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Lift-Slide Drawbridge with the Varying Force Counterweight System

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LIFT-SLIDE DRAWBRIDGE
WITH THE
VARING FORCE COUNTERWEIGHT SYSTEM

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ABSTRACT

The retractable drawbridge innovation, the lift-slide drawbridge— US patent no.: 6,851,149 offers an economic alternative to the conventional movable bridge types. Its principal benefit to reduce construction costs, to accelerate the construction process reducing construction time to a year or less and to allow opportunity for improvement in movable bridge operation, maintenance and safety.

The lift-slide drawbridge design will be a simple, yet rapid operating, retractable drawbridge. By providing a short initial vertical lift of the retractable span to clear the adjacent bridge approaches, the conflict between them is avoided, then the span is retracted over the adjacent roadway.

With continued development, there is reasonable confidence that the lift-slide drawbridge will become a new cost effective, functional and versatile movable bridge type added to the mix of the conventional movable bridge types.

Movable Bridge Needs

According to information from the Federal Highway Administration‘s data, there are approximately 892 movable bridges in the United States National Bridge Inventory (NBI) on the public roads in the United States. According to FHWA’s National Bridge Inspection Standards approximately 589 (66%) of these of these movable bridges are structurally or functionally obsolete. This data does not consider the need for movable bridges in new locations.

Economic Issues

The cost to construct or reconstruct a movable bridge can easily exceed the cost of a comparable fixed bridge meeting similar design parameters by 3 to 6 times. For example, a bascule drawbridge recently constructed in Miami, Florida — the Second Avenue drawbridge (1) — costs approximately $44 million while a comparable fixed bridge without the vertical navigation clearance requirements would have cost approximately $10 million. Another example is the vertical lift drawbridge under construction in Houma, Louisiana — the Daigleville Bridge. It costs approximately $6 million dollars while a comparable fixed bridge without the vertical navigation clearance requirements costs approximately $1.5 million. Because of the high costs of movable bridges, many communities cannot afford to replace their existing, deficient movable bridges or to construct new movable bridges on navigable stream crossings where needed.

The *low-level movable bridge crossing* is the most common application for movable bridges and the substantial part of the discussion herein. A low-level movable bridge alternative will typically have the lowest construction cost and the highest daily operating costs in terms of power consumption and manpower required. Low-level movable bridge crossings necessarily expose the movable span to collision damage by the most massive components of marine vessels that are nearest to the water surface. This results in high economic losses due to severity of the damage and loss of service for the months that are necessary to effect emergency repairs.

The *high-level fixed bridge crossing* is an alternative to the low-level movable bridge crossing. Due to its height above the water — the vertical clearance required over the navigation channel — the high-level fixed bridge requires the construction of substantial substructures and costly approach structures making this alternative typically a more expensive alternative to construct than a low-level movable bridge. A high-level fixed bridge normally takes substantially longer to construct than a low-level movable bridge and it can permanently disrupt a community separated by a navigable waterway.

The *semi-high-level movable bridge crossing* combines a movable bridge with longer approaches to the semi-high-level crossing. It combines some of the higher construction costs of the high-level fixed bridge with the ongoing operating costs of a low-level movable bridge making this alternative usually the most expensive. An intersecting high volume marine channel and high traffic volume highway facility in an urban environment, where limiting the frequency of bridge openings to accommodate only the larger vessels and a limited length of approach structures is acceptable, this configuration becomes feasible by the unique conditions if not economically the best alternative considering user costs.

Construction Issues

With the prevailing traffic conditions in most communities, shutting down an existing route segment on the public street system for 2 to 4 years to reconstruct a movable bridge is generally unacceptable. The aforementioned Second Avenue drawbridge (1) in Miami, Florida, took over 2 years to construct. Similarly, the Daigleville drawbridge in Houma — expected to be completed by January 2004 — will have taken nearly 3 years to construct.

For the Daigleville drawbridge, there has been at least one petition filed by frustrated businesses and property owners concerned about its lengthy construction time. While construction time for movable bridges may be expedited as much as it is possible, it is not uncommon that unanticipated, additional construction time is required to deal with unexpected problems associated with the complex nature of the design and construction of the conventional movable bridges.

History

Conventional Movable Bridge Types

In his history of movable bridges, titled *Remember the Past to Inspire the Future – Historic Development of Movable Bridges* (2) reveals that the modern versions of the three conventional movable bridge types — namely the vertical lift, bascule and swing drawbridges — are 19th century developments. Each of the conventional movable bridge types features a unique movement including vertical translation, vertical rotation and horizontal rotation respectively.

One may ask, why did these bridge movements become *standards*? From a review of bridge history and given 19th century technology, bridges with these three movements were the easiest to construct, the most cost effective and the most reliable to operate. It appears that once these three standards were available, the 19th century spirit of movable bridge innovation may have faded into simply updating and improving on the three standards.

Retractable drawbridge

The r*etractable* drawbridges — also referred to as the *traversing* or *sliding* drawbridge — has been designed and constructed in the past. However, it never gained the broad acceptance of the conventional moveable bridge types — vertical lift, bascule and swing drawbridges. A reason the retractable drawbridge did not come into common use is explained by F. C. Kunz, CE in his book, *Design of Steel Bridges — Theory and Practice for the use of Civil Engineers and Students* (3). He writes,

> A traversing bridge is not desirable as it requires more power than any other kind and is slow of motion. It has been used in only a few cases for railroad bridges, but has proved satisfactory for small highway bridges.

Given the technology of 90 years ago, the retractable drawbridge was apparently not a technically or economically a competitive choice. However, it is believed that the two disadvantages expressed by Kunz — excessive power consumption and a slow operation — can be effectively overcome through invention and using current technology. This will be discussed later in more detail.

