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Raymond M. Brach
University of Notre Dame
Notre Dame, IN

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Raymond M. Brach
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ABSTRACT

More and more stores and catalog mail order houses have been offering the consumer a new type of towing device. Braided ropes and woven straps are being sold as replacements for towing chains and cables. Usually made from polypropelene or similar materials, they are strong, lightweight, inexpensive and easy to use. Unfortunately they are also easy to misuse; serious accidents have occurred. This paper presents a force, deflection and energy analysis of these straps in some idealized, but typical situations. It is shown that the relatively high strength but low flexibility can lead to point-of-attachment failures.

INTRODUCTION

Various methods are used to extract vehicles which are immobilized due to conditions of snow, mud, sand, rough terrain, etc. The most common commercial methods use tow trucks and/or power winches for extractions. Many people use other road vehicles such as automobiles, pickup trucks, four wheel drive utility vehicles, etc., with devices such as chains, ropes, cables and straps. Unfortunately, these latter devices are often used improperly and used in situations where they are inappropriate. Recently, this is more true of the relatively flexible devices such as polymer straps, web slings and braided ropes. These have become popular because they are soft, lightweight and occupy small volumes. They are also inexpensive and readily available in drug stores, service stations, and mail order catalogs. These straps have come with advice to take advantage of their high flexibility by starting with a slack device and bringing the tow vehicle up to a running start [1]. This takes advantage of the momentum of the tow vehicle in the extraction process but can be dangerous and must be done with extreme care. It is the purpose of this paper to examine the forces and stored energy in these devices and their attachments under severe, but physically realistic, situations.

Figure 1 shows a pickup truck with a tow device attached to a rear hitch. The other end of the device is attached to a vehicle being extracted (not illustrated). It is assumed that the stuck vehicle does not move until some threshold force is exceeded. In practice this threshold varies greatly. One of the goals of this paper is to examine upper limits on the tow device force, so the threshold is assumed to be always greater than the capability of the tow vehicle's pulling force which in turn is limited by traction and momentum.

Many properties of different tow devices are important to their utility. For this study, stiffness in tension is the most significant. A heavy chain in tension has negligible elongation compared to a braided rope, for example. A major consequence of the difference in stiffness and the existence of a threshold force is the large disparity between devices for energy storage. Recall that potential energy is the area under the force deflection curve. Figure 2 illustrates that for a given force, F_0, the potential energy stored in each device during use can differ greatly depending upon stiffness.

With these concepts in mind, . a mass-spring model is set up to examine the dynamics of the tow vehicle and device. See Figure 3. Some flexible devices are kept slack for a distanced while the tow vehicle gets up to speed and "snatches" the stuck vehicle. This is taken into account in the model. First, a linear model is examined since a general analytical solution can be obtained easily. But braided and woven devices can be quite nonlinear; computer solutions are obtained for these.

The method of attachment of any of these vices is critical from the point of view of safety. Although specific methods are not considered in this paper, the results found here directly relate to the importance of proper attachment. In fact, if an attachment method fails, it is the stored elastic energy of the tow device which is suddenly released. Reference to Figure 2 and specific results found later, show that the energy can be significant for flexible devices.

CONCEPTS AND ASSUMPTIONS

The process of using a tow vehicle and a tow device to extract a stuck vehicle consists of numerous interrelated and complicated events. With the tow device attached, the driver accelerates the tow vehicle until the device is taut and then typically with visual feedback regulates acceleration. When the stuck vehicle begins to move or some other event occurs (wheel slip, excessive device stretch, etc.) the accelerator pedal position is again modified. Driver reaction, drive train response and traction properties are difficult to model; the number of realistic scenarios is unlimited. To eliminate this complication from the modelling process, a constant traction force will be assumed during the extraction process. Though constant, rious values will be examined to cover different traction conditions. The tow force is assumed parallel to the ground and along the axis of the tow vehicle.

