Proposal of Plant Material Application in Elevators

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Abstract: Owing to their light, low-carbon nature, plant fibers are recognized as the material for future automotive. The idea was applied to hydraulic elevators as a kind of vertical automotive. By comparing the densities and carbon intensities of different currently used plant fibers, hemp was selected as the potential substituting material. By calculating the relative mass of cars in hydraulic elevators made by stainless steel and hemp fibers, the amount of electricity cost saved by making different types of hydraulic elevators lighter was estimated.

1. Introduction

The environmental impact of transportation cannot be neglected, as approximately 1/4 of the global carbon emissions [1] and large amounts of pollution [2] come from such a system. To deal with the existing shortages, a potential approach is to apply some newly developed plant-based materials, with examples of Mercedes A-Class W169[3]. Eighty years since Henry Fort proposed using plant fibers in the car body, it is still a field of rapid development. However, such an attention of lighter materials was disproportionately focused on transportation that moves horizontally, such as cars, buses, and subways.

Elevators, in the meantime, should be viewed as a representative type of vertical transportation, which shares a high degree of similarity with the horizontal transportation on the road. From the aspect of technology, an elevator is basically a metal built, signal controlled, rail guided, and machine-driven device that carries people or their belongings in a more rapid and relaxing manner. Therefore, an elevator can be viewed as a subway train that moves up and down, rather than forward and backward. From the aspect of society, elevators are another type of public transportation, with the majority belonging to non-private owners, the service operated inclusively, and the fee being paid indirectly.

Multiple reports have been done to investigate the environmental and economic benefit of material substitution in road vehicles, and in this report, several potential substitutes for making the current elevators lighter, and analyses of its applicability based on the situation of mainland China's market will be proposed. The major concern will be whether currently used, steel-based elevators can be well substituted by some plant fibers in a desirable way, which include three sub-topics. First, whether such substitutions will meet the basic safety standard of elevators. Second, whether such substitutions will be beneficial to the environment, especially their carbon footprint. Last, whether such substitutions will be cost-effective.

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2. Methods

2.1 Elevator Selection

Currently, elevators fall into different technological categories, including traction, hydraulic, and multiple other forms. Comparing their mechanisms, hydraulic elevators would be a good choice, since the weight does matter with respect to energy consumption. Hydraulic elevators are composed of a pump system that can pump oil into a hydraulic cylinder, and a piston, a hydraulic system that lift up the elevator, a car and door system that transport passengers and cargo, a guide system for the car, an electrical system that provides energy, and a safety system that deals with emergencies. What these systems do is to push the hydraulic piston up by pressure of the liquid oil stored in the tank, and thus move the car and the load attaching to it [4].

2.2 Mass Estimation

Among all systems, the stainless-steel based car and the door affect the energy consumption the most, since they are the heaviest components being lifted, so they will be the components for applying substitution. In order to rationally analyze the environmental and economic impact of material substitution, basic information of the mass of different components of hydraulic elevators is required, which varies according to their usage.

However, no such data was found from sources in and out of China. Therefore, the mass of the cars and doors of elevators will be based on estimations of their size, which can be used to calculate their mass as the mass of steel is known. Since the size and load of different elevators varies significantly based on their usage, separate estimations will be done. In this report, I'm going to discuss four major types of elevators, which are public passenger elevators that are found in offices, markets or hotels, public cargo elevators that are found in offices, markets or hotels, domestic passenger elevators that are found in apartment buildings, and private passenger elevators that are found in villas.

2.3 Material Selection

Although there are not many examples of plant fiber integration in elevators, potential choices of materials can be found by referring to examples from the automotive industry. As demonstrated above, elevators satisfy the basic properties of transportation infrastructure and can be viewed as a means of vertical transport. Cars and doors of an elevator resembles exterior automotive components, such as doors, covers, and guards. The requirements of the materials of elevators are designed for protecting them from forces of passengers or cargo, while those for automobiles are designed for protection from car accidents. Therefore, if plant materials have already been tested to be applicable for substituting traditional metal materials in automobiles, then they shouldn't face too many difficulties when applied to elevators.

