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ANALYSIS OF COMPRESSED AIR REGENERATIVE BRAKING AND A THERMALLY ENHANCED OPTION

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ABSTRACT

Obtaining a net benefit from regenerative braking is difficult. Various forms of regenerative braking systems have been proposed. They include electric batteries, capacitors, flywheels, and compressed air. Some have been implemented on a limited scale. The benefits of regenerative braking systems are easy to qualitatively describe, but can be challenging to quantify. The potential benefits depend upon obvious things such as driving patterns and the often overlooked considerations such as additional weight and cost, the less than ideal charge-discharge efficiency and a strategy for energy storage management that requires a forecast of the future driving pattern, such as uphill or downhill or stopping or accelerating. This paper will analyze a hydraulically coupled compressed air storage system that has been proposed for heavy vehicles. It uses the hydraulic system for transferring energy between the compressed air and the vehicle. The paper will also consider the possibility of thermal enhancement of the compressed air with engine exhaust heat. With this enhancement the compressed air system becomes an Otto cycle engine. The expansion can occur at a higher pressure than the compression. Thus, thermally enhanced storage has the potential of recovering more work for the vehicle with the discharge expansion than was put in during the charging compression.

1. Introduction

Friction versus regenerative braking analysis for a vehicle requires the recognition of two classes of energy. Energy can be classified as orderly energy such as work, potential and kinetic or disorderly energy associated with molecular motion and bonding in the form of internal energy and heat. Each time a vehicle is stopped by friction all of its orderly energy is lost. Most is converted to internal energy and then heat via the brakes, while some is lost to aerodynamic and rolling drag during the stopping process.

It takes orderly energy in the form of a force and a motion in the same direction to drive a vehicle. Electric power is also orderly, with the voltage being the force that moves the current. Regenerative braking means to convert the orderly kinetic energy of the car to some form of stored orderly energy, and then discharging the stored energy back to the vehicle when motion is resumed.

Most existing and proposed regenerative braking systems for vehicles transfer energy with generators and motors and use batteries and possibly capacitors for storage. Other proposals transfer the kinetic energy of the vehicle to the kinetic energy of a flywheel and back. An alternative regenerative braking system using a hydraulic drive with compressed air or nitrogen was displayed for a Ford Tonka Truck shown in Figure 1 during the 2002 New York Auto Show (Reference 1). This system provided the motivation for the authors' analysis and for this paper.

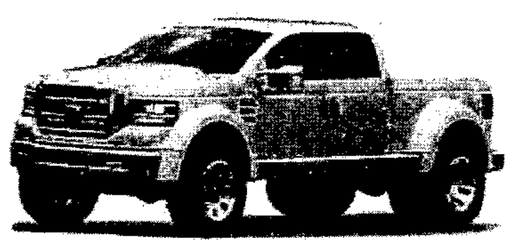

Figure 1. Ford Tonka Truck

The article claims this system can result in a 35% fuel savings during stop and go traffic, and recover and reuse 80% of the braking energy. Another claim is that the energy recovered from regenerative braking from 32 mph is sufficient to propel the truck from a stop back to 25 mph, which is equivalent to a 61% charge-discharge efficiency. Hydraulic fluid from the drive system is used to pressurize nitrogen to a pressure of 5,000 psia. The system is shown in Figure 2.

