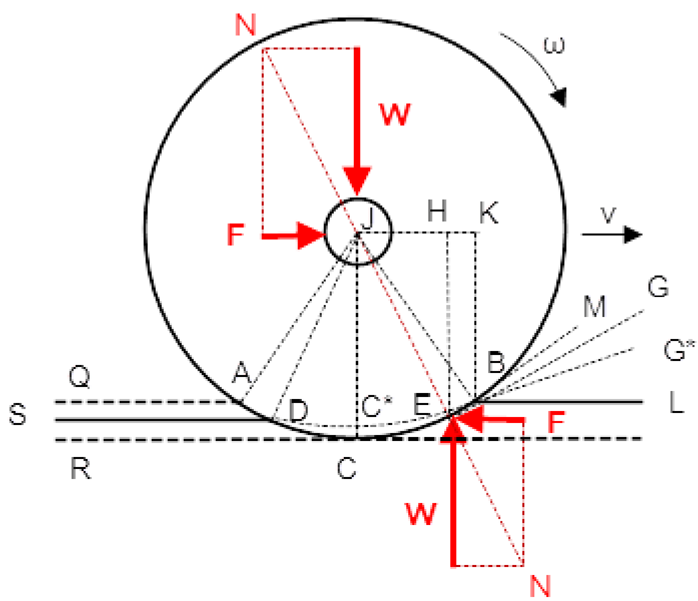

Fig. 2 The rolling wheel model

The rigid wheel rolling resistance is discussed first, followed by that of the wheel with inflated tire. After these two common cases, in the next paragraph, the rolling resistance of the ASW will be explained.

At rest ($\omega = 0$ and thus $v = 0$), a rigid wheel penetrates into its support by depth h_0, which is the distance of the central point C to line L and Q, where line L represents the level ground in front, and Q, behind the wheel. The wheel on a dirt road, having a constant width w, is thus supported by uniform vertical soil stresses of $\sigma = W/(ws_0)$, where W is the vertical gravity load on the wheel and s_0 is the distance between points A and B, which is the contact length. While under the contact area of (ws_0), horizontal shear stresses (τ) are also present, however for being small, here, those are neglected. Thus, W, σ and w defines s_0, which by geometry defines the static penetration depth as $h_0 = r_0-(r_0^2-s_0^2/4)^{1/2}$. On concrete h_0 may be as small as $1/100^{th}$ inches, while on soft soil it exceeds 10". At wheel rest, the resultant of stresses σ is equal W. It is vertical, opposes the gravity load and passes through the wheel hub (collinear with line JC, not as shown).

Fig. 2 illustrates the wheel as towed with force F. However, at rest, F = 0. Had the wheel been lifted from its rest, in plastic soil, such as clay, it would leave an s_0 long, h_0 deep, w wide indentation of radius r_0. In ideal elastic soil, the indentation would instantly disappear, however. In real soils, some indentation would remain, but not as deep as h_0. Calculation of the remaining depth is not given here, for being involved and requiring soil engineering knowledge and data. Neglected is also the discussion on soil strength, which is between 7 and 140 psi. Understanding the stationary wheel penetration to the soil shall help in understanding the rolling mechanism of the same wheel at towing, driving and braking. The towed wheel is discussed next.

In order to move off this wheel from the above-described static penetration, we need to apply a horizontal towing force F to the wheel hub. The wheel now needs to climb a steep grade, which is illustrated by line BM, which is tangential to the wheel perimeter circle at point B, and thus, it is perpendicular to line BJ. The towing force is measurable by dynamometer as towing cable tension. The $\varphi = F/W$ ratio is the tangent of a slope on which, under these forces, the wheel would remain stationary. Expressing that ratio in percentage (100φ) is the grade of that slope (GR). Thus, rolling-off in soft soil, may be considered equivalent of climbing over a road bump (obstacle) of height h_0, facing the wheel by inclination angle MBL = BJC. Angle φ, measured in radians, is also called rolling resistance (RR) or rolling resistance coefficient (RRC). RR, as F/W in lbs/tons is usually measured and tabulated or plotted for common roads, soils and wheels (see Fig. 1 and Fig. 5).