Existing Limitations

There are design requirements that tend to make the conventional movable bridge types — vertical lift, bascule and swing drawbridges — expensive to build. To operate and move the movable spans to a position that provides the required unobstructed navigation clearances, the conventional movable bridge types typically require components of their structures to be larger and/or more complex than would otherwise be required of the comparable fixed bridge necessary to span the navigation channel and accomplish the intended traffic carrying purpose.

The *vertical lift* drawbridge requires the movable span to be translated vertically enough to provide for the maximum vertical navigation clearance required above the water. To do this, it requires an expansive and massive superstructure to support the span, counterweights, sheaves, cables, and power and control equipment to lift the movable span typically 50' to a 100' or more vertically. This superstructure is very expensive to build.

The *bascule* drawbridge requires the movable span — a bascule leaf — to be rotated vertically up and away from the navigation channel to provide the maximum horizontal navigation clearance and unlimited vertical navigation clearance. Depending on the depth of a bascule girder, the distance between piers supporting the bascule girder is typically greater than what is necessary to meet the maximum horizontal navigation clearance. Live load resistance provisions — particularly for a double leaf bascule drawbridge — and the counterweight configuration typically result in a massive pier required to support a bascule span.

The *swing* drawbridge requires the movable span to be rotated horizontally parallel to — and out of — the navigation channel to provide the maximum horizontal navigation clearance and unlimited vertical navigation clearance. The swing span rests on a *turntable* or *pivot* pier for which its center and the center of rotation of the span typically coincide and it must be horizontally offset from the edge of the navigation channel by more than half the width of the movable span. This is necessary to locate the movable span outside of the navigation channel when in the opened position. As a result, a swing drawbridge superstructure and substructure are oversized to meet the offset and operation requirements. Wider roadways require greater offsets and therefore greater size for the turntable pier and length of movable span for the swing drawbridge. Because of the required offset, swing drawbridges are normally best suited for relatively narrow spans of those providing for fewer traffic lanes. Of the conventional movable bridge types, the swing span drawbridge requires the most right of way in which to operate the movable span.

Innovation

Considering the opportunities that may be available in the use of 21st century technology, and the specific needs of highway transportation and the nature of highway transportation facilities today; it is suggested that it may be the right time to — as Shultz's title suggests — *Remember the Past to Inspire the Future* (2). It may be time to rekindle the 19th century spirit of movable bridge innovation by leveraging 21st century technology to address the functional and economic needs of the 21st century.

Goals

Every movable bridge location has its own unique site parameters that require consideration in the design. When reviewing initial design and construction costs, construction time, maintenance and operations costs, and safety issues both during and after construction, it appears that the costs for every movable bridge project has the potential to be reduced substantially through innovation in movable bridge design. For this reason, it is reasonable that an innovation in movable bridge technology should be sought outside of the three conventional movable bridge types. Such an innovation should provide a high quality facility that can be constructed, operated and maintained easily; provided at a significant cost savings; and constructed in a minimum time.

Could there possibly be an innovative movable bridge design that may be equal to or more effective than the time-tested conventional movable bridge types and yet draws on the knowledge base developed for them? If there is such a type of movable bridge, it most likely would be discovered through the aforementioned tenet, *Remember the Past to Inspire the Future,* (2) and in doing so, the best conventional features would be extracted. The effectiveness of any type of movable bridge measured against the conventional movable bridge types is in the context of true practical worth *relative* to

- cost to design and construct
- time to construct
- cost and speed of operation
- cost and frequency of maintenance and
- general safety concerns.

In his book titled, *Design of Steel Bridges — Theory and Practice for the use of Civil Engineers and Students,* F.C. Kunz, CE, (3) writes

> It is impossible to give any general rule as to which kind of bridge is best adapted in a certain case, as there are many factors to be considered. The following general principles should be observed:
> (1) When the bridge is closed it should be as nearly as possible a fixed span.
> (2) The machinery should be designed so that the bridge can be easily operated while moving.

The most simple design which gives the least first cost and cost of operation is the best.
(3) The structural and machinery parts of the bridge should be separate; that is, when the bridge is closed, acting as a fixed span, the machinery parts should not receive any stress.

Lift-Slide Drawbridge

The economic and construction issues experienced with the conventional movable bridge types suggest that there may be a niche for a lower cost movable bridge type. It is proposed that a retractable drawbridge innovation, the *lift-slide drawbridge* - patent pending, may offer a lower cost alternative to the conventional movable bridge types. Its principal benefit appears to be reducing the construction costs by an estimated 30 to 50 percent making movable bridge projects more affordable. Some broad goals achievable with this simple, innovative drawbridge design are

- free up millions of transportation dollars to fund additional, badly-needed highway transportation projects
- accelerate the construction process reducing construction time to a year or less and
- allow opportunity for improvement in movable bridge operation, maintenance and safety.

The lift-slide drawbridge with a unique *varying force counterweight system* — patent pending — was conceived to meet the above goals in addition to incorporating the best features and avoiding the disadvantages of the conventional movable bridge types. The anticipated features of the lift-slide drawbridge are

- a high quality, safe highway bridge
- rapid and simple operation
- accessible components for safe and easy maintenance
- low maintenance requirements — as a fixed span, machinery parts do not support loads
- can be maintained while in service
- can be constructed without disrupting marine traffic
- can be constructed safely and quickly
- unlimited vertical clearance for marine traffic
- structure is well protected from damage by marine traffic
- is scalable in width so that it can be designed to accommodate one to six lanes of traffic
- is scalable in length so that it can accommodate a horizontal navigation clearance up to 150' and perhaps more
- is scalable in duty so that it can be designed to accommodate light or heavy-duty traffic
- can be built inexpensively (scalability in width, length and duty makes it possible for a drawbridge to be sized to meet the needs of a location with a resultant substantial cost savings)
- can be built within existing or minimal right-of-way, and
- the structure is attractive, low profile and would be welcome in any neighborhood.

