Ref.[1] describes a design problem involving the transport of small hiking parties over a river in deep banks, with the solution restricted to products based on human-powered transit of a tram car supported by a cable spanning the river. Ref.[1] developed an Engineering Design Specification (EDS) for this problem. Ref.[2] presents a functional decomposition of this problem, and a morphological matrix of working principles that might be applied as subfunction solutions. The following memorandum describes the assembly of working principle options into overall concept solutions, and presents a decision process for choosing the leading concept.

Choice of Working Principles
As a human-powered device, effort – mainly propulsive effort – is a key design metric.

A key form-setting working principle choice is whether the suspension cable is fixed or moving. The transported load hangs from the suspension cable. To limit deflection, and limit human effort necessary to pull the car ‘uphill’, the cable must have high tension. If tension is high on a moving cable, then bearing loads (on sheaves, necessary to return a moving cable in a continuous loop) will be high, leading to high friction, and higher propulsion effort. High tension on a fixed cable does not lead to higher propulsive effort. A fixed suspension cable is chosen.

If the suspension cable is fixed, then remote propulsion must use a secondary cable, attached to the load-carrying car, which pays out behind the car, so it can be retrieved from the other side.

As a public transportation device, public acceptance is necessary. Acceptance may be adversely affected by generation of fright due to high lateral or roll accelerations.

Another key form-setting working principle involves the number of suspension cables. A car can hang from a single cable, and its lateral motion would be governed by pendulum dynamics (slow – low-acceleration), only lightly excited by the cable’s vibration. If hung from (or riding over) multiple cables, any out-of-phase cable vibration could lead to high roll accelerations which might upset passengers. A single suspension cable is chosen.

It must be assumed that inert passengers might be animals, injured persons, or children, all incapable of carrying cargo. Active passengers must contribute propulsive effort, and probably cannot carry cargo. Cargo could be hung, but this would lead to the possibility of damage to the
cargo (ripping a pack, for instance), and injury to people as they go into the river to retrieve their lost cargo. Cargo should have sitting accommodation.

Sitting accommodation for a mountain bike might invite carriage of motorcycles or even horses. Mountain bikes are unlikely to rip and spill. Hanging accommodation for bikes would make it easier to accommodate only bikes.

Judicious selection of working principles suggests that: fixed, single suspension cable; secondary cable for remote propulsion; seated support for cargo and inert passengers; and hanging support for bicycles are most likely to meet the Engineering Design Specification.

Working principles that are not so easily selected include:

- Support for passengers and cargo. This could be by a suspension of a single car, or by multiple hangers connected with varying degrees of rigidity. It could be on a simple platform or on dedicated seats.
- Self-propulsion. This could grip the suspension cable, grip the remote propulsion cable, or grip a third cable. (Aerodynamic thrust is rejected as a working principle because of the probably high cost of feasible embodiments). Cable-grip self-propulsion could be direct-drive (human grip on cable) or indirect through a drivetrain (altering the force/speed coupling).

Integration of Overall Concepts
Concept 1:
Focus of this concept is simplicity and cost reduction. Support by simple platform (with railings, and external bike hook). Combine self and remote propulsion by attaching a propulsion cable to the car, looping through sheaves at each landing. Self-propulsion is by pulling on the unattached part of the loop where it passes by the car. Remote propulsion is by pulling on the attached part from either landing. This concept is illustrated in Figure 1.

![Figure 1 – Simple concept](image)
Concept 2:
Focus of this concept is reduction in human effort for propulsion. Indirect drive allows the ‘engine’ to run at its ‘speed for best torque’ (it may be desirable to allow this to be varied for different model ‘engines’ – within the variation of human size/strength). More propulsive force is available in leg muscles. For lowest compliance and highest efficiency in the propulsive mechanism, the (tight) suspension cable should be gripped. To deploy active passenger leg muscles in self-propulsion, support should be ‘seated’. For minimum self-propulsion effort, capacity is one active passenger and one inactive passenger (inactive passengers are ferried one by one). For remote propulsion, suspension cable sag should be lower (reduced load in car), friction should be lower (rollers on cable), and so propulsion force should be much lower. Arm muscles deployed from the landings should suffice, and this mechanism (and installation) will be cheaper than a leg muscle mechanism for remote propulsion. Further, an indirect grip on remote propulsion would cause additional propulsion drag due to friction and inertia in the mechanism, and so return grip should be direct. For lowest resistance to motion along the suspension cable, connection to the cable should be distributed in multiple hangers (bearing friction coefficients are not independent of load). The inert passenger/cargo capacity should be flexible. Bicycles may be hung independently from the suspension cable. This concept is illustrated in Figure 2.