Distributed on the contact area, the soil must resist the applied forces of W and F, which has a resultant normal force $N = (W^2+F^2)^{1/2}$ of inclination angle φ. The normal stresses of the soil must align with N and oppose it. That results in offset of the gravity load W and its balancing vertical force of magnitude W. That offset is denoted by e (eccentricity, $e = \varphi r_0$) and measured between points J and H. Upon rolling, the moment resulting from this eccentricity, $M = eW$, must be equal and opposite to the moment resulting from towing $M = r_1F$, where r_1 is the distance between points E and H. It shall be obvious however, that M may be applied over the hub as torque, when the wheel is not towed but driven.

In any case, for all practical purposes, we assume that φ is small and thus the laws of small angles apply so $F/W \approx F/N$. We also assume that the wheel does not slip, which condition is met, when the *rim-pull* (lbs) = 375 x *hp* x *eff* / *speed* (mph) < F. If unknown, the driving train effectiveness may be taken as *eff* = 0.85. For simplicity, one may calculate *rim-pull*, using the engine's horsepower (hp). At wheel start, when the initial eccentricity is distance JK, which is higher than that of JH, this condition may not be met and limited slippage may occur.

The wheel now leaves a track behind. The soil at level L, in front of the wheel, is depressed to level R (at point C) and recovers to level S behind the wheel. The wheel meets the road at point B and leaves it at point D. On plastic soil, however it would leave it at point C, leaving a track at level R, while on elastic soil, it would leave at point A, leaving a track behind at level Q. For being the wheel rigid, its indentation radius remains r_0, in any of these three cases.

The contact area and the soil stresses may be calculated the same way as that was done for the static case above. The shear stresses however now cannot be neglected, but rather balanced with a uniformly distributed stresses applied upon the vertical area of h_1w, where h_1 is calculated similarly to ho but over distance s_1 between points B and D. The normal stresses of the soil align with the normal force on the wheel, so $\tau/\sigma = \varphi$, while soil stresses shall be below soil strengths.

One may recognize now that braking of this rolling wheel is equivalent to its driving, but with the soil resistance applied as reverse towing force or equivalent reverse torque on the hub. In any case, $F = P/v$, where P is the engine power. P and v may be shown on the vehicle dashboard.

Before advancing to discuss the ASW rolling, we discuss the case of the inflated tire. The rigid wheel on flat and level rigid road case may help in understanding ASW rolling or driving assistance, thus it will be discussed later on.

The inflated tire deforms locally and thus it has larger contact area, which reduces soil stresses and wheel penetration thereof. That implies that lowering the tire pressure on soft soil reduces rolling resistance and therefore eases driving and saves fuel. This case may be assessed the same way as described above, except that the contact curve BCD of radius r_0 now becomes BC*D of radius r_2, where $r_2 > r_0$. Consequently, the tire now needs to overcome a shallower obstacle (dip or bump). Grade G now becomes G*, which is, at point B, tangential to the indentation circle of radius r_2. W and the tire pressure define the tire deflection h_2, which subtracts from h_1, when calculating s_2, the contact length.

The Rolling Resistance of an ASW

In order to transfer towing, driving and braking forces, the ASW has eccentrically arranged push-pull shocks. See that illustrated in Fig. 3.