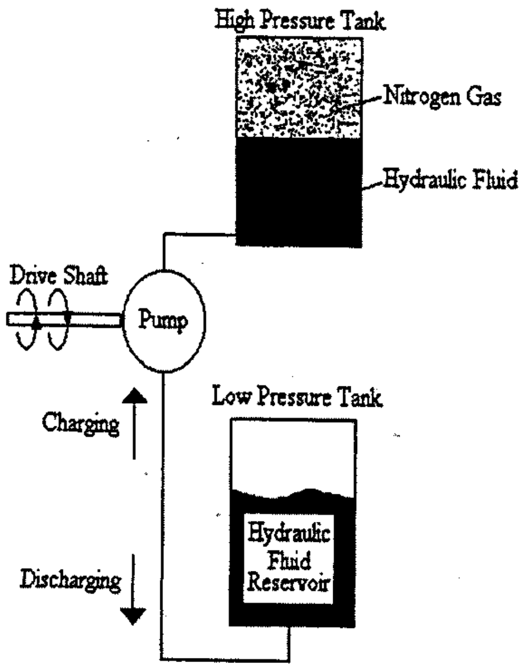

Figure 2. Hydraulic Coupled Compressed Gas Regenerative Braking System

The authors noted that such a system that stores the kinetic energy of the vehicle in the form of a compressed gas rather than as electricity provides the additional possibility of recovering more than 100% of the kinetic energy of the vehicle. This can be done by using the engine exhaust to heat the gas after compression and to cool after discharge.

Thus, the storage becomes an engine cycle similar to the idealized Otto cycle. The adiabatic compression of the air happens during the stopping process. The constant volume heating is performed from the engine exhaust while the vehicle is stopped. The adiabatic expansion then occurs at a higher pressure and thus transfers more energy back when the vehicle is accelerated. The air is then cooled to ambient temperature in preparation for the next stop.

This enhanced regeneration system option is possible only if the temperature of the compressed air after the compression process is lower than the temperature of the engine exhaust.

2. Analysis

This paper will analyze a best case compressed air storage system using the 8500 lb weight and maximum pressure of 5000 psia for the truck and the storage system described in Reference 1. The tank pressure at the end of dis charge was not specified. Thus, the first step in the analysis is to determine the optimal initial pressure. The objective is to determine the discharge pressure that minimizes the total weight or the total volume of the regenerative braking system.

An ideal system which is defined by a 100% charge-discharge efficiency will be assumed for the initial analysis. Three cases will be analyzed under the constraint of a maximum pressure of 5000 psia. Case #1 will size the storage to equal to the kinetic energy of the truck at 32 mph. Case #2 will size the storage equal to the kinetic energy at 64 mph. Case #3 will size the system for 64 mph but will be used at 32 mph for braking, and then use thermal enhancement from the exhaust to heat the storage at a constant volume to a pressure of 5,000. Thus, the work recovering expansion will occur at a higher pressure than the work absorbing compression.

The first step for Case #1 was to determine the best pressure of the compressed air or nitrogen in the initial condition. Accordingly, a reference case was developed by hand calculation for an initial pressure of 15 psia. The computations were then programmed for a parametric analysis with initial pressures ranging from 15 up to 4500 psia. The results are presented in Table I.

Table I

Case #1 Analysis for 32 mph as a Function of Initial Pressure

Regenerative Breaking Analysis for 8500 lb Truck Travelling at 32 mph
Using Hydraulic Coupled Compressed Air Storage

Vehicle Specifications and assumptions:

Weight (lb)= 8500
V (mph)= 32 V(ft/sec)= 46.93
Pmax(psia)= 5000
Fuel ($/gal) = 1.20
Engine efficiency= 0.20
Heat Value (Btu/gal)= 120000.0

Nitrogen and Fluid Constants and Specifications:

T1(F)= 40 T1 (R)= 500
Cp (Btu/lbm-R)= 0.248 Density(lb/ft^3)= 50
K= 1.4
Cv (Btu/lbm-R)= 0.177

Kinetic Energy:

KE(ft-lbf)= 292551.1
KE(Btu)= 376.03

Maximum Savings per stop ($/stop)= 0.0188

P min (psia)	T2 (R)	T2 (F)	N2 m (lbm)	V1 (ft^3)	V2 (ft^3)	V dis (ft^3)	Fluid m (lbm)	Vtotal (ft^3)	Mtotal (lb)
15	2629.0	2169.0	1.00	12.72	0.20	12.52	626.13	25.25	627.13
30	2156.7	1696.7	1.28	8.18	0.21	7.96	398.19	16.14	399.47
50	1863.6	1403.6	1.56	5.96	0.22	5.74	286.83	11.70	288.38
100	1528.9	1068.9	2.06	3.95	0.24	3.71	185.37	7.68	187.43
250	1176.8	716.8	3.14	2.40	0.28	2.12	105.95	4.52	109.08
500	965.3	505.3	4.56	1.75	0.34	1.41	70.46	3.16	75.02
1000	791.9	331.9	7.27	1.39	0.44	0.95	47.55	2.34	54.82
1500	705.3	245.3	10.34	1.32	0.56	0.76	38.06	2.08	48.40
2000	649.6	189.6	14.19	1.36	0.71	0.65	32.61	2.01	46.79
2500	609.5	149.5	19.38	1.48	0.90	0.58	28.98	2.06	48.36
3000	578.6	118.6	27.02	1.72	1.20	0.53	26.35	2.25	53.37
3500	553.6	93.6	39.57	2.16	1.68	0.49	24.34	2.65	63.91
4000	532.9	72.9	64.49	3.09	2.63	0.45	22.73	3.54	87.22
4500	515.3	55.3	138.92	5.91	5.48	0.43	21.42	6.34	160.34

The first observation is that the initial pressure of 15 psia would require an unacceptably high volume of 12.52 cubic feet and combined fluid and gas mass of 627 lb. Further review of Table I shows the best initial pressure would be 2000 psia. This would result in an acceptable combined tank volume of two cubic feet and a combined fluid and gas mass of 47 pounds.

Figures 3 and 4 help explain why the optimal pressure initial pressure is a surprisingly high pressure of 2000 psia. Figure 3 shows that for a very low initial pressure a large displacement volume results in a high mass of hydraulic fluid. At a very high initial pressure like 4500 psia a large mass of nitrogen is needed. Thus the total mass which is the sum of the fluid and the gas is minimal at about 2000 psia initial pressure.

Figure 4 shows that the required fluid volume decreases with initial pressure while the nitrogen tank volume first decreases and then increases again at very high initial pressures. The volume minimizing initial pressure is again found to be 2000 psia. Thus, an initial pressure of 2000 psia will store the kinetic energy of the vehicle while minimizing both the total volume and total mass of the regenerative braking system.