Invention

The main components of the lift-slide drawbridge invention include

- the movable or retractable span
- the lifting apparatus in the lift-slide mechanism,
- the varying force counterweight system in the lift-slide mechanism and
- the sliding apparatus in the lift-slide mechanism.

The anticipated advantages of the retractable drawbridge previously discussed can be realized with the development and deployment of the lift-slide drawbridge described. The lift-slide drawbridge design will be a simple, yet rapid operating, retractable drawbridge. By providing a short initial vertical lift of the retractable span to clear the adjacent bridge approaches, the conflict between them is avoided. The lifting of the heavy retractable span led conceptually to an energy efficient and cost effective scissors lift apparatus assisted by a varying force counterweight system. The resulting reduced power consumption expected allows the use of smaller motors for the system with overall cost savings. The power consumption for operating the lift-slide drawbridge is expected to be similar to — or possibly less than — that for the conventional movable bridge types.

Unlike the conventional movable bridge types, the lift-slide drawbridge operation will not generally require components of their structures to be larger and/or more complex than would otherwise be required of the comparable fixed bridge necessary to span the navigation channel and accomplish the intended traffic carrying purpose. This is because

- the operation of its movable span is within its plan limits
- the open position for the movable span that provides unobstructed navigation clearances coincides with the approach spans
- the substructure components will be approximately the same size as that required for a fixed bridge and
- the movable span (deck) components will be approximately the size of those for a fixed bridge.

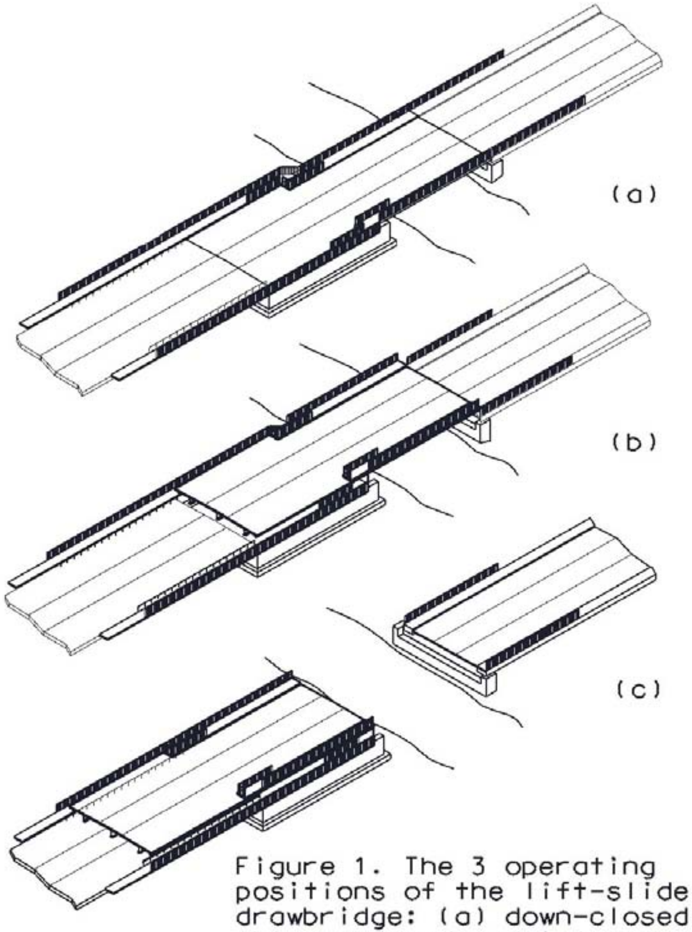


Figure 1. The 3 operating positions of the lift-slide drawbridge: (a) down-closed, (b) up-closed and (c) up-open.

Movement

The lift-slide drawbridge is a movable bridge invention that when it is supporting roadway traffic it is a two-span continuous structure. When roadway traffic is not present and it is being operated (retracted), it is an equal-arm, cantilever beam structure. Operationally, it is initially lifted (translated) vertically to an elevation that will clear it over the adjacent approach spans, then it is retracted from the navigation channel by sliding (translating) it horizontally back over the adjacent approach span.

The three operating positions of the bridge follow in more detail:

- In the *down-closed position* as shown in Figure 1a with roadway traffic present, the bridge is a two-span continuous beam structure supported directly on its by piers with one span over the navigation channel.
- In the *up-closed position* as shown in Figure 1b with roadway traffic not present, the bridge is an equal-arm cantilever beam structure supported on the lift-slide mechanism with one cantilever span over the navigation channel and lifted vertically by the lift-slide mechanism high enough to clear the adjacent spans on the bridge approach and any other obstacles when the span is retracted horizontally from the navigation channel.
- In the *up-open position* as shown in Figure 1c with roadway traffic not present, the bridge is an equal-arm cantilever beam structure supported on the lift-slide mechanism and retracted horizontally from the navigation channel with one cantilever span over the adjacent spans on the bridge approach. As a design alternate, in *up-open position* the adjacent approach spans may be used to support the bridge deck by means of rollers attached to the underside of the retractable span.

Operation

When in the down-closed position, the retractable span is supported directly by the piers and functions as a two-span continuous beam fixed span for live loads. To operate the span, roadway traffic service is ceased and the vertical lift apparatus the lift-slide mechanism is activated. It is a hydraulically driven scissors lift apparatus used in conjunction with the varying force counterweight system to provide an effective means to lift the retractable span typically 2.5' to 5.0' to clear adjacent approach spans as shown in Figures 2a and 2b.