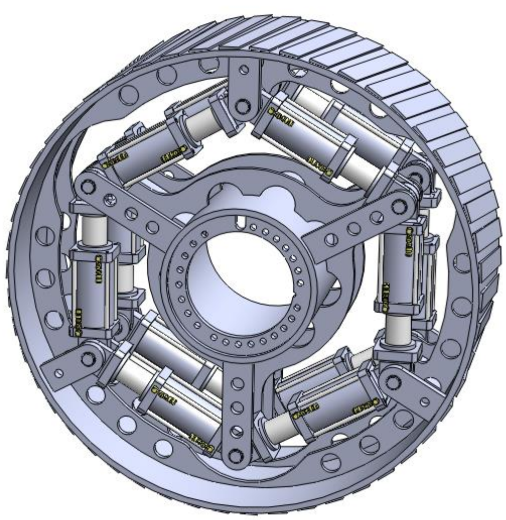

Fig. 3 ASW without side cover restrainer

The ASW has similar benefits to that of the inflated tire, however with further beneficial differences, due to the fact that, tire deflection is substituted with shock deflection (so r_0 does not change) and the hub deflects forward, reducing φ. The shocks are elastic air springs, hence the hub deflection. Under W, the hub also deflects downward. In every ASW revolution, the spokes, which are pre-compressed (pressurized and thus remain compressed at all times), are compressed under the hub and decompressed above it. That is similar to tire wall deflection, alas more favorable. The air heating and cooling in a ASW-revolution duty-cycle cancels, so only hysteresis generates heat, which originates in shock viscosity and friction. That heat however is effectively cooled, for metal is heat conductor, while rubber is an insulator. In a rolling inflated tire, the tire pressure remains constant, and thus the cooling cycle is not present. The repeated tire wall deflection, due to rubber viscosity, however accumulates tire heat.

The rolling ASW model is illustrated in Fig. 4, however, for simplicity, with the general soil only.

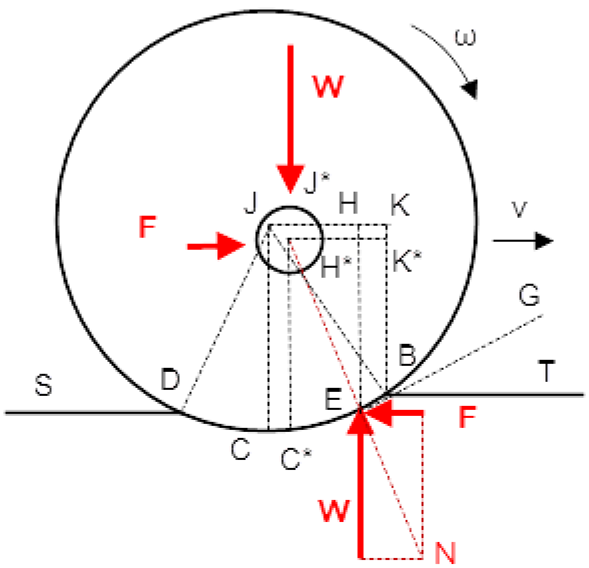

Fig. 4 The rolling ASW model

Due to the hub offset, points C, J, H and K are now moved to C*, J*, H* and K*. Consequently, distances JC, JH and JK are reduced to J*C*, J*H* and J*K*. Both the initial and the maintained rolling resistances are reduced thereof (e* = J*H* < e = JH). The differences of these distances are elastic displacements, which are obtained by dividing the forces by the spring-constants.

One may recognize that both the inflated tire wheel and the ASW rolls on soft soil with smaller rolling radius and larger contact radius than the rigid wheel do. Hence, if the ASWs flexibility is harmonized with that of the tire flexibility, the reduction in rolling resistances must be commensurate. An ASW configured that way may be used to substitute wheels with inflated tires. However, the ASW would never get flat, and may never skid on ice or snow, for its flexible hub-to-rim connection limits torque and thereby it can reduces vehicl maintenance need and the associated downtimes by 20%(-). At rolling off from a ditch, the spokes deflect until W move over point B, and the ASW rolls off effortlessly. The same happens at mounting a road bump.

Measured Rolling Resistances

Engineering standards classify soils, dirt roads and pavements, as well as vehicle wheels.

In the US and some other countries, the Unified Soil Classification System (USCS) is often used for soil classification [2]. Other classification systems include the British Standard BS5390 and the AASHTO [3] soil classification system.

Classification of sands and gravels

In the USCS, gravels (given the symbol *G*) and sands (given the symbol *S*) are classified according to their grain size distribution. For the USCS, gravels may be given the classification symbol *GW* (well-graded gravel), *GP* (poorly graded gravel), *GM* (gravel with a large amount of silt), or *GC* (gravel with a large amount of clay). Likewise, sands may be classified as being *SW*, *SP*, *SM* or *SC*. Sands and gravels with a small but non-negligible amount of fines (5 % - 12 %) may be given a dual classification such as *SW-SC*.

