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SAFETY BRIEF

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5950 West Touhy Avenue Niles, IL 60714-4610 (847) 677-4730

FAX: (847) 647-2047

e-mail: infoserv@triodyne.com

Vehicle Lifts: The Hyperstatic Problem

by Ralph L. Barnett[1] and Peter J. Poczynok[2]

Abstract:

Occasionally, vehicles topple off of structurally sound automobile lifts, even when they are properly supported at their lift points. This happens with a family of lifts that use four arms to position lifting pads under the vehicle chassis. The arms operate in a horizontal plane and are positioned by swinging and telescoping. Gravity loading of the pads and the attendant horizontal friction resistance cannot be relied upon to maintain the set-up position of the pads. There is a non-obvious structural phenomena called hyperstatic behavior that may easily lead to minimal, or even zero, pad loading with the attendant loss of resistance to horizontal pad movement. Unless otherwise restrained, the bumping and jostling associated with vehicle maintenance can produce random forces that will push a pad from beneath the vehicle. The resulting three-point support almost always leads to toppling of the vehicle from the lift.

I. INTRODUCTION

The four arms shown in Fig. 1 are outfitted with four lift pads to support a vehicle from beneath its chassis at lift point locations specified by the vehicle manufacturer. To gain access to vital repair sites, mechanics may select other lift points that will

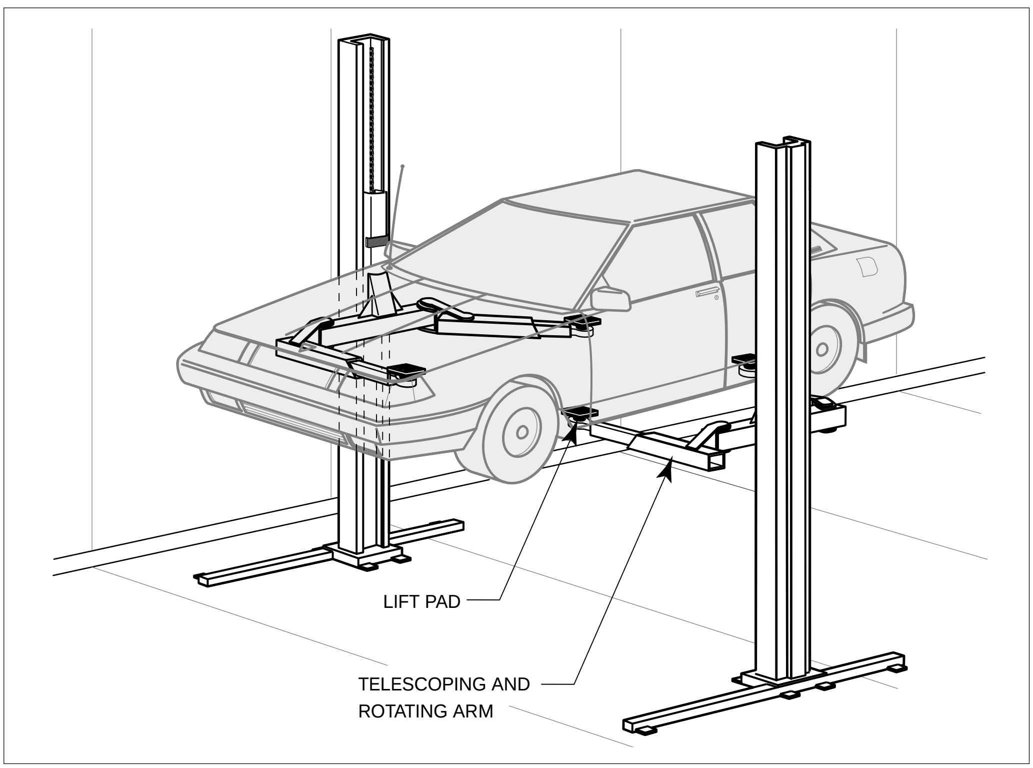

Fig. 1 Vehicle Lift

[1] Professor, Mechanical and Aerospace Engineering, Illinois Institute of Technology, Chicago, and Chairman, Triodyne Inc., Niles, IL.

