yOPTIMAL DESIGN OF HIGHWAY CRASH CUSHIONS

A Senior Scholars Thesis

by

HAO ZENG

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2011

Majors: Civil Engineering & Applied Mathematics

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Approved by:

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Director for Honors and Undergraduate Research:	Sumana Datta

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ABSTRACT

The Optimal Design of Highway Crash Cushions. (April 2010)

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Crash cushions are deployed at gores and in front of other fixed objects along the roadway when their proximity to the travelled way poses an unacceptable risk to the travelling public. A crash cushion is intended to act as a deformable shield that causes an errant vehicle to decelerate more slowly, dramatically reducing the potential severity of injuries suffered by vehicle occupants. This paper formulates the design of such a system as a constrained optimization problem which is solved using contemporary search techniques implemented in commercial software. The methodology is demonstrated on high-molecular-weight, high-density polyethylene (HMW/HDPE) cylinders arrayed in a single line to form a crash cushion which carries the trade name REACT® 350 system. The wall thickness of each cylinder in the array is treated as a design variable. The diameter of the cylinders and the total number in the array are treated as parameters and not directly addressed by the optimization process. A simple one dimensional array of masses and nonlinear springs are used to simulate the dynamic interaction of a vehicle and the cushion system and yield a value for the Occupant Impact Velocity (OVI) and Ride Down Acceleration (RDA) for a given set of cylinder parameters. Prescribed upper limits on OVI and RDA under impact of two standard mass vehicles form the four implicit, nonlinear constraints in the problem. The objective function to be minimized is the total weight of the barrels used over all cylinders in the system. Optimization results are presented for one REACT® system reported in the literature.

ACKNOWLEDGMENTS

I am heartily thankful to my supervisor, Dr. Harry Jones, whose encouragement, guidance and support from the initial to the final draft enabled me to develop an understanding of the subject.

Also, this thesis would not have been possible without the support from my girl friend, Xin Lin, who used her talented and accomplished Photoshop mastery to help me extract crash curves from published papers

Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of the project.

NOMENCLATURE

GA	Genetic Algorithm
HMW/HDPE	High-Molecular-Weight, High-Density Polyethylene
NCHRP	National Cooperative Highway Research Program
OVI	Occupant Impact Velocity
RDA	Ride Down Acceleration
TTI	Texas Transportation Institute
t	Time
TxDot	Texas Department of Transportation
FHWA	United States Federal Highway Administration

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CHAPTER I

INTRODUCTION

Crash cushions, or impact attenuators, are placed on urban freeways at sites where head-on impact between a vehicle and a fixed object on the roadway might occur. Crash cushions act as a deformable shield to dissipate kinetic energy of the vehicle and cause an errant vehicle to decelerate more slowly, dramatically reducing the potential severity of injuries vehicle occupants may suffer. The kinetic energy of an impacting vehicle is transformed into energy absorbed by crushable objects making up the cushion, bringing the vehicle to a controlled stop. Early crash cushions were constructed in the 1960s with discarded 55 gallon steel barrels as the crushable objects, arranged in 6 to 10 rows of 1 to 3 barrels per row. Crash cushions currently in use on America's National Highway System are frequently proprietary systems incorporating newer materials and more sophisticated hardware to fuse the individual crushable units together in such a way that all can participate in energy dissipation during a crash event, even when the vehicle impacts the system in other than a head-on orientation. Figures 1 and 2 [5] are typical contemporary crash cushions installed at gores on an urban freeway. Many contemporary crash cushions systems still use barrel-like objects for energy dissipation, as seen in the below figures below.

This thesis follows the style of International Journal of Crashworthiness.

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Figure 1.

Commercial crash cushion

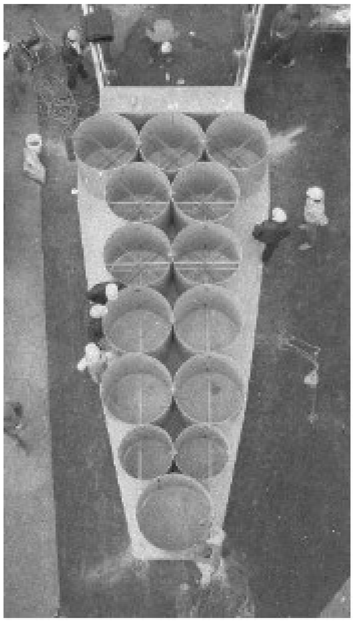


Figure 2.