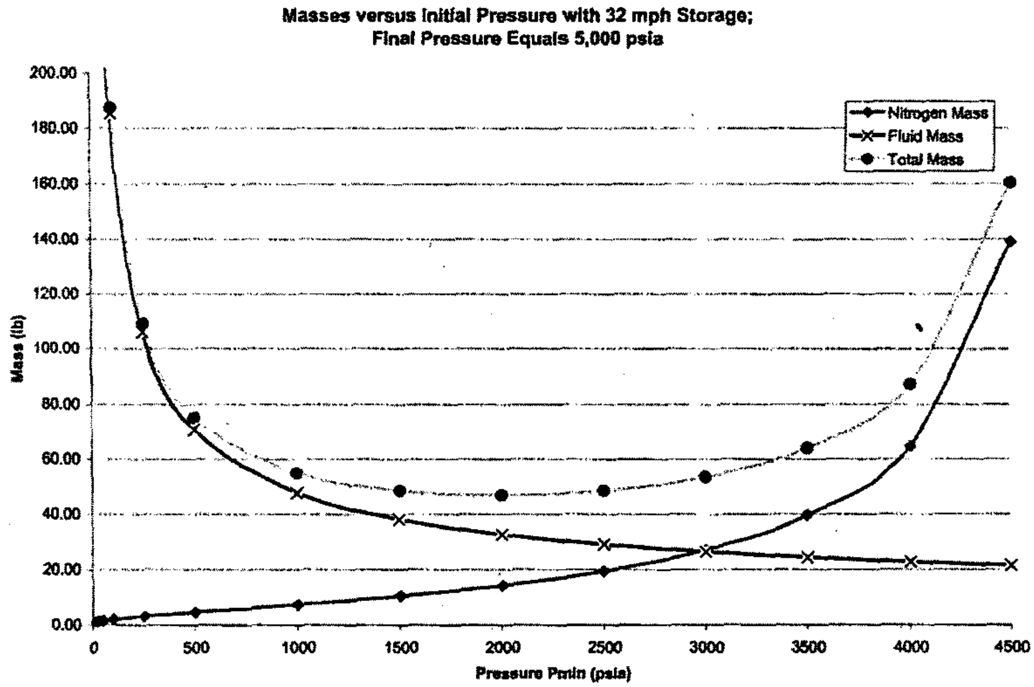

Figure 3. Mass versus Initial Pressure

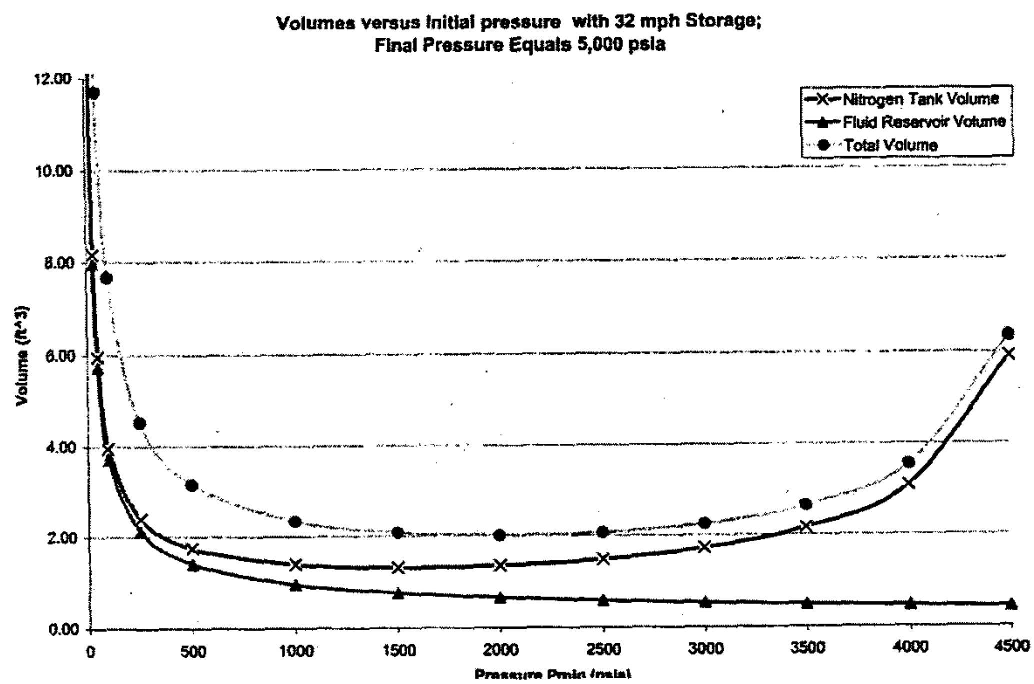

Figure 4. Volume versus Initial Pressure

The analysis is repeated for Case #2 and is presented in Table II. This system stores the kinetic energy of the truck at 64 mph rather than 32 mph as in Case #1. Doubling the speed increases the kinetic energy by a factor of four and thus the energy storage requirement in terms of volume and mass also increases by a factor of four. The optimal initial pressure remains 2000 psia for a maximum charged pressure of 5000 psia.

Finally, Case #3 is presented along with Case #1 and #2 on a pressure versus gas volume diagram in Figure 5. Case #3 which sizes the system for 64 mph but operates from 32 mph can be idealized as a four process cycle corresponding to the classical Otto cycle. Process 1 to 2 is reversible adiabatic compression while the vehicle is stopping. Process 2 to 3 is heating at constant volume by the engine exhaust while the vehicle is stopped. Process 3 to 4 is discharge of energy from storage to the vehicle during acceleration. Process 4 to 1 is cooling to the ambient temperature while the vehicle is running.