[2] Mechanical Engineer, Triodyne Inc., Niles, IL.

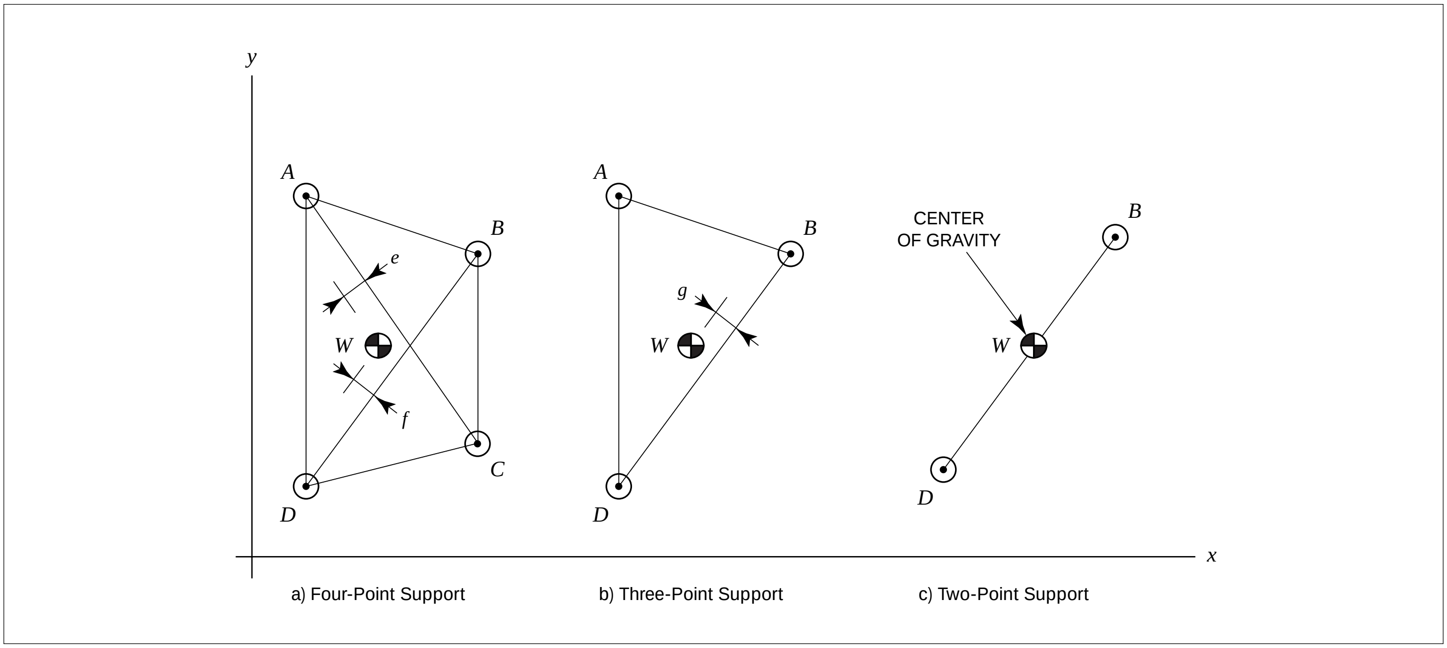

Fig. 2 Equilibrium Configurations for Lift Pads

also resist lifting forces without causing vehicle damage. Generally, the support surfaces are horizontal and maintain the vehicle in a level attitude. On this basis, each pad gives rise to a vertical reaction force and the four forces acting together must equilibrate the downward gravity forces acting on the vehicle.