Classification of silts and clays

According to the Unified Soil Classification System (USCS), silts and clays are classified by plotting the values of their plasticity index and liquid limit on a plasticity chart. The A-Line on the chart separates clays (given the USCS symbol *C*) from silts (given the symbol *M*). LL=50% separates high plasticity soils (given the modifier symbol *H*) from low plasticity soils (given the modifier symbol *L*). A soil that plots above the A-line and has LL>50% would, for example, be classified as *CH*. Other possible classifications of silts and clays are *ML*, *CL* and *MH*. If the Atterberg limits plot in the "hatched" region on the graph near the origin, the soils are given the dual classification 'CL-ML'.

Common rolling resistances for construction vehicles are shown in Fig. 5. The plots were generated from the table given in Ref 1 (Ch. 6, p.145). The RR values of the ASWs, as calculated above, are added for reference.

The construction and mining industry uses simplified rolling resistance (RR in lbs) calculations [1], as follows:

RR = {40 + (30 x TP)} x GVW, where TP is the tire penetration in inches and GVW is the gross vehicle weight in tons. Dividing this RR by 20, thus gives the equivalent grade in %.

Others use experimental RR data or calculated resistances based on wheel penetration as described above for both the wheel and the ASW. From Fig. 5, the advantage of the ASW over the wheel is seen eloquently.

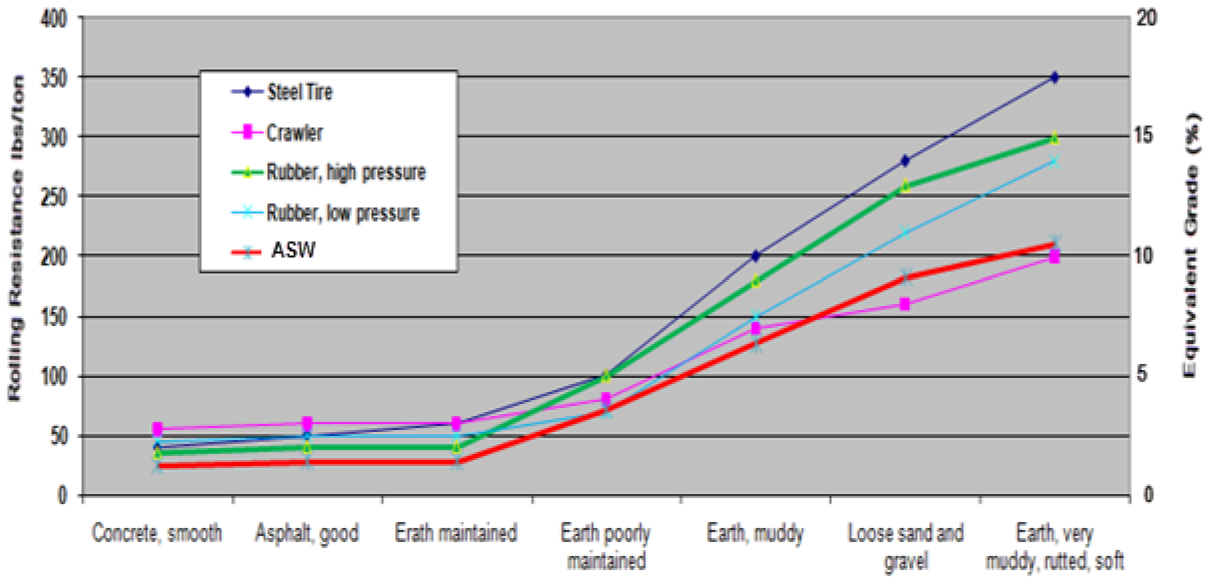

Fig. 5 Common construction/mining/agricultural/military vehicle rolling resistances compared

Fuel Savings due to Reductions in Rolling Resistances

Vehicles spend considerable energy to overcome rolling resistance. For example, on average, passenger cars and vans 20%, trucks 33% and construction or mining trucks 50%. For having different efficiencies and average fuel consumptions, to save 1% fuel, these vehicles need to reduce rolling resistance by 5%, 3% and 2% correspondingly [4]. Hence, one may perceive that the ASW helps best in construction, mining, agriculture and in the military. Wheel speed and size may impose some limitations in other applications.