As stated earlier, an extreme case approach is taken by assuming the stuck vehicle does not move significantly until some threshold force is reached. A mechanical model then resembles a mass-spring system with the base of the spring rigidly attached as in Figure 3. As stated earlier, the traction force, F_t, is to be constant and the spring can be linear, with rate k, or nonlinear. The quantity m represents the mass of the tow vehicle.

Consider for a moment what happens to this model when the force threshold is exceeded. Instead of the end of the tow device connected rigidly, it should then be connected to another mass, that of the stuck vehicle. The model becomes a two degree-of-freedom system, instead of the single degree-of-freedom system shown in Figure 3. Consider further that as the stuck vehicle begins to move the tow force will begin to decrease under almost all conditions. Consequently, the peak device force occurs at the threshold. To determine peak forces and energy storage, calculations only up to the threshold are necessary. Since the actual lue of the threshold depends upon individual ircumstances, calculations will be carried out until the largest force possible is reached, limited by the traction (tire-ground friction) of the tow vehicle. It is assumed that the device does not fail; its performance is dictated only by its force-elongation characteristics.

LINEAR ANALYSIS

If the tow device is linear, the mechanical system shown in Figure 3 is a linear single degree-of-freedom system covered in numerous vibrations text books. If the force is constant and suddenly applied, the displacement is given by

$$x(t) = F_t(1 - \cos \omega_n t)/k \qquad (1)$$

where $\omega_n^2 = k/m$. Eq. 1 corresponds to zero displacement and velocity at the instant the device becomes taut and the force is applied. Since the force in the device is kx(t), Eq. 1 indicates a force which grows from zero to as high as twice the traction force, F_t. (The maximum force reached in a given situation depends upon the threshold if the threshold is lower.) If the vehicle gets a "running start" with speed v_o when the device becomes taut, the displacement is

$$x(t) = \frac{F_t}{k}(1 - \cos \omega_n t) + \frac{v_o}{\omega_n} \sin \omega_n t \,. \qquad (2)$$

The corresponding force is

$$F(t) = k\,x(t) = F_t + k[(\frac{F_t}{k})^2 + (\frac{v_o}{\omega_n})^2]^{1/2} \cos(\omega_n t - \phi) \qquad (3)$$

where ϕ is a phase angle dependent upon $-v_o/F_t$. The force reaches a maximum when $\cos(\omega_n t - \phi) = 1$, so

$$F_{max} = F_t + [F_t^2 + mkv_o^2]^{1/2} \,. \qquad (4)$$

If the speed v_o is reached due to a constant tractive force F_t, then

$$v_o^2 = 2F_t d/m \qquad (5)$$

where d is the distance covered with full traction during the running start, then

$$F_{max} = F_t\left\{1 + [1 + 2\frac{kd}{F_t}]^{1/2}\right\} \qquad (6)$$

$\leftarrow$ ok!

Figures 4 and 5 show this maximum force plotted for a wide range of linear tow device stiffnesses and for a tow vehicle with a weight of 1800 kg (17650N, 3968 lb). Figure 4 corresponds to a running start of 1.0 m and Figure 5 to 2.0 m. Both display maximum force as a function of a traction coefficient, μ, which is the ratio of the tractive force to vehicle weight, $\mu = F_t/W$. For a running start, d = 0, the maximum force is always $2F_t$. Figures 6 and 7 display the corresponding maximum potential energy stored in the tow device.

NONLINEAR STRAP ANALYSIS

Before discussing the significance of these force and energy levels, consider a specific device, a nylon strap. Figure 8 shows a force deflection curve for a typical two inch wide, commercially available nylon strap. The final point on the curve approximately represents failure of the strap. Because of the nonlinearity of this curve, the solution of the dynamics problem solved earlier must be obtained numerically. The scenario used with this strap is the same as before. Constant traction for the tow vehicle is used (with the traction coefficient expressed as a fraction of the vehicle's weight) and the stuck vehicle is assumed to be rigidly imbedded. The maximum tow strap force and potential energy are found by numerical integration of the differential equation of motion. Figures 9 and 10 show these quantities for various values of slack length of the strap (a "running start" for the tow vehicle).