There are three possible equilibrium configurations that may be encountered while supporting a vehicle. These are indicated in the plan views of Fig. 2 for the four, three, and two-point support scenarios. For each configuration the upward reaction forces are symbolized using circles with a center point, ⊙ ; the downward force representing the total vehicle weight W applied at its center of gravity is shown as a partially shaded circle, ◒. In each figure the reaction pads are connected by straight lines; the outermost defining the vehicle's footprint. If the center of gravity of the vehicle is not outside of the footprint, the vehicle will not overturn. When tipping or toppling occurs, it is always a rotation about one of the boundary lines; e.g., in Fig. (2a) overturning may be about $\overline{AB}$, $\overline{BC}$, $\overline{CD}$, or $\overline{DA}$.

If support pad D in Fig. (2a) were to vanish, the center of gravity would lie outside of the triangle ABC and the overturning moment eW would topple the vehicle about the line $\overline{AC}$. Similarly, if pad A disappears, overturning occurs about $\overline{BD}$ under a moment fW. On the other hand, either pad B or C could be eliminated leaving, respectively, equilibrating triangles ACD or ABD containing the vehicle's center of gravity. The tripod support represented in Fig. (2b) will equilibrate the vehicle as long as the center of gravity does not fall outside the footprint; if it is exactly centered on the border $\overline{BD}$, $g = 0$, pad A is unloaded and the two-point force system of Fig. (2c) is obtained.

To complete our elementary discussion of equilibrium it should be noted that the usual six equations of static equilibrium are reduced to three when all of the forces are parallel (up and down). The summation of forces in any two horizontal directions gives no information concerning the vertical forces. Furthermore, vertical forces cannot produce twisting about a vertical axis. Consequently, with reference to the four-point system, the three available equilibrium equations relating the various pad forces may be written as:

$$F_A + F_B + F_C + F_D = W \qquad \text{Eq. (1)}$$

$$\sum M_x = 0 \qquad \text{Eq. (2)}$$

$$\sum M_y = 0 \qquad \text{Eq. (3)}$$

where F_A, F_B, F_C, and F_D are the unknown upward forces at pads A, B, C, and D respectively and where Equations 2 and 3 represent respectively the moments about the x and y axes shown in Fig. 2. Observe that there are four unknown reaction forces for the Four-Point Support system with only three equilibrium equations. This condition is known as statically indeterminate or hyperstatic to the first degree. To solve for the unknown pad forces, we need another equation which, unfortunately, cannot be furnished physically for the four-point system. The total pad forces, according to Eq. 1, must always add up to W; but, their distribution is always elusive. The force distribution will depend on, among other things, the preloading of the pads, the flexibility of the pads and arms, the flexibility of the chassis, the temperature profile of the lift, and the location of the vehicle's center of gravity which varies with fuel level and the addition and elimination of vehicle elements. Because it's a moving target, it is difficult to measure and interpret the force distribution. On the other hand, if the center of gravity is known, the three equations of equilibrium given by Equations 1, 2, and 3 precisely determine F_A, F_B, and F_D for the three-point system; the same is true for F_B and F_D on the two-point system. When systems are