Once in the up-closed position, the equal-arm cantilever beam structure is supported by the slide-lift mechanism the sliding apparatus driver is activated to retract the cantilevered span translating it horizontally to the up-open position thus opening the navigation channel to marine traffic. The sliding apparatus is secured atop the lift-slide mechanism and coupled to the bottom of the retractable span. It allows the retractable span to slide or translate horizontally over the adjacent approach spans and the navigation channel while in the up position as shown in Figures 3 and 4.

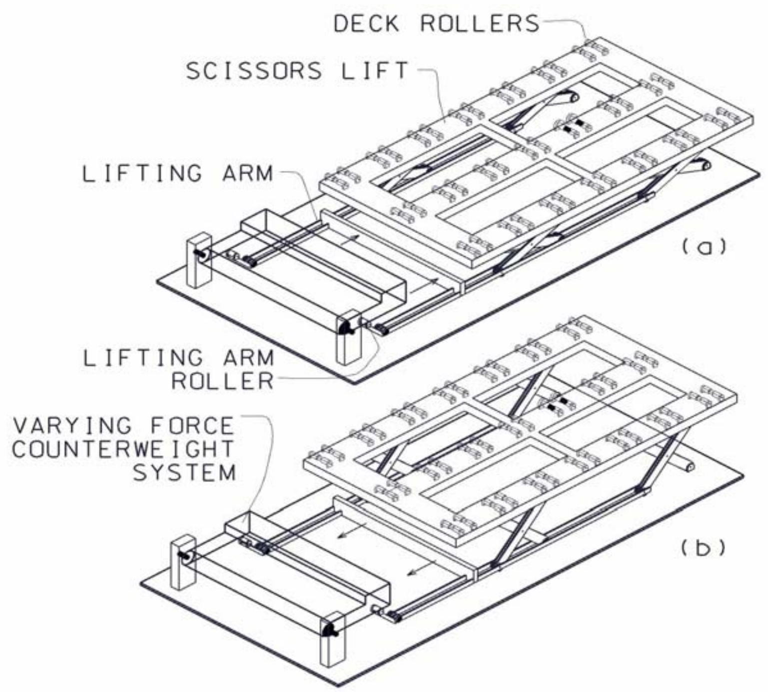


Figure 2. The lift-slide mechanism showing the varying force counterweight system and the operating positions of the scissors lift apparatus: (a) down-closed and (b) up-closed or -open.

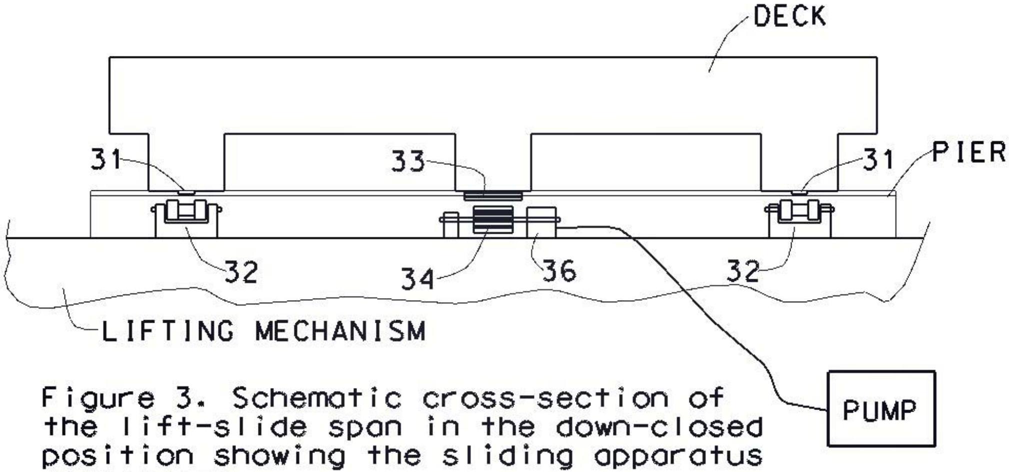


Figure 3. Schematic cross-section of the lift-slide span in the down-closed position showing the sliding apparatus disengaged.

Following the item numbers shown in Figures 3 and 4 and in braces in this text, the sliding apparatus driver consists of a span rack [33] attached to the underside of the retractable span. It is engaged by a span pinion [34] coupled to a span drive motor [36] that are both attached to the lift-slide mechanism. The retractable span is guided by span guides [31] that are attached to the underside of the retractable span seated in flanged wheel trucks [32] that are attached to the lift-slide mechanism.