The most important mechanical properties of cars and doors is tensile strength, which, for traditional stainless steel, ranges from 400 to 1400 Mpa [5]. Some plant fibers, including flax, ramie, hemp, and sisal have tensile strengths that fall into this range [6]. To select the most optimal alternative plant fibers for material substitution, life cycle analysis of different potential materials should be done, with a focus on density and carbon emission.

2.4 Life Cycle Analysis

In order to calculate the environmental value of such substitutions, the next step is to check the life cycle analysis for steel to make a tentative comparison. However, the comparison cannot directly lead to a conclusion as the number of materials may be different due to differences in density. Thus, the amount of plant fibers needed will be calculated by multiplying the estimated volume with the density of such materials.

2.5 Cost Analysis

With lighter materials substituted, the weight of the elevator can be reduced, which will lead to a decrease in electricity consumption. In order to estimate the potential advantages or disadvantages of such material substitution, a cost analysis will be carried out to estimate savings arising from such a reduction.

2.5.1 Elevator Usage Estimation

Due to differences in the locations and applications, different types of elevators will have different average energy consumption arising from working hours, their weights, and loading capacities. Thus, separate estimations will be proposed based on the specific situations of different types of elevators.

Working hours will be divided into three categories: rush hours, normal hours, and resting hours. During rush hours, the elevators will likely be used continuously under full load. During normal hours, the elevators will likely be used occasionally in partial load. During rest hours, the elevators will not be used. More specifically, it should be pointed out that rush hours can be further divided into double sided rush hours and single sided rush hours, indicating the period the elevators will be full in both directions or those during which elevators will only be full in a single direction.

Based on the formula W=FVT, an efficient way to estimate the usage of different types of elevators is to calculate the full load hours by standardizing all types of hours into equal amounts of hours when elevators work in full load without stopping. To complete such a conversion, one must multiply the period length of different hours by the frequency of usage, and then divide the result by the weight ratio between the full load and the partial load. To simplify the calculation, the mass of a full load will be set as the sum of the elevator's mass and its loading capacity, and the mass of a partial load will be set as the self-mass, as one person is negligible in weight.

Importantly, according to the mechanism of hydraulic elevators, work is only needed when the elevator is moving upward, since it takes no extra energy to let the liquid level drop down. For this case, only double-sided rush hours and single-sided rush hours when people move upward will be calculated as full loads, and the rest will be calculated as partial loads.

When alternative materials are selected, the same steps can be applied to estimate the full load hours, since the change in the elevator's own mass will only affect the ratio between a full load and a partial load, while the usage of users is unlikely to be affected.

2.5.2 Electricity Price Estimation

According to current regulations, elevators in China are charged for electricity based on the same price for domestic electricity use, which differs from province to province. To make the cost analysis more applicable to the whole of mainland China, a selected set of provinces was used to calculate an average to be used in the following analysis.

There are 31 provincial districts documented in the National Bureau of Statistics of the PRC, and data of income per capita, population and electric energy production was downloaded directly from its website. Electric energy production per capita was calculated by dividing the total electric energy production with its population. For both the income and the electric energy production per capita, I divided all the provinces into three groups, which are high ($Z \geqslant 0.5$), medium ($-0.5<Z<0.5$) and low ($Z \leqslant -0.5$), where Z is the Z value in statistic.

By averaging the cost of electricity of the selected provincial districts, the average cost of electricity can be calculated, and the cost for traditional elevators and plant-based elevators of different usage can be estimated.

3. Results

3.1 Material Selection

The density of flax, ramie, hemp, and sisal are 1.49g/cm³ [7], 1.50g/cm³ [8], 1.39g/cm³ [9], and1.45g/cm³ [10], respectively. From previous studies or calculations, the carbon dioxide equivalent for a ton of flax, ramie, hemp, and sisal fibers are 2076kg [11], 1770kg [12], 345kg [13], and 380kg [14], respectively. It is critical to mention that the carbon equivalent of sisal fibers is calculated by averaging two significantly different results from two locations [14].