DISCUSSION

The results from the linear and nonlinear analyses show significant differences. Comparisons can be made on the basis of an equivalent linear stiffness [5] for a nonlinear system. An equivalent stiffness for a nonlinear system is that stiffness of a linear system which causes the same maximum potential energy and the same maximum displacement. For example, from Fig. 10, for d = 1.0 m and for a traction coefficient of 0.4, the maximum potential energy is 14 kN-m (10300 ft-lb). The corresponding maximum stretch is about 0.95 m (3.1 ft). The equivalent linear stiffness is about 30 kN/m (2060 lb/ft). For this linear stiffness (Fig. 4), a maximum force of about 30 kN (6750 lb) is predicted. This contrasts with a value of 41 kN (9200 lb) from the nonlinear analysis (Fig. 9) and demonstrates that the linearized analysis can be inaccurate and on the low side for maximum force calculations.

Although in specific cases, the nonlinear and linear analyses may predict different results, the trends from both are the same. In general, the results show that the lower a device's stiffness, the lower its maximum force level but the higher its potential energy. Higher stiffness devices show the opposite trend, higher forces but lower potential energy. On the other hand, the stiffer the device, the more rapid the rise time to the peak force. High stiffness devices cause shock loading particularly if used with a running start (initially slack device). In fact it is the elimination of this shock that is claimed to be one of the advantages of the low stiffness devices. Unfortunately this is not really an advantage. Because of the potential for shock loading most people would not think of using a running start with a slack chain. This effectively imposes a practical force limitation based on traction for stiff devices.

With a flexible device, and for the scenario analyzed, relative force levels are lower than chains or cables. Though relatively lower, they can be higher than safe levels. In addition, the higher potential energy can be dangerous. Consider an example. A commonly used method of attachment is a trailer hitch ball. Current standards [2,3] permit Class 1 hitch balls to have a breaking strength of 26.7 kN (6000 lb). Linear system results show that this force level can be reached by a flexible device. The nonlinear analysis does also. Fig. 9 shows that for a traction coefficient of 0.4 and a slack length of 1/2 meter, a hitch ball failure could occur. Furthermore, if a hitch ball failed and the strap's potential energy propelled it (as a slingshot), it is not difficult to show that its speed could become well over 100 m/s (220 mph).

The more flexible devices have some definite advantages over cables and chains in the area of consumer convenience. On the other hand they can be dangerous if used improperly or without care.

REFERENCES

1. Madigan, Tom, "Snatch-Um Strap," Off Road Magazine, December (year unknown), p. 64-65.

2. SAE Standard J684f, SAE, Warrendale, Pennsylvania.

3. Regulation V-5, "Minimum Requirements for Motor Vehicle Connecting Devices and Towing Methods," Vehicle Equipment Safety Commission, Washington, DC, July, 1977.