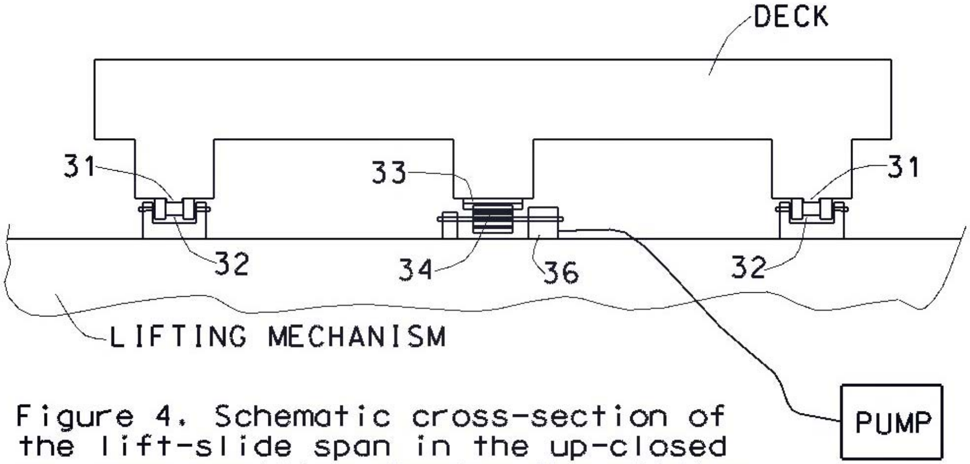
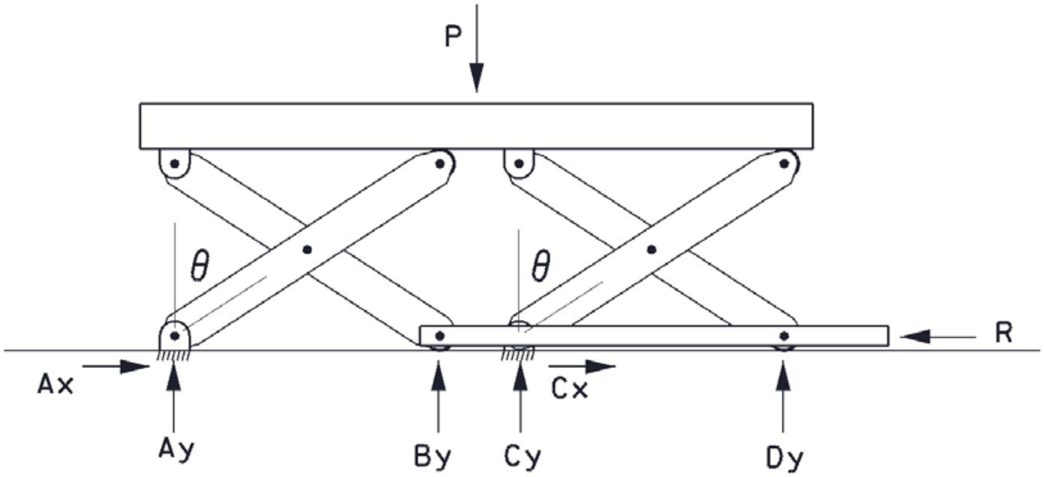


Figure 4. Schematic cross-section of the lift-slide span in the up-closed or -open position showing the sliding apparatus engaged.

Varying Force Counterweight System

Movable bridges having a vertical lift motion require a counterbalance to effectively and safely handle the heavy load of the movable span. The only practical counterbalance design for the large vertical movements of a vertical lift drawbridge is counterweights suspended by cables passing over sheaves supported at the top of lift towers. Since the lift-slide drawbridge only requires the lifting of its retractable span a few feet, the traditional counterweight design if feasible would appear to be a prohibitively expensive and complex, so a simple innovative counterweight system was invented.



R= Ptanθ (NEGLECTING FRICTION)
IF $\theta_1 > \theta_2$ THEN R1 > R2
θ VARIES FROM 57° TO 20°

Figure 5. Schematic diagram of the scissors lift apparatus showing the relationship between the weight of the span (P) to the horizontal force (R) in the lifting arm.

The varying force counterweight system shown in Figures 5 and 6 is a counterweight designed to counter the characteristic forces inherent in operating the scissors lift apparatus proposed to lift the span. This is done by providing a counterweight coupled to the scissors lift apparatus via its lifting arm. The counterweight is mounted on — and cantilevered from — a hinged support and supported by a lifting arm attachment roller.

Raising or lowering of the scissors lift apparatus moves the lifting arm attachment roller support point on the counterweight and thereby varies the length of the moment arm to the ballast end of the counterweight. The change in length of the moment arm between the lifting arm attachment support point roller and the ballast end of the counterweight is designed to vary the force applied to the lifting arm to correspond closely with the variation in the force required to rise and lower the scissors lift apparatus (See Figure 7). In this way, the varying force counterweight system is designed to effectively counterbalance the forces in the system throughout the full range of movement.

The application of a varying force counterweight system, coupled with a scissors lift apparatus, provides a very simple means to counterbalance the large variable forces encountered in operating the scissors lift apparatus used to lift the heavy retractable span. The design of the varying force counterweight system requires that the counterweight weigh 25 to 30 percent of the weight of the retractable span to be lifted. This compares to the weight of the counterweights for a vertical lift drawbridge — 100 percent of the weight of the span. This is a substantial material cost savings when considering that a typical span may weigh 150 to 500 tons or more.