Fuel savings due to rolling resistance reductions, calculated as described above, is shown in Fig. 1, where for simplicity, the ASW is compared only to the most commonly used high-pressure inflated tire. The ASW in construction and mining may save up to 14.5% fuel on paved roads, 15% on dirt roads and soft off-roads. The average fuels savings is about 12%(-).

The ASW Rolling Assistance

Whether it is towed or driven by engine torque, rolling downhill or uphill, the hub of the ASW gets ahead of its ground contact line. The gravity load on the wheel thus has a positive torque, which helps the towing or the driving and reduces the rolling resistance. That reduction is equivalent to an added downward slope, which adds negative rolling resistance (rolling assistance).

Towing and driving a wheel or ASW is equivalent, involving the same forces and torques. Since the more a towing force pulls the hub forward, the more it deflects forward. The gravity load on the hub thus will have an eccentricity forward. That adds a torque, equivalent to driving, which in turn, further adds an incremental amount of eccentricity, alas in gradually diminishing extent. The settling eccentricity may be 50% larger than the first increment. This is called the P-Δ effect. This effect is larger for softer shock stiffness, but independent of the ASW size.

In reference to Fig. 4, we may say that a ASW on rigid flat road R, under the hub loads of W and F, is supported at point C (not E). Then the load eccentricity is e, which is distance JH, and the height difference of points E and C is h. The equilibrium of the works done by W and F then requires that hW = eF, from which we obtain that F/W = φ = h/e. Now, since e = φr*, h = r*[1-(1-$\varphi^2)^{1/2}$], where r* is the apparent rolling radius (distance J*E). Thus, e/h is the measure of the first order amplification effect of the hub pushing forward. The P-Δ effect modifies this, and the amplification factor will simplify to AF=1+2ε/(1-ε), where ε is the shock strain (its deflection under load divided by its unloaded length). Fig. 6 illustrates AF (also called gain):

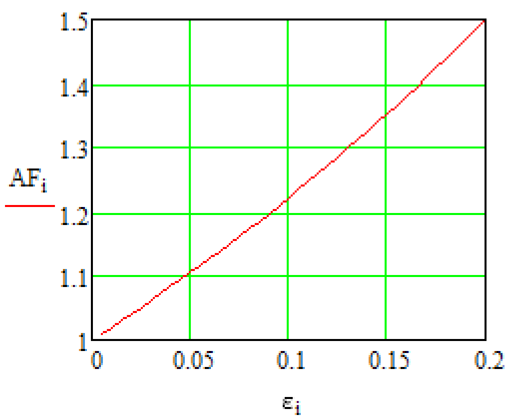

Fig. 6 The amplification factor vs. the shock strain

Conclusion

The ASW (air suspension wheel) is a unique wheel, capable to reduce rolling resistance and thereby to save fuel. It substitutes tire flexibility with eccentrically arranged air shock elasticity. Instead of deforming the tire locally at the contact with the road, the shocks act as air springs, allowing the hub to advance within the rim over the point of support, thereby reducing the resistance against rolling by up to 30% (rolling assistance).

Mining/construction/agricultural/military trucks can save 15% fuel thereof. The air spring cools down at down loading as much as it heats up at uploading once in every ASW revolution. The limited heat, generated by the shock friction, demands much less cooling than tire flexing does. The metal shock, for being a heat conductor, cools more effectively than the rubber tire, which is a heat insulator. The ASW is flat proof, fireproof, bulletproof and may be driven soft or hard. It may not skid on ice or snow. Its elastic hub-to-rim connection is torque limiting, which reduces vehicle downtime and cost for vehicle maintenance by up to 20%.

References

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