Based on these sets of data, hemp is the best choice since it, at least theoretically, is the best at reducing weight and greenhouse gas emissions.

3.2 Mass Estimation

The height, length, and width of public passenger elevators, public cargo elevators, domestic passenger elevators and private passenger elevators were listed in the following table.

Table 1 : Sizes Of Different Types of Elevators

Type	Height(mm)	Length(mm)	Width(mm)
Public passenger elevators	2400	1600	1600
Public cargo elevators	2200	1800	2000
Domestic passenger elevators	2200	1200	1200
Private passenger elevators	2200	1100	1100

In China, the top and bottom of cars usually have a 3mm thickness, and the sides of cars usually have a 1.2mm thickness. As the door has the same thickness as sides, the door can be viewed as a part of the side with the door, so that the volume of steel used in an elevator can be calculated by the formula $V=2\times3mm\times length\times width+2\times1.2mm\times length\times height+2\times1.2mm\times width\times height$. With the density of stainless steel standardized as 8g/cm³ [15], the mass of the car and door of different types of hydraulic elevators can be calculated by the formula $m=(2\times3mm\times length\times width+2\times1.2mm\times length\times height+2\times1.2mm\times width\times height)\times8g/cm^3$.

Based on these formulas, the mass of the car and the door in a typical public passenger elevator, a typical public cargo elevator, a typical domestic passenger elevator, and a typical private passenger elevator is 270.3kg, 333.3kg, 170.5kg, and 151.0kg.

3.3 Life Cycle Analysis

The environmental impact of steel differs with usage, respectively, with an average carbon dioxide equivalent of 1770kg per ton [16]. In that case, the material needed for producing cars and doors of a traditional public passenger elevator, a traditional public cargo elevator, a traditional domestic passenger elevator, and a traditional private passenger elevator will produce 478.4kg, 589.9kg, 301.8kg, and 267.3kg, respectively, of carbon dioxide equivalents.

By comparison, if hemp fiber is applied and substitute all steels in the cars and doors, the masses of cars and doors of an altered public passenger elevator, an altered public cargo elevator, an altered domestic passenger elevator, and an altered private passenger elevator will be 46.8kg, 57.7kg, 29.5kg, and 26.1kg, and the carbon dioxide equivalent will be 16.1kg, 19.9kg, 10.2kg, and 9.0kg, respectively, meaning that the reductions are 462.3kg, 570.0kg, 291.6kg, and 258.3kg, respectively.

3.4 Elevator Usage Estimation

The double-direction rush hours, single-direction rush hours, and normal hours of public passenger elevators, public cargo elevators, and domestic passenger elevators were listed in the following table in China are listed in the following table.

Table 2 : Hours For Different Types of Elevators Except for Private Passenger Elevators

Type	Double-direction rush hours	Single-direction rush hours	Normal hours
Public passenger elevators	11.30am-1pm People move in and out for lunch	8am-10am, 5pm-7pm, People arrive/leave the office	6am-8am, 10am-11.30am, 1pm-5pm, 7pm-9pm
Public cargo elevators	11.30am-1pm People move in and out for lunch	4am-7am, Workers taking the cargo up 8am-10am, 5pm-7pm, People arrive/leave the office	7am-8am, 10am-11.30am, 1pm-5pm, 7pm-9pm
Domestic passenger elevators		6am-8am, Going to work 6pm-9pm, Going back home	8am-6pm

In China, private passenger elevators make a special case since their usage is far less than that of the other types of elevators. To make an estimation for private passenger elevators, it is assumed that each private house has three generations, with a child, his or her parents, and two of his or her grandparents.