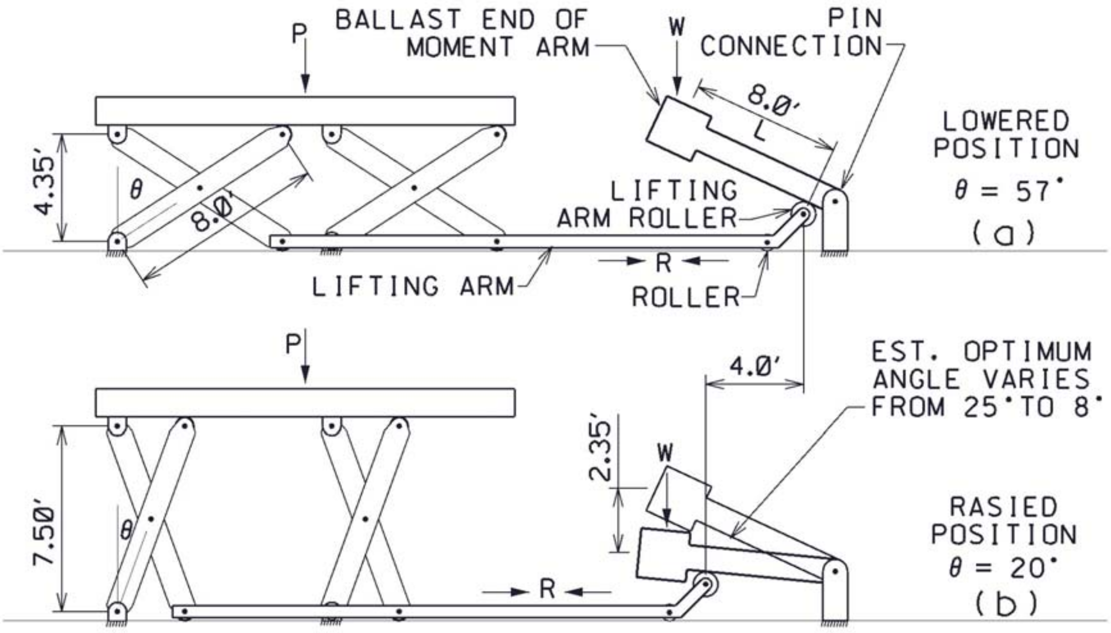


Figure 6. Schematic diagram showing the lift-slide mechanism with the scissors lift apparatus connected to the varying force counterweight system through the lifting arm and the lifting arm roller.
(a) Lift-Slide mechanism shown in the lowered position.
(b) Lift-slide mechanism shown in the raised position.

The advantages of a properly configured varying force counterweight system coupled to the scissors lift apparatus are

- *less dead weight* - In a variable load counterweight configuration, a moment arm is formed between the counterweight ballast and the lifting arm creating a mechanical advantage that magnifies the ballast load on the said lifting arm roller allowing for less ballast than would otherwise be required to counterbalance the forces in the system.
- *simplicity* - The design is very simple with few parts making it easy to fabricate, install and maintain.
- *reduced cost* - The overall cost of design, fabrication, materials and installation is a fraction of that of the other methods considered.
- *reduced installation time* - The time required to install the varying force counterweight system is also expected to be a fraction of the time required for conventional systems.
- *flexibility* - The varying force counterweight system can be configured in a multitude of ways to effectively meet the counterbalance needs of a specific project.
- *efficiency* - The varying force counterweight system makes practical the employment of a scissors lift (or similar) apparatus for the lifting of very heavy loads.

Configurations

It is foreseen that there will be two configurations of the lift-slide drawbridge — the single leaf configuration and the double leaf configuration. To cross the larger navigation channels, twin opposing lift-slide drawbridges are positioned opposite each other and the extended leaves of the cantilevered spans are connected by a shear lock and then lowered simultaneously onto their piers creating a double leaf lift-slide drawbridge as shown in Figures 8a and 8b. In the down-closed position, the double leaf configuration will be a three-span continuous beam with a hinge at the midpoint of the center span and provisions for live load uplift on the end supports.

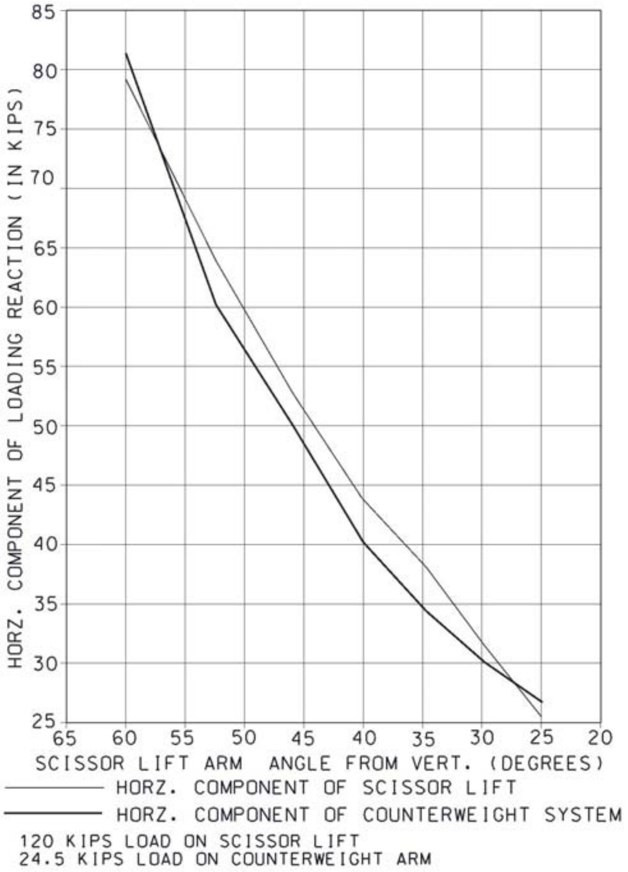


Figure 7. Forces produced by varying force counterweight system in the lift slide mechansim and the corresponding horizontal component of the force in the scissors lift apparatus.

It is anticipated that the single leaf lift-slide drawbridge will be practical for navigation channels up to 75' fender-to-fender clear width. The double leaf lift-slide drawbridge will be practical for navigation channels from approximately 75' and greater fender-to-fender clear width.

Conclusions

The lift-slide drawbridge is expected to require less technical effort to design than the conventional movable bridge types and its fabrication is expected to require only the standard tools and processes in a well equipped machine and fabrication shop. It is a low-tech solution with expected construction, operating and maintenance costs to be equal to or lower than the conventional movable bridge types while using conventional components and materials. The construction and operations requirements for a lift-slide drawbridge should be greatly reduced compared with those of the conventional movable bridge types. Perhaps more importantly, the construction time is estimated to be approximately one year cutting the construction time by at least half that of the conventional movable bridge types. The process for biding and letting a project for a lift-slide drawbridge is expected to be similar to that for any bridge construction project.