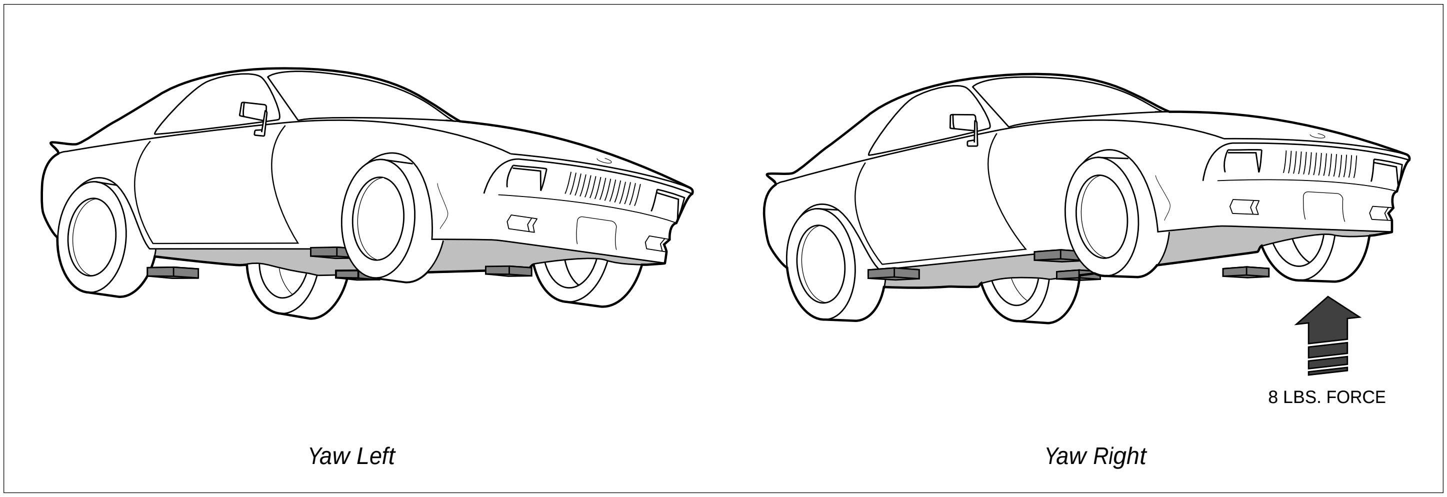

Fig. 3 Dual Equilibrium Status

statically determinate, the force analysis is unrelated to stiffnesses, temperature distributions, differential settlement of the support columns, and the like.

Safe vehicle lifts cannot be determined by equilibrium conditions alone in the sense that a ball supported on a pin represents a precarious equilibrium state. This is precisely the state represented by the two-point support shown in Fig. (2c) where the slightest perturbation causes the vehicle to fall to the right or left of line $\overline{BD}$. Because the center of gravity of most automobiles lies close to the diagonals shown in Fig.(2a), it is very easy to produce a "near" two-point support condition by simply backing off (loosening) one of the support pads, e.g., pad A. This gives rise to a dual equilibrium status in the sense that a few pounds of external vertical force can rock the automobile about line $\overline{BD}$. This condition is illustrated in Fig. 3. We all experience this instability phenomenon whenever a chair or table leg is too short. The balancing act represented by the two-point support system illustrated in Fig. (2c) can be duplicated precisely in the four-point system when the center of gravity is located at the intersection of the two diagonals $\overline{AC}$ and $\overline{BD}$. As previously noted, the three-point system mimics the two-point system when the center of gravity falls exactly on the line $\overline{BD}$. In all three cases, the spacial loads can be characterized as coplanar and parallel; either condition represents a classically unconstrained system for the general loading of a rigid body [Timoshenko, Ref. 1]. The real differences among the three systems lie in the observation that, in the two-point system, toppling will occur to the right or left when the vehicle is perturbed; the three-point system allows toppling to the right but catches the vehicle if it tries to overturn to the left; the four-point system catches the vehicle in either direction of rotation and avoids an accident.

II. HYPERSTATIC STRUCTURAL BEHAVIOR

The safety problem presented by the four-point vehicle lift is entirely related to the fact that the pads can be moved out of their set-up position giving rise to either a dangerous three-point or two-point system which is unstable or nearly unstable. Historically, the only physical mechanisms for retaining the pads in position were the small internal friction in the telescoping and swinging support arms and the horizontal frictional restraint on the pads associated with and proportional to the large vertical reaction forces developed to support the vehicle. Consequently, if a vertical force becomes very small, its associated horizontal pad restraint almost completely disappears.