![Figure 2 – Efficient concept](image)

Concept 3:
Focus of this concept is robustness – reduction in the probability of failure, and the frequency of repair. To extend the life of the suspension cable (and reduce the probability of failure), self-propulsion should not grip the suspension cable. To provide propulsive redundancy, the remote propulsion cable should not be used for self-propulsion. The result is a second secondary cable. For robustness, propulsion grip should be direct. Support should be in a single car, since the additional degrees of freedom allowed by multiple hanging cars offer more failure points. Active passengers, inert passengers, cargo, and bicycles should be specifically located and contained, so that interactions between these do not lead to failure. This concept is illustrated in Figure 3.
Table 1 summarizes these concepts by the working principles applied.

<table>
<thead>
<tr>
<th>Subfunction</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation</td>
<td>Roll on fixed cable</td>
<td>Direct grip to secondary cable</td>
<td>Direct grip to second secondary cable</td>
</tr>
<tr>
<td>Self-propulsion</td>
<td>Direct grip to secondary cable</td>
<td>Indirect grip to suspension cable</td>
<td></td>
</tr>
<tr>
<td>Remote propulsion (secondary cable)</td>
<td>Direct grip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car to cable connection</td>
<td>Hung from single cable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active passenger support</td>
<td>Single car, standing</td>
<td>Seated with feet hanging, multiple cars</td>
<td>Single car, standing - ergonomically configured for human propulsion</td>
</tr>
<tr>
<td>Inert passenger support (seated)</td>
<td>Sitting with feet supported</td>
<td>Sitting with feet supported</td>
<td>Sitting and contained, with feet supported</td>
</tr>
<tr>
<td>Cargo support (seated)</td>
<td>Sitting</td>
<td>Sitting</td>
<td>Sitting, with containment</td>
</tr>
<tr>
<td>Bicycle support (hanging)</td>
<td>Hung from car</td>
<td>Hung from cable</td>
<td>Hung from car with restraints</td>
</tr>
</tbody>
</table>

Table 1 – Working principles applied to concept alternatives

Satisfaction of the Engineering Design Specification
The EDS requires performance in terms of speed, capacity, cost, and motion. These Engineering Characteristics (EC’s) will be accommodated during configuration design, and evaluated during parametric design. Non-EC specifications include:
- Safety of dogs (as inert passengers or cargo)
- Ease of ingress/egress
- Unsuitable for horses
- Unsuitable for motorcycles
- Limited maintenance
- Discourage overload
- Difficult to fall from
- Difficult to fish from
- Difficult to lounge in
- Inhibit pitch and yaw
- Limited land rearrangement during construction

A means for accomplishing each non-EC specification is identified, as a guide to configuration design. Many of the specifications against overuse are met by restricting the car volume, and making it awkward in some ways. This has the side advantage of keeping the car small and easy to move, but limits legitimate capacity. Unwanted pendulum dynamics can be limited to roll (removing yaw and pitch) by connecting to the suspension cable with multiple, spaced-out rollers. Environmental impact is mainly limited to construction, and the amount of digging, blasting, or drilling necessary. The impact at the river banks is taken to be more important, as this connects to the river as a carrier, and is a less stable micro-geology. Table 2 summarizes the means for these specifications for each concept.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety of dogs</td>
<td>Enclose bottom of car sides; car sides high above nearest flat (floor or seat)</td>
<td>Same – refers to inert passenger/cargo car</td>
<td>Same</td>
</tr>
<tr>
<td>Ingress/egress</td>
<td>Enter/exit on level (no climbing or lifting)</td>
<td>Same (for cargo car)</td>
<td>Same</td>
</tr>
<tr>
<td>Unsuitable for horses</td>
<td>Storage space too low for horse; entry/exit too narrow for horse</td>
<td>Inherently small cargo car</td>
<td>Same</td>
</tr>
<tr>
<td>Unsuitable for motorcycles</td>
<td>Car entry too crooked for motorcycle; bicycle hook too high to easily place motorcycle</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Limited maintenance</td>
<td>Solid or plastic lubricant (Teflon or grease)</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Discouraging of overload</td>
<td>Capacity suitable only for load (passengers/cargo)</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Difficult to fall from</td>
<td>High car sides, intermediate rail</td>
<td>Same for cargo car; propulsion station with safety belts</td>
<td>High car sides, intermediate rail</td>
</tr>
<tr>
<td>Difficult to fish from</td>
<td>High car sides, intermediate rail</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Difficult to lounge in</td>
<td>Limited stretching room; claustrophobic</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Inhibit pitch and yaw</td>
<td>Multiple rollers (front/rear) on suspension cable</td>
<td>Rigidly connect propulsion rollers to cargo car and bicycle hanger rollers</td>
<td>Multiple rollers</td>
</tr>
</tbody>
</table>
Selection of Leading Concept
Selection of a leading concept is based on a belief map-based decision matrix comparison of the three concepts generated so far against the Customer Requirements (CR’s – [1]). Of these CR’s, “retrievable from the opposite bank” is a feasibility requirement that all concepts meet, and so is not included in the decision process. The CR “crew can propel entire party” is in some ways a feasibility requirement, but is translated here as “crew can propel party with moderate delay” and “crew can propel party with moderate effort”, for comparison purposes. (Note that performance now has two scores, and thus an exaggerated weight). Each concept is rated for confidence that each CR can be satisfied, and knowledge of the accuracy of the confidence rating. These scores are summarized in Table 3. In general, there is good knowledge about ease of learning and safety from falling, less knowledge about whether crossing performance can be assured (performance modeling remains to be done), and some concern over knowledge about construction tool mobility.