Constitution of a commercial crash cushion

In the design of a crash cushion system, the most influential elements are the barrel-like crushable objects – how many rows, how many objects per row, and what physical dimensions each object should have are decisions faced by the designer. I formulated the selection of the object dimensions as an optimization problem and solved it using commercially available software. Manufacturers of proprietary systems [2,4] often release limited information in order to protect their trade secrets and this makes it difficult to assemble data needed to predict the behaviour during a crash event. In the case of the REACT 350® system published information was supplemented with several assumptions as explained in subsequent sections of their thesis. I address the optimal design of a Narrow REACT® 350 system [2,4] used in locations where the roadway section receiving the cushion is so narrow that each row can accommodate only a single barrel. Figures 3 and 4 [6] show two Narrow system installations, one with 4 and the other with 6 barrels.

Figure 3.

React 350.6 system

Figure 4.

React 350.4 system

The barrel are 4 ft. tall and have a 36 in. diameter. The wall thickness of each barrel may, in general, differ from the others in the array. The wall thickness have a very strong effect on the safety performance of the system, as well as being a significant factor in the cost of the system.

This thesis is organized into chapters that explain how computer simulation is used to predict the behaviour of a crash cushion, how I obtained the properties of React 350 barrels needed by the simulation and then how the barrel wall thickness were optimized to improve the designs currently in use.

CHAPTER II

OPTIMIZATION

High-molecular-weight, high-density polyethylene (HMW/HDPE) barrels

High-molecular-weight, high-density polyethylene possesses certain beneficial characteristics, like high ductility, high toughness and high tensile strength, all of which make this material attractive for use in crash cushions [2]. A cylinder made of HMW/HDPE is able to deform absorb kinetic energy from an impacting vehicle, helping to decelerate it more gently and then to spring back to essentially its pre-crash dimensions without permanent damage. This is a highly coveted property that greatly reduces maintenance cost where crash episodes are frequent. Additionally, for most impact events, there is no down period when the cushion is unable to protect motorists while it awaits repair.

Simulating the behaviour of a crash cushion begins with a crush curve for the barrels. This is an experimentally established relationship between force applied to the barrel and the reduction in its diameter (the “crush”). Data to generate a crush curve can be obtained by placing a barrel on its side in a universal testing machine and applying a sequence of increasing measured forces along a diameter line while measuring the change in diameter at each force. If the barrel material is highly strain rate sensitive, the rate of application of the forces to the barrel may be matched to anticipated vehicle impact velocities [1]. This affect, however, appears minimal in HMW/HDPE barrels and is not addressed in this work. Figure 5 depicts a typical crush curve where total force F is plotted against the reduction in barrel diameter Δ.

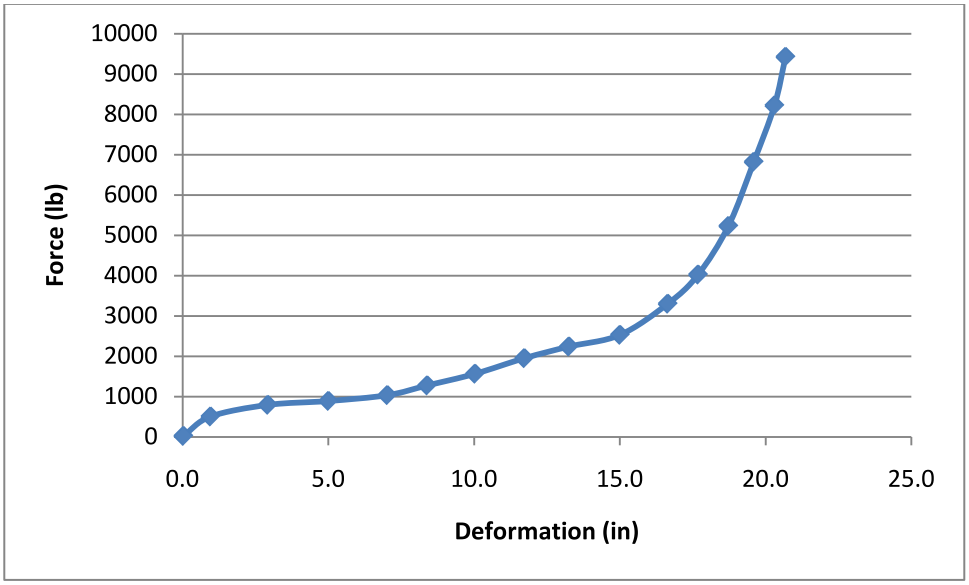


Figure 5.

Force vs. deformation of a typical HMW/HDPE barrel

The specifics of the curve are affected by barrel dimensions; most notably, barrel length, diameter and wall thickness. For example, the magnitude of the force needed to make Δ equal to the initial barrel diameter (the barrel is completely flattened) increases with barrel length and wall thickness.