With the prospective advantages of the lift-slide drawbridge, preliminary estimates indicate the construction cost will be approximately 50 to 70 percent that of a conventional vertical lift drawbridge. Consider for example the $6 million Daigleville Bridge in Houma — the aforementioned drawbridge now under construction. According to preliminary cost estimates, the cost to construct a lift-slide drawbridge at that site would be approximately $3.5 million or a 40 percent savings.

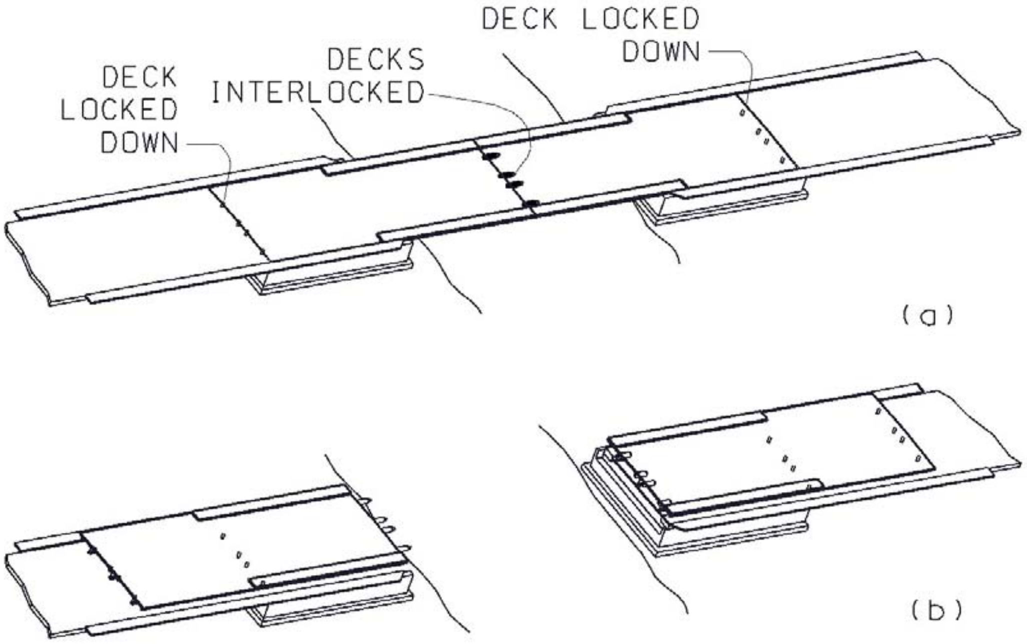


Figure 8. Two operating positions foe a double leaf lift-slide drawbridge: (a) down-closed and (b) up-open.

The aforementioned $44 million Second Avenue drawbridge (1) in Miami, Florida — a bascule bridge — was constructed with 2,300 tons of structural steel and 2,400 tons of counterweight ballast steel. A lift-slide drawbridge design constructed at the site could reduce the structural steel by 15% and the counterweight ballast by 70% for a total estimated reduction in steel of 2,025 tons. Assuming steel costs an average of $4,000 per ton, this structure would save $8 million or 18 percent less to construct.

The cost saving in fabrication methods associated with the lift-slide drawbridge was not considered in these estimates. A more refined cost analysis comparison obtained from a complete preliminary design of a comparable lift-slide drawbridge design and a conventional movable bridge type at the same site will better reveal the particular cost savings.

With continued development, there is reasonable confidence that the lift-slide drawbridge will become a new cost effective, functional and versatile movable bridge type added to the mix of the conventional movable bridge types. It is expected to compete well and it may become the first choice among alternatives for most movable bridge projects.

Supplement: Varying Force Counterweight System

To simplify the lifting components and minimize the cost and effort required to lift the movable span of the lift-slide drawbridge, the *varying force counterweight system* (VFCS) – patent pending, was conceived in conjunction with the *scissors lift apparatus* (SLA) and it is in the early stages of development. The mechanics of the VFCS are based on a relatively simple mechanical lever principle.

The findings presented are preliminary and based on computer analysis and 1/6 scale model testing.

The VFCS will provide:

- neutral stability counterweight function for the SLA for the full range of its movement
- minimum power requirements as a result of the counterweight function and
- level power requirements throughout the operating cycle.

To design an adequate counterweight system for the SLA three issues need to be resolved.

- The counterweight and SLA force to lift the span are in neutral equilibrium over the full range of the SLA movement.
- The amount of power required and its associated cost to lift the span in approximately 30 seconds is minimized.
- The cost and time to construct the counterweight system equal to or less than that provided with the conventional movable bridges; and its ongoing maintainability must be equal to or better than that provided with the conventional movable bridges.

To explain the mechanics behind the *coupled scissors lift apparatus and varying force counterweight system* (SLA/VFCS) it must be envisioned how the SLA is actuated. The horizontal and vertical force components of the reaction from the weight of the span through the SLA are shown in Figure 5. Following the schematic diagram shown in Figure 5, the equilibrium of the SLA will be maintained for its full range of movement by opposing P; the total horizontal component of the reactions resisting P, the weight of the span and the SLA.

The total horizontal component of the reaction R, is a function of the angle of the scissors lift arm from the vertical θ, where $R = P \tan(\theta)$. Given the full range of the SLA is $20\text{deg} < \theta < 57\text{deg}$ then for all values of $\theta_1 > \theta_2$ the corresponding values of $R_1 > R_2$ consistently throughout the defined full range of the SLA movement. A mechanism is needed that will continuously apply a horizontal force –R to oppose the horizontal component of the reaction R over the full range of horizontal movement of the SLA. This would place the system in continuous neutral equilibrium over the full range of the SLA movement.