<table>
<thead>
<tr>
<th>Customer Requirement</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Easy to learn</td>
<td>0.9</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>2. Safe from falling</td>
<td>0.8</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>3. Easy lateral motions</td>
<td>0.7</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>4. Construction loads fit in HMMWV</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>5. Cost a small fraction of a bridge</td>
<td>0.8</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>6. Cross with moderate delay</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>7. Cross with moderate effort</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

CR confidence and knowledge are plotted on standard belief maps to produce CR scores:

![Belief map concept 1](attachment:image.png)
CR scores for each concept are interpolated from the belief maps and listed in Table 4. Weights are necessary to complete a decision matrix, and these are also listed in Table 4. A low weight (0.5) is chosen for ease of learning, as it is not expected that any of the concepts will have much trouble here. Safety, cost, and constructability are highly weighted (1.0). Performance is even more highly weighted, though split into two segments, delay and effort.

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to learn</td>
<td>0.5</td>
<td>0.84</td>
<td>0.58</td>
<td>0.67</td>
</tr>
<tr>
<td>Safe from falling</td>
<td>1.0</td>
<td>0.75</td>
<td>0.58</td>
<td>0.76</td>
</tr>
<tr>
<td>Easy lateral motions</td>
<td>0.8</td>
<td>0.62</td>
<td>0.77</td>
<td>0.70</td>
</tr>
<tr>
<td>Construction loads fit in HMMWV</td>
<td>1.0</td>
<td>0.59</td>
<td>0.50</td>
<td>0.59</td>
</tr>
<tr>
<td>Cost a small fraction of a bridge</td>
<td>1.0</td>
<td>0.64</td>
<td>0.54</td>
<td>0.64</td>
</tr>
<tr>
<td>Cross with moderate delay</td>
<td>0.7</td>
<td>0.50</td>
<td>0.70</td>
<td>0.63</td>
</tr>
<tr>
<td>Cross with moderate effort</td>
<td>0.7</td>
<td>0.50</td>
<td>0.70</td>
<td>0.57</td>
</tr>
<tr>
<td>Weighted sum (Satisfaction)</td>
<td>3.60</td>
<td>3.51</td>
<td>3.72</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Concept comparison decision matrix
The overall satisfactions are 3.60, 3.51, and 3.72 for concepts 1, 2, and 3, respectively. The distinction between these scores is not high enough to choose one particular concept for further development. Therefore, it will be necessary to regenerate a concept, using the best combination of working principles. As might be expected, the simple Concept 1 is inexpensive and easy to use, while the refined Concept 2 is expensive and less safe. The regenerated concept might best be based on Concept 3, the robust device with compartmentation to reduce misuse and add to safety. Concept 3 might gain the best of each set of working principles if it replaces the direct grip style of propulsion with a hand-cranked system, gaining considerable propulsive efficiency at a small increase in cost. The car on Concept 3 would then be redesigned around a propulsion bay for this new working principle.

Note that the capacity of the device has not been explicitly addressed. This issue is reserved for Configuration Design, for which a model of the suspension cable’s catenary shape must be developed to solve the necessary propulsive force, and the human effort necessary for a crossing. Crossing time simulations from this model will guide the choice of capacity to meet the requirements of the customer profile.