The example of a chair with three long legs and one short one illustrates how one or two legs can be completely unloaded as the chair is flip-flopped between equilibrium positions. Indeed, mechanics avoid such an obvious condition by strong-arming a vehicle after raising it only a few inches off of the floor. They reset the arms and pads if the vehicle rocks. Unfortunately, the problem is more insidious and will not manifest itself through visual and tactile feedback. All four pads can be in contact with a vehicle when one or two reaction forces are almost zero. Clearly, there is no visual feedback indicating the critical contact status. Furthermore, the stiffness of a system with four heavily loaded pads is identical to a system in which one or two pads have very small reaction forces but which nevertheless maintain the vehicle/pad contact while the mechanic rocks and manhandles the vehicle in his checking mode. Attempts to tighten one pad may actually loosen other ones. Thus, small contact forces may not be uncovered and their concomitant horizontal friction components may not maintain the pad positions under the expected load environment associated with vehicle maintenance.

III. CODES AND STANDARDS

Recognizing the danger associated with random movements of the pads, the vehicle lift industry has promulgated several standards governing the design of the lift arms.

ANSI B153.1-1990; Automobile Lifts-Safety Requirements for the Construction, Care, and Use:
4.1.5 Arm Restraints.

> *Frame-engaging lifts not having a rigid superstructure, or portion thereof, under the raised vehicle shall be provided with swing-arm-pivot restraints capable of resisting 150 pounds of horizontal force at the end of the fully extended arm.*

German Accident Prevention Regulation; Lifting Platforms; VBG 14; April 1, 1977:
Platforms: C1. 17.

(7) Articulated joints on vehicle lifts shall be automatically secured against inadvertent movement. The securing devices shall be effective by self-locking or positive locking, even if the articulated joint is not under load.

German Accident Prevention Regulation; Lifting Platforms; VBG 14; January 1, 1995;
Loading devices.

Section 17 (1) Loading devices have to be built and attached in such a way that they can not swing, can not tilt unintentionally, can not rotate unintentionally and can not shift. Individual parts are not allowed to be loosened unintentionally.

Section 17 (7) At vehicle lifts the loading devices which are designed as linked arms have to have compulsory protection against unintentional movement. The protections have to be effective through self-locking or positive mechanics, even for non-loaded link arms.

To Section 17 Subsection 1 Sentence 1:
Implementation instruction

Movements of the loading device caused by its construction to compensate for small angle and rigging up inaccuracies are not considered swinging, unintentional tilt, rotation or shift.

Remark

At double column vehicle lifts the swing arms are often designed telescopic in order to shift them for loading in the lengthwise direction. In general, one can assume that an unintentional shift of the arms is blocked sufficently due to the friction between the individual telescope parts. Fixed end stops to limit the telescope path exist in order to avoid that the individual telescope parts can be unintentionally disengaged or that they be extended too far apart, which at loading could lead to higher bending moments for which the lift is not designed.

A different situation, however, exists if the individual telescope parts are in roller guide shoes. Then under any circumstances protection has to exist in order to prevent unintentional shifting.

To Section 17 Subsection 7:
Implementation instruction

For vehicle lifts with linked (hinged) arms, the lifted vehicle can slide off under the influence of side forces, if the loading points under the vehicle are located too close together. A furthest apart position of loading points should therefore be desired. Side forces can result, for example, from entering the vehicle or from work at the vehicle.

Remark

The loading arms of a vehicle lift are called linked arms if they are connected to the lifting device through a link which allows them to swing in the horizontal plane. The arms themsleves can be designed as telescopic arms or a second link can be built into the arm in order to angle the arm for the vehicle pick-up. In the latter case one also refers to double linked arms.

The length of the linked arms does not play a role in regard to the compulsory protection against unintentional movement. Furthermore, it is unimportant if the arms grip underneath the vehicle from the outside or from the inside.