Table II. Case #2 Analysis for 64 mph as a Function of the Initial Pressure

Regenerative Breaking Analysis for 8500 lb Truck Travelling at 64 mph
Using Hydraulic Coupled Compressed Air Storage

Vehicle Specifications and assumptions:

Weight (lb)= 8500
V (mph)= 64 V(ft/sec)= 93.87
Pmax(psia)= 5000
Fuel ($/gal) = 1.20
Engine efficiency= 0.20
Heat Value (Btu/gal)= 120000.0

Nitrogen and Fluid Constants and Specifications:

T1(F)= 40 T1 (R)= 500
Cp (Btu/lbm-R)= 0.248 Density(lb/ft^3)= 50
K= 1.4
Cv (Btu/lbm-R)= 0.177

Kinetic Energy:

KE(ft-lbf)= 1170204.44
KE(Btu)= 1504.12

Maximum Savings per stop ($/stop)= 0.0752

P min (psia)	T2 (R)	T2 (F)	N2 M (lbm)	V1 (ft^3)	V2 (ft^3)	V dis (ft^3)	Fluid M (lbm)	Vtotal (ft^3)	Total M (lbm)
15	2629.0	2169.0	3.99	50.89	0.80	50.09	2504.52	153.98	2508.51
30	2158.7	1698.7	5.13	32.70	0.85	31.86	1592.77	64.58	1597.90
50	1863.6	1403.6	6.23	23.83	0.89	22.95	1147.31	46.78	1153.54
100	1528.9	1068.9	7.25	15.80	0.97	14.83	741.49	30.83	748.74
250	1176.8	716.8	12.55	9.61	1.13	8.48	423.78	18.08	436.33
500	965.3	505.3	18.25	6.99	1.35	5.64	281.83	12.62	300.08
1000	791.9	331.9	29.09	5.57	1.78	3.80	190.20	9.37	219.29
1500	705.3	245.3	41.36	5.28	2.23	3.04	152.23	8.32	193.59
2000	649.6	189.6	56.75	5.43	2.62	2.81	130.42	8.04	187.17
2500	608.5	148.5	77.54	5.94	3.62	2.32	115.91	8.25	193.45
3000	578.6	118.6	108.07	6.90	4.79	2.11	105.40	9.00	213.47
3500	553.6	93.6	158.29	8.66	6.71	1.95	97.35	10.60	255.65
4000	532.9	72.9	257.98	12.34	10.53	1.82	90.94	14.16	348.90
4500	515.3	55.3	556.68	23.64	21.92	1.71	85.68	25.35	641.36