The VFCS/SLA as shown in Figure 6 was specifically designed to produce continuous neutral equilibrium over the full range of the SLA movement. When the SLA is in the down position as shown in Figure 6(a), the lifting arm roller is forced toward the counterweight pin connection in continuous contact with the counterweight arm resulting in a large force directed approximately 25deg from vertical producing a horizontal component to oppose the total horizontal component of the reaction R in the SLA resisting the weight P of the span and the SLA. When the SLA is in the up position as shown in Figure 6(b), the lifting arm roller is drawn away from the counterweight pin connection while in continuous contact with the counterweight arm resulting in a much smaller force directed approximately 8deg from vertical producing a horizontal component to oppose the much smaller horizontal component R of the reaction in the SLA resisting the weight P of the span and the SLA.

It can be appreciated that the opposing horizontal force produced by the VFCS will vary continuously between the lowered and raised position of the SLA. By design this will produce a continuously varying horizontal force that approximates the continuously varying horizontal forces produced by the horizontal component of the reaction R in the SLA throughout its full range of movement as is the case and shown in Figure 7. This results in the approximate neutral equilibrium throughout the full range of movement of the SLA.

The SLA/VFCS is a system of connected rigid bodies with one degree of freedom. To exchange potential energy between the VFCS and the SLA, there must be vertical movement of the counterweight. This vertical movement is enabled by the hinge support of the cantilevered counterweight of the VFCS. To assure the potential energy is exchanged between the SLA and the VFCS through the lifting arm, the lifting arm roller support relies on the SLA for stability. The potential energy is exchanged between the VFCS and the SLA through the horizontal force and associated movement in the lifting arm that couples the two.

An approximately 1/6 scale model of the SLA/VFCS was built and initial tests using it are consistent with the previous explanation of the mechanics. The scale model was constructed with a 38 lb. counterweight physically cantilevered 7.66 feet with a center of mass including the arm located 4.00 feet from its pin connection. A series of tests were conducted with approximately 150 lbs. simulating the weight of the span and the SLA.

In the first test, the VFCS was uncoupled from the SLA and the horizontal reaction R required to lift the span and the SLA over the full range of movement of the SLA (25deg < θ <54deg) was observed. The maximum horizontal reaction R required to lift the span and the SLA over its full range of movement was greater than 150 lbs.

In the second test, VFCS was coupled to the SLA suspending the 38 lb. cantilevered counterweight on the lifting arm roller. With no additional weight added to the cantilevered counterweight, the maximum additional horizontal force required to lift the SLA over its full range of movement was reduced to 140 lbs.

In the third test an additional 37 lbs. weight was placed on the cantilevered counterweight arm at a position 7.66 feet from its pin connection resulting in a center of mass located approximately 5.8 feet from the counterweight pin connection. The maximum additional horizontal force required to lift the SLA over its full range of movement was 30 lbs. and the SLA/VFCS was operating in neutral equilibrium. A summary of additional test results is provided in Table 1.

At the neutral equilibrium achieved in the third test, the SLA/VFCS model provided a 80% reduction in energy requirement compared with the SLA uncoupled from the VFCS. If similar results are obtained on a full scale, movable bridge with a span and SLA structure weighting 300 tons the power required to lift the deck 3.5 feet in 30 seconds would be approximately 29 horsepower delivered with 4 - 6" diameter hydraulic rams at 1200 psi.

In another series of tests, it was observed that the force required to lift the SLA dropped in proportion to the weight added to the cantilevered counterweight. Weight was incrementally added to the counterweight until the SLA/VFCS began operating in neutral equilibrium. The maximum force required to lift the SLA was approximately 1.5 of the calculated frictional forces in the system. More weight was incrementally added to the counterweight and the SLA/VFCS continued to operate in neutral equilibrium until the force to lift the SLA was reduced to zero and the SLA tended to lift on its own. These observations demonstrate that the SLA/VFCS operates in neutral equilibrium over a large variation in the weight of the cantilevered counterweight.

In conclusion, the VFCS appears to favorably resolve the 3 previously stated issues. It balances the forces to lift the span and the SLA in neutral equilibrium over the full range of movement of the SLA. It provides an energy efficient mechanism that can readily lift a bridge span and SLA 3 to 5 feet in 30 seconds. The hope of minimum cost and time to construct and good maintainability of the SLA/VFCS would appear to be in the evident simplicity demonstrated in the details provided.

Table 1

Neutral Equilibrium Test Data from an Approximately 1/6 Scale Model of the Coupled Scissors Lift Apparatus and Varying Force Counterweight System (Patent Pending)
Angle of the scissors lift apparatus varies from 54E to 25E from vertical.
Angle of cantilever counterweight arm varies from 16.7E to 8.4E from horizontal.

Load on SLA (1)	Load on CWA (2)	Max. force req'd. to lift SLA (3)	Max. force req'd. to lower SLA (4)	Dist. from pin to CWA center of mass (5)	Dist. from pin to CWA roller (6)	(2)/(1) (7)	(3)/(1) (8)
lbs.	lbs.	lbs.	lbs.	feet	feet	ratio	ratio
100	50	20	15	5.0	0.52	0.5	0.2
100	70	20	15	4.0	0.52	0.7	0.2
100	100	20	15	2.5	0.52	1.0	0.2
150	75	30	20	5.8	0.52	0.5	0.2

SLA - Scissors lift apparatus   CWA - Counterweight Arm
(3) Note: For all test sets, the system is in neutral equilibrium.
(7) Note: As the distance from the pin to the CWA center of mass increases, the ratio of the load on the CWA to the load on the SLA weight increases.

Note: On a working system the load on CWA will likely be 25 to 33 percent of the load on SLA.

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