The linked arm protection has to be dimensioned for a force which is at least 3% of the bearing capacity of the lift; if such calcuated force is less, it has to be at least 750 N. Here it is assumed that the force is applied in the horizontal direction perpendicular to the completely extended, respectively stretched linked arm and the force attachment point is located in the vertical axis of the vehicle pick-up plate. From this force, resulting stresses are not allowed to exceed, at any location of the linked arm, the allowed stresses of the utilized material.

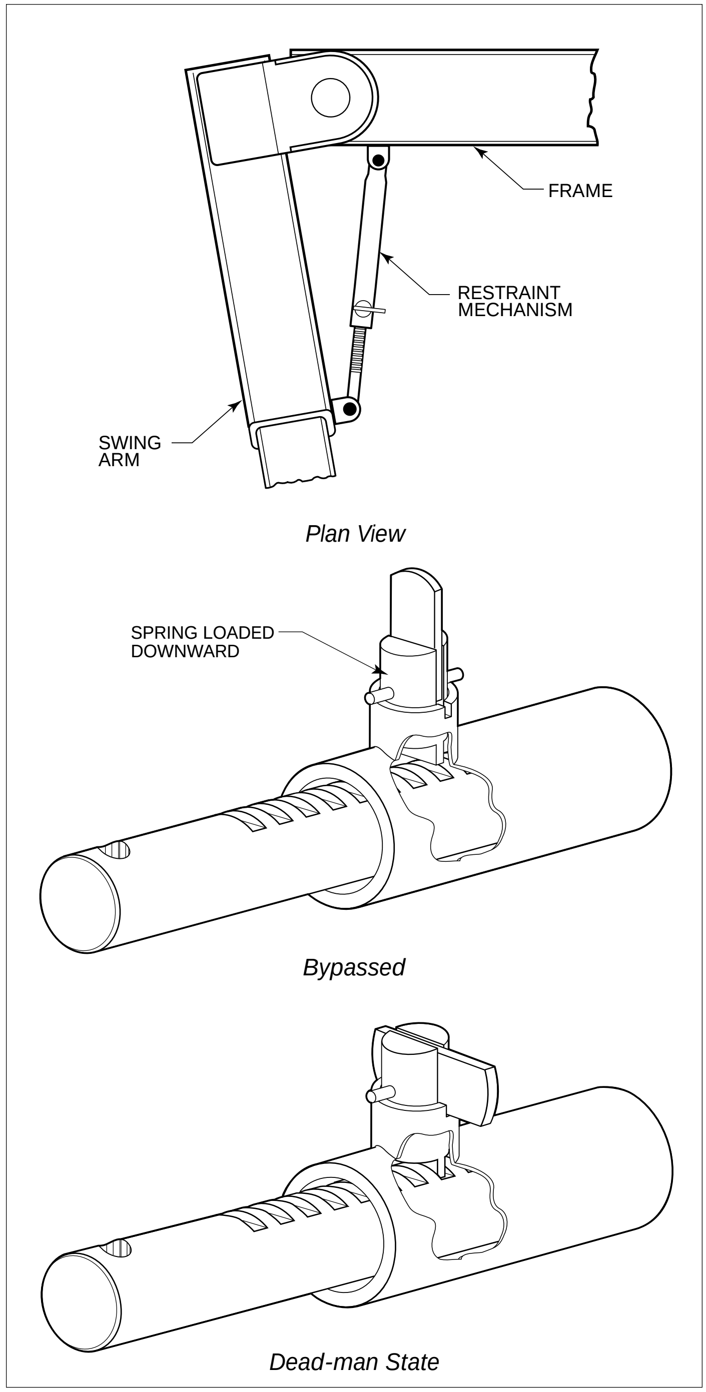

Fig. 4 Telescoping Swing Arm Restraint Mechanism

Each of the three standards calls for restraints against the pivoting motion of the non-loaded swing arms but not against the telescoping motion. Nevertheless, the standards require that horizontal forces of 150 lbs. and 750 Newtons be resisted. It is inexplicable that forces available for causing rotation are not also available for producing telescoping.