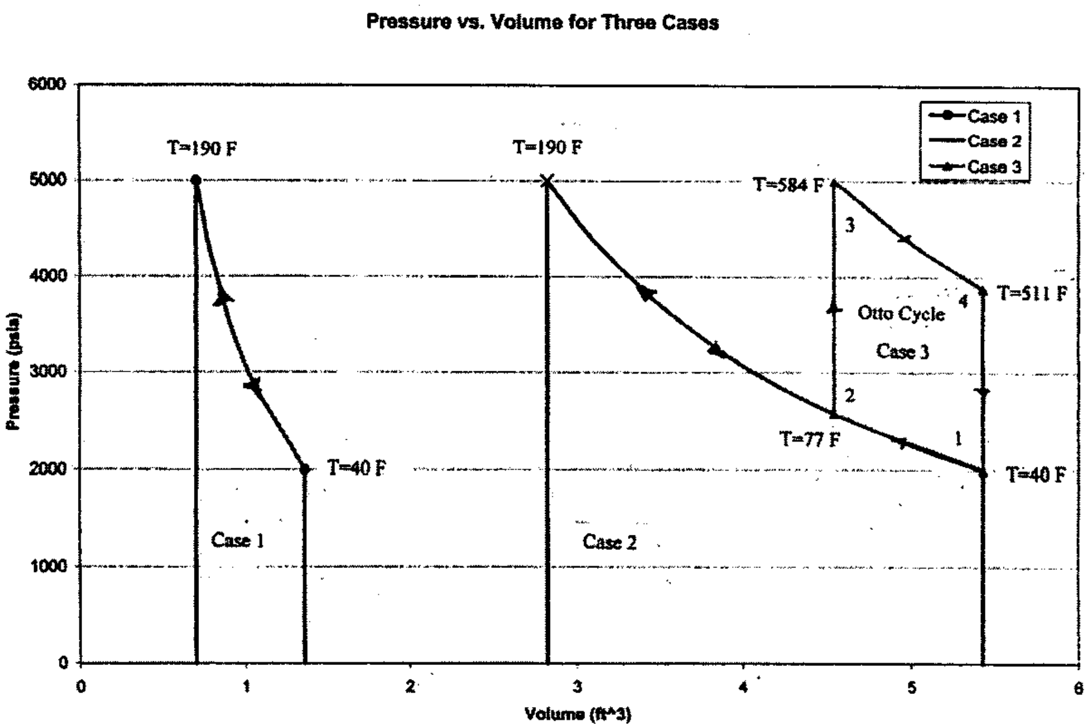

Figure 5. Pressure versus Volume Analysis for the Three Cases

Table III presents the corresponding properties at each point and the heat, change of internal energy and work for each process in this enhanced storage Otto cycle.

Table III
Property and Process Table for Enhanced Storage Otto Cycle

Thermal Enhanced Property Table

Point	P (psia)	Temp (F)	Temp (R.)	Volume (ft^3)	U (Btu/lb)
1	2000	40.0	500	5.431	88.57
2	2574	77.4	537.4	4.535	95.20
3	5000	583.7	1,043.7	4.535	184.89
4	3884	511.1	971.1	5.431	172.02

Thermal Enhanced Process and Cycle Table

Process		Q(Btu)	m(u-u) (Btu)	W (Btu)
Stopping	1–2	0	376.03	-376.03
Heating	2–3	5089.82	5089.82	0
Starting	3–4	0	-730.30	730.30
Cooling	4–1	-4735.55	-4735.55	0
Net		354.27	0	354.27

The amount of stored energy for the enhanced storage nominally doubles from 376 Btu to 730 Btu. This means that the enhanced regenerative cycle can ideally result in accelerating the vehicle to 44.6 mph rather than 32 mph without the thermal enhancement as shown in Table IV.

Table IV
Pre Stop Speeds and Ideal Recovered Speeds

Summary

Case	System	Prestop Speed	Recovered Speed
1	Ideal Regenerative	32	32
2	Ideal Regenerative	64	64
3	Ehanced Regenerative	32	44.6

A remaining question is the amount of time required to heat the gas by 5,089 Btu from the exhaust during the stopped condition. Assuming an idle fuel consumption of 1 gallon per hour or 120,000 Btu per hour it would take about three minutes for the constant volume heating from 77 F to 583 F. This is longer than the typical stopping time which normally will not exceed one minute.

3. Results, Conclusions and Discussion

The hydraulic coupled and compressed gas regenerative braking system described in this paper seems to have advantages relative to often proposed electric or flywheel systems for heavy vehicles such as garbage trucks that typically already have a hydraulic system for loading and compacting and also have a highly stop and go driving pattern.

The thermally enhanced regenerative system can virtually double the amount of stored energy. Its evaluation and design also provide an interesting academic exercise. However, the time required for heating the gas from the exhaust is considerably longer than the typical time that such a vehicle would be stopped.

The initial pressure was found to be optimal at 2000 psia for Cases #1 and #2 without thermal enhancement. A different optimal initial pressure may exist for Case #3 with the thermally enhanced storage. A lower initial pressure would yield a higher compression ratio and thus a higher efficiency of the Otto cycle. A higher initial pressure would require less heat from the exhaust and thus the thermal enhancement process while the vehicle is stopped could be performed in less time.

While any type of storage is challenging, the systems analyzed in this paper should be competitive and in some situations preferable to electric or mechanical flywheel storage.

Acknowledgement

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Reference

1. Jim Motavalli, "From Stops, Energy to Go", New York Times Automobiles Section, Page F1, March 22, 2002.