4. Paul, W., "Failure of a Nylon Strap Tow Connection," Technical Report 0258, Annapolis, MD, 1985.

5. Thomson, W.T., Theory of Vibration with Applications, Prentice-Hall, Englewood Cliffs, 1981.

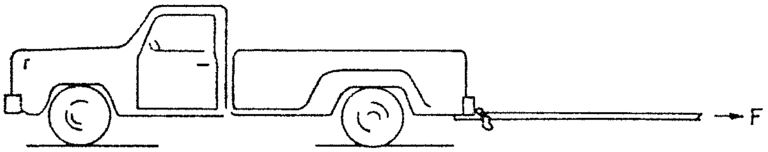

FIG. 1: Tow Vehicle and Extraction Force

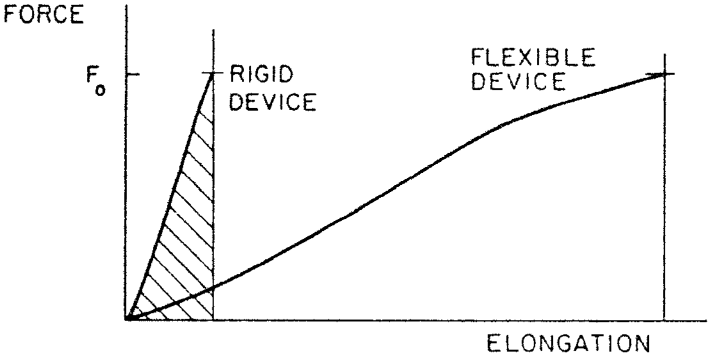

FIG. 2: Comparison of Potential Energy (Area under the Curves) for Differing Device Stiffness

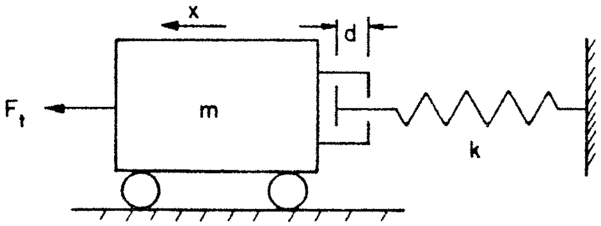

FIG. 3: Equivalent Mechanical Model

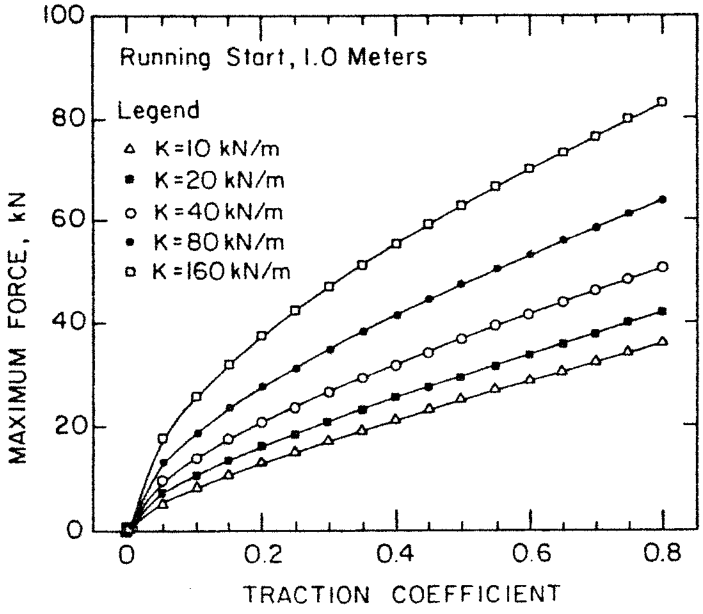

FIG. 4: Maximum Force Developed in Tow Device; Linear Analysis with 1.00 m Running Start

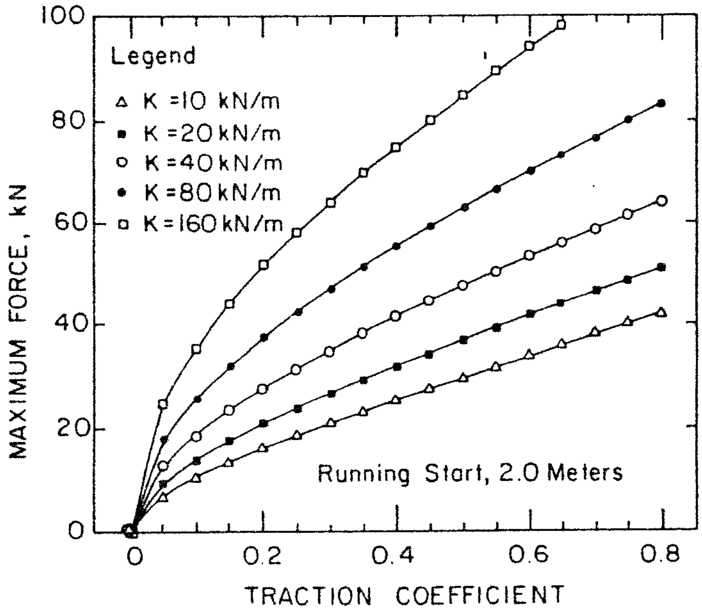

FIG. 5: Maximum Force Developed in Tow Device; Linear Analysis with 2.00 m Running Start