Family use of elevators follows a regular pattern, if each child and the parents use it once when they leave and return to the house in the morning and the afternoon, it will add up to 6 rides. If each of the grandparents will use it to get up and down twice during the day for any reason, it will add up to 8 rides. If each of the family members take another 2 cycles when they are in the house, it will add up to 12 rides. In total, that is 26 rides per day, which is approximately 13 minutes.

If we assume that occasional use translates to 10 minutes per hour, and with only a few people for each ride means that the loading weight is the weight of the car, then based on the above estimation of the masses, the daily full load using hours can be calculated by the following formula:h=(h1×1+h2×1×m1/(m1+m2)+h3×1/6×m1/(m1+m2))/2. In the formula, h1 is the total time for double-direction rush hours and single-direction rush hours that move up in full load, h2 is the total time for single-direction rush hours that move down in full load, and h3 is the total time for normal hours. m1 is the the elevator's mass of the car and the door, while m2 is the full load mass.

With this formula, the daily full load working hours for a traditional public passenger elevator, a traditional public cargo elevator, a traditional domestic passenger elevator, and a traditional private passenger elevator will be 2.21 hours, 3.49 hours, 1.13 hours, and 0.03 hours.

According to current regulations in China, there are 52 weekends and 11 public holidays [17], so the number of working days per year will be 365-(52×2)-11=250 for every common year and 251 for every leap year. It is reasonable to suggest that public elevators will only have the working load calculated above for working days, and domestic and public elevators will have the working load calculated above every day.

So, for a 20-year lifetime for an elevator, the full load working hours for a traditional public passenger elevator and a traditional public cargo elevator can be calculated by the formula H=h×250×15+h×251×5, and the total full load working hours for a traditional domestic passenger elevator and a traditional private passenger elevator can be calculated by the formula H=h×365×15+h×366×5, where h is the daily full load working hours.

With the formula above, the full load using hours for a traditional public passenger elevator, a traditional public cargo elevator, a traditional domestic passenger elevator, and a traditional private passenger elevator will be 11061,17467, 8255, and 219 hours.

Using the same formulas, the daily full load using hours for an altered public passenger elevator, an altered public cargo elevator, an altered domestic passenger elevator, and an altered private passenger elevator will be 1.84, 3.30, 0.82, and 0.006 hours.

In that case, over a 20-year period, the full load using hours for an altered public passenger elevator, an altered public cargo elevator, an altered domestic passenger elevator, and an altered private passenger elevator will be 9209, 16516, 5990, and 44 hours.

3.5 Electric Price Estimation

Table 3 : Electricity Price for Some Provinces in China

Province	Electric energy production per capita [18]	Level of advancement [19]	Cost of electricity [20]
Xinjiang	High (14548kh)	Low (23103¥)	0.390¥/kh
Inner Mongolia	High (21634kh)	Medium (30555¥)	0.450¥/kh
Guizhou	Medium (6090kh)	Low (20397¥)	0.456¥/kh
Hubei	Medium (4990kh)	Medium (28319¥)	0.558¥/kh
Guangdong	Medium (4384kh)	High (39014¥)	0.592¥/kh
Heilongjiang	Low (2964kh)	Low (24254¥)	0.510¥/kh
Hunan	Low (2254kh)	Medium (27680¥)	0.588¥/kh
Beijing	Low (2154kh)	High (67756¥)	0.488¥/kh

Unfortunately, there is no "high-high "province in China, other combinations are all satisfied with one example. In that case, the 8 selected provinces will make a set of good indicators for the estimation of electricity costs.

By averaging the eight values of electricity costs above, the cost I will use for future analysis is 0.504¥/kh.

The speed of a typical hydraulic elevator is 1m/s, so by the formula W=FVT, the cost of electricity over a 20-year life cycle can be calculated by the following formula:

P=(m1+m2)×9.8N/kg×1m/s×H×3600s/h÷3600000J/kh×0.504￥/kh, where H is the total full load working hours, m1 is the self-mass of the car and the door, while m2 is the full load mass.