IV. LOCKING SYSTEMS

Swing restraint mechanisms are currently employed which are both manually and automatically deployed and feature dead-man controls to passively maintain their locked status. Locks of this type are described in United States Patents 4,105,097, 4,715,477, and 4,825,977. Almost no attention has been focused on the restraint of the telescoping capability of the arms, however. Each arm on the vehicle lift shown in Fig. 1 forms a polar coordinate system. The pads may be positively secured in position by precluding both radial and circumferential movements. A typical mechanism for restraining an arm against swinging is shown in Fig. 4, where a telescoping diagonal member is attached to the arm. Splines are regularly cut into the inner member of the brace which is held in a fixed extension by a spring-set dog which is insinuated into the spline teeth. Different polar angles are achieved by holding the dog out of position while the arm is oriented. Releasing the dog passively introduces it into an adjacent valley. Another method of circumferential constraint is shown in Fig. 5 where a gear segment is fixed at the hinge location of the lifting arm. Matching gear teeth are fixed on the arm so that mating the segment teeth with the arm teeth locks the polar angle of the arm as described in U.S. Patent 4,825,977.

A simple design for locking the telescoping member of the lift arm is shown in Fig. 6. A spring urges a dog between the closest spline teeth to provide an interference against retraction. A vertical projection of the dog below the arm shows when the dog is set. The dead-man dog is manually held out of locking position when the arm is extended or retracted.

Field measurements made by the authors indicate that some arms may be swung out of position by forces of 1.1 to 4.8 lbs. Forces that retract the telescoping portion of the arms have been measured in the range of 6.1 to 73.4 lbs. Static and impact forces sufficient to move the unrestrained pads can be developed by human contact. Pads which touch inclined surfaces can give rise to very large horizontal forces. Consider the wedging action that would be developed if the vehicle lift were to attempt to lift a boat by the hull.