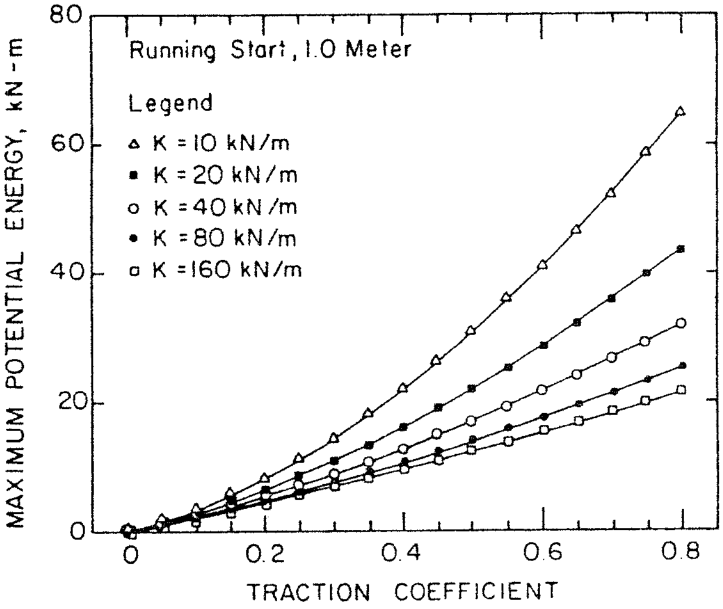

FIG. 6: Maximum Potential Energy Developed in Tow Device; Linear Analysis with 1.00 m Running Start

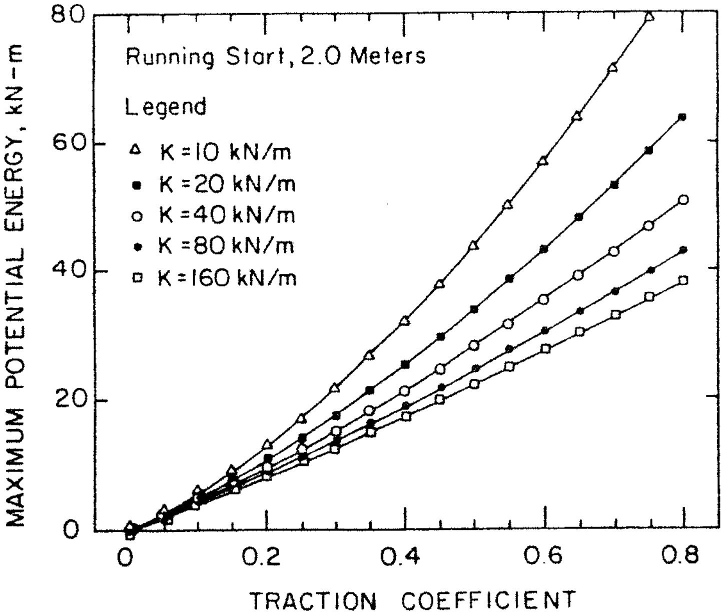

FIG. 7: Maximum Potential Energy Developed in Tow Device; Linear Analysis with 2.00 m Running Start