With this formula, the cost of electricity for a traditional public passenger elevator, a traditional public cargo elevator, a traditional domestic passenger elevator, and a traditional private passenger elevator over a 20-year cycle will be 88521￥, 201341￥, 47734￥, and 650￥.

Under the same sets of conditions, the cost of electricity for an altered public passenger elevator, an altered public cargo elevator, an altered domestic passenger elevator, and an altered private passenger elevator over a 20-year cycle will be 63526￥, 167892￥, 26795￥, and 103￥.

Therefore, the reduction in costs of electricity are 24995￥(28.2%), 33449￥(16.6%), 20939￥(33.0%), and 547￥(84.2%), respectively.

4. Discussion

From the above estimations and calculations, it is clear that substituting currently used stainless steel with plant fibers such as hemp in the cars and doors of hydraulic elevators will significantly reduce both the environmental and the economic costs, making it a potential strategy for future hydraulic elevator production and application.

Among different types of elevators, the absolute effectiveness of such a material substitution seems to relate with the time of use and the loading capacity positively. However, if we focus on the relative effectiveness, it seems that a more significant reduction of both environmental impact and cost were achieved for lighter elevators. Such a relationship is definitely reasonable as the lighter the elevator's weight and its loading capacity, the more beneficial the reduction.

However, it should be noted that the results are based on several assumptions beyond the specific values, which may systematically increase or decrease the value.

Firstly, it was assumed that hemp fiber is able to completely replace the steel in constructing cars and doors. However, even if cars and doors are simply constructed from plates, it is not very likely that all steel can be replaced, meaning that such an assumption may have made the environmental and economic benefit appear systematically higher.

Secondly, it was assumed that the weight of passengers is neglectable when only a small number of people are using the elevators. However, such a value does matter, especially for the altered elevators with low weights. Consider the fact that $(a+c)/(b+c)>a/b$ when $a<b$ and $c>0$, such an assumption may have made the environmental and economic benefit appear systematically lower.

Apart from these two assumptions, it was assumed that all cars and doors of traditional hydraulic elevators are made primarily of stainless steel. However, there exists at least one alternative case, which is sightseeing elevators with glass sides. Considering the fact that both the carbon footprint [21] and the density [22] of glass are lower than that of steel, the replacement of traditional materials on sightseeing elevators will be lower than that of stainless-steel elevators.

The largest uncertainty, however, was created by the manufacturing process. The life cycle assessments above were primarily focused on the raw materials, which did not take into consideration the process and techniques of manufacturing hydraulic elevators. Without a deeper understanding about the properties of different materials and real experiments, it is hard to tell whether and how the manufacturing process will be altered, which further affects the environmental impact.

Based on the current achievements and findings, the next step is to specifically test the compatibility of hemp fibers and stainless steel, with a focus on the mechanical properties to know whether the combination is practical and what the best ratio is in the newly made materials. If hemp passes the property test, a more detailed life cycle assessment can be carried out to determine the precise impact. If it doesn’t, other potential fibers may have to go through the same set of steps until an optimal one is found.

5. Conclusion

Re-establishing sustainability is never an easy task, which requires a combination of scientific, economic, political, and cultural approaches. From an engineering point of view, solving the currently existing problems by technological breakthroughs is always more reliable than individual virtue or public regulations. Elevators are still important, so important as a public transportation system that it is unlikely to be abandoned before another groundbreaking innovation happens. In that case, refinement may be the best and the only choice remaining.

Plants have been the most important source of materials for millions of years, only after the industrial revolution were they challenged by some advanced alternatives. However, with their advantages and fewer residual drawbacks, they are gradually being regarded as the path towards a brighter future. In this proposal, I demonstrated the tentative idea of transferring already existing plans used in road transport to elevators, and showed its theoretical feasibility, which marks the first step in any new voyage. At this point, hydraulic elevators only make up a modest percentage of elevators in China, which may be altered in the near future.

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