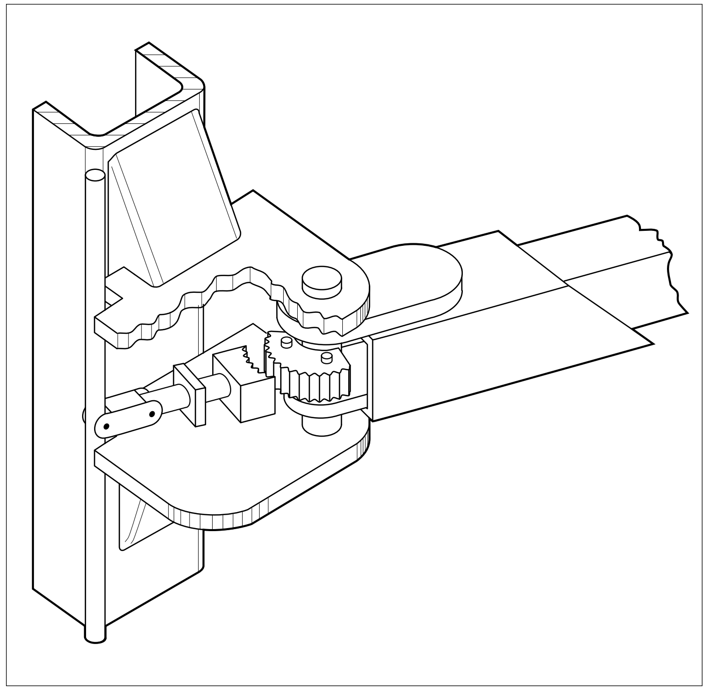

Fig. 5 Gear-type Swing Arm Restraint Mechanism

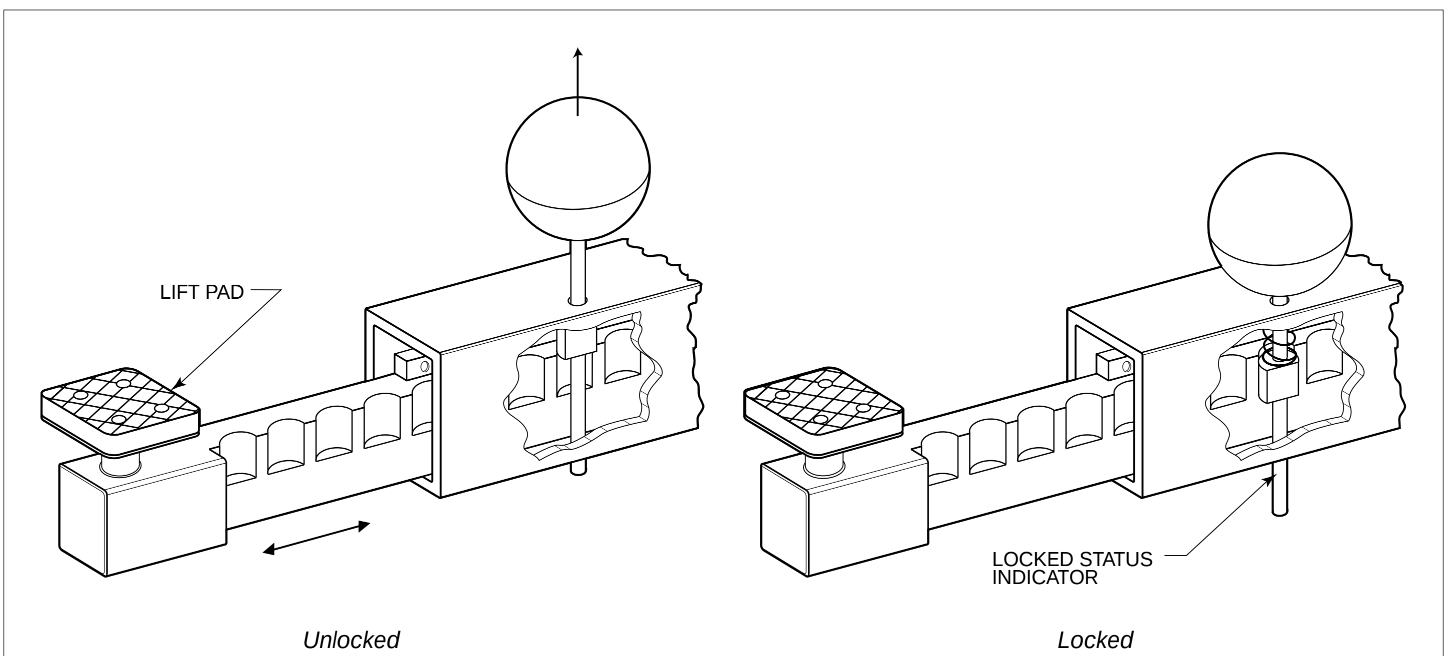

Fig. 6 Telescoping Arm Restraint Mechanism with Locked Status Indicator

V. CONCLUSIONS

1. The four pad reaction forces must add up to the total vehicle weight W.
2. The distribution of pad reaction forces cannot be determined.
3. It is possible for one or two pad reaction forces to be zero (or near zero).
4. Horizontal restraint of the lifting pads cannot be reliably obtained using pad friction developed through the pad reaction forces.
5. Proper mounting of a vehicle on the lifting pads cannot be assured by visual and tactile feedback strategies. Furthermore, vigorous tightening of a pad may unload other pads.
6. Restraining only the swing motion of the lift arms can still allow the pads to escape the chassis of a raised vehicle by telescoping action alone.
7. Positively restraining both the telescoping and swinging movements of the lifting pads will prevent vehicles from toppling off of vehicle lifts.

VI. REFERENCE

1. Timoshenko, S., and D. H. Young. 1945. *Theory of Structures*, pp. 177-180. New York: McGraw-Hill.

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