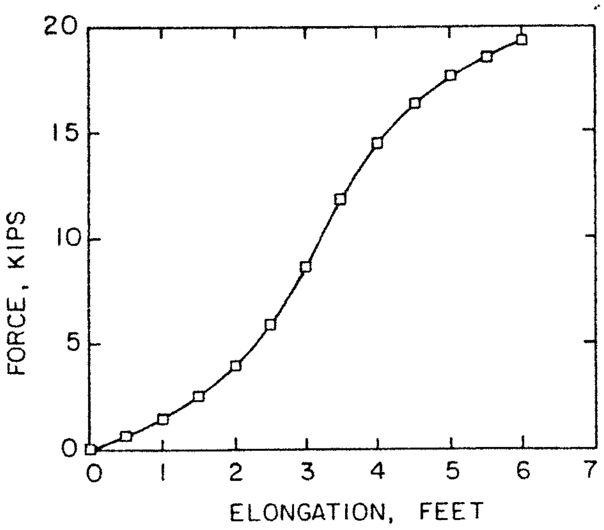

FIG. 8: Typical Force Deflection Curve for a 28 ft, Two Inch Wide Nylon Strap with 9800 lb/in Ultimate Strength

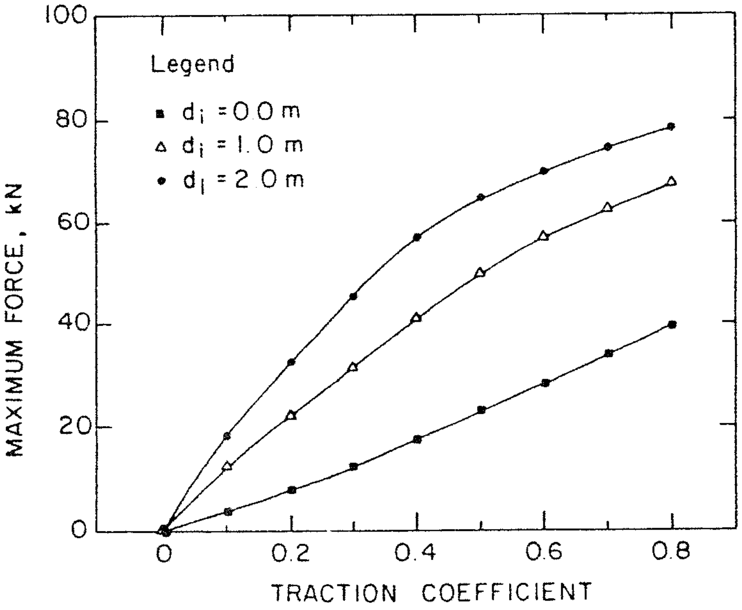

FIG. 9: Maximum Force for 2 Inch Nylon Strap

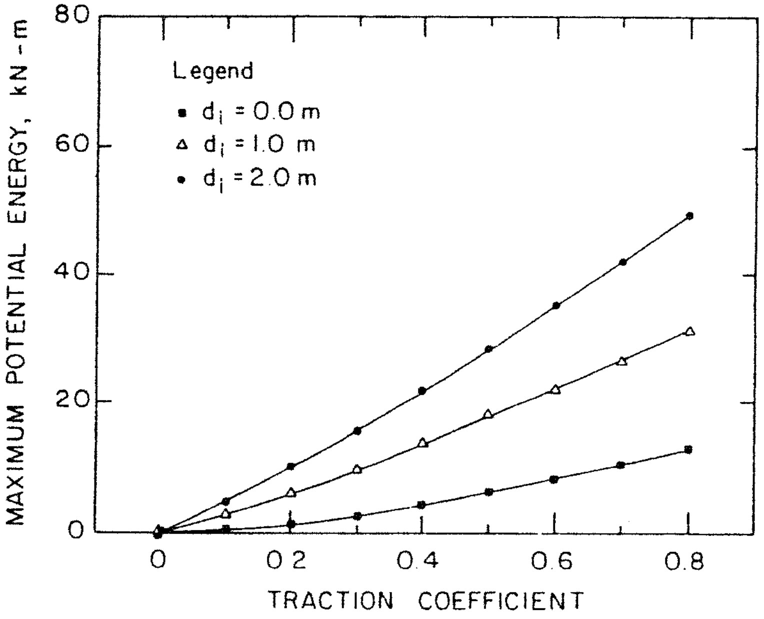

FIG. 10: Maximum Potential Energy for 2 Inch Nylon Strap