Test Data for only one 36 in. diameter barrel and wall thickness 1.108 in. was given in the reference [3]. I used the established result from linear elasticity to propose the following model to account for wall thickness and barrel length on the crush curve.

$$F_{\text{int}erpolated} = F_{\exp erimental} \times \left(\frac{t_{\text{int}erpolated}}{t_{\exp erimental}}\right)^3$$

$$F_{\text{int}erpolated} = F_{\text{int}erpolated} \times \left(\frac{L_{real}}{L_{\exp erimental}}\right)$$

$t_{\exp erimental}$: wall thickness of the 36 in. diameter barrel

$t_{\text{int}erpolated}$: wall thickness of the interpolated barrel

$L_{\exp erimental}$: barrel length in experiment

L_{real} : barrel length in React 350 system

The excel plot in Figure 6 shows the data from reference [3] for a 36 in. diameter barrel, 8in. long and having a wall thickness of 1.108 in. for this barrel of this particular dimension.

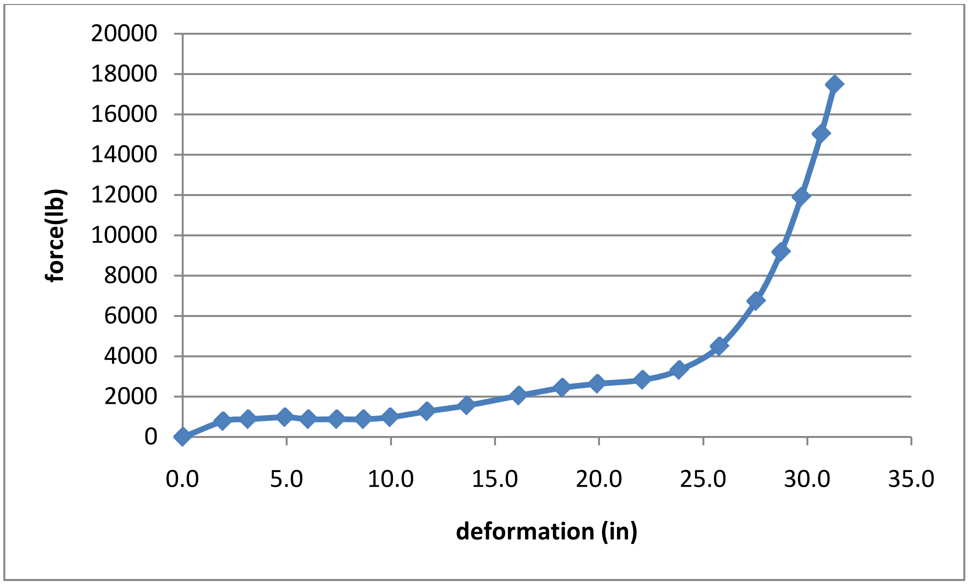


Figure 6.

Force vs. deformation of a barrel
with 36 in. diameter, 8 in. long and a wall thickness 1.108 in.

Predicting crash cushion performance

A crash cushion must be certified by the United States Federal Highway Administration (FHWA) before it can be used on the national highway system. The certification process requires full scale crash testing of a system following the procedures prescribed in reference [1] and which exhibit performance measures below prescribed limits. The most demanding of the certification tests are head-on collisions by 4,400 lb. and 1,800 lb. vehicles travelling at 60 mph. The former vehicle class represents the light truck/SUV class found on American highways, while the latter is typical of the compact car classification. Cushions that perform satisfactorily for one vehicle class may fail to satisfy performance criteria for the other. In fact, design choices to facilitate heavy vehicle deceleration may be detrimental in a collision event involving a compact car. A crash tests performed for certification purposes uses an instrumented vehicle which records various physical quantities that are useful in characterizing the severity of a crash event. The two severity measures used by the FHWA are obtained from accelerations measured at the center of mass of the vehicle. The first, called the Occupant Impact Velocity (OIV), is a surrogate measure of the velocity a driver's torso would experience at impact with the steering wheel. It is obtained by first integrating the vehicle acceleration to obtain a vehicle velocity record from which the OIV is computed by the process described in [1]. The second is called the peak ridedown acceleration (PRA). The correlation between occupant injuries and the magnitude and duration of occupant deceleration during a crash event are well established. The PRA is a surrogate measure of the damaging deceleration an occupant experiences and is based on the deceleration record of the vehicle. The details of its calculation are also found in [1], but it can be succinctly described as the largest average vehicle deceleration over a 10 millisecond period from crash initiation until the vehicle comes to rest. To receive certification, the OIV cannot exceed 12m/s and the PRA can't exceed 20gs in the crash of either the 4,400 lb. and 1,800lb vehicles.

Computer simulation of highway crash events is an important tool in the design of safety systems such as the crash cushion. [2], among others, have demonstrated that a simple one dimensional dynamic model in which the vehicle is represented by a single lump mass with a front spring and each barrel by a lump mass and nonlinear spring can predict with acceptable precision the OIV and PRA in a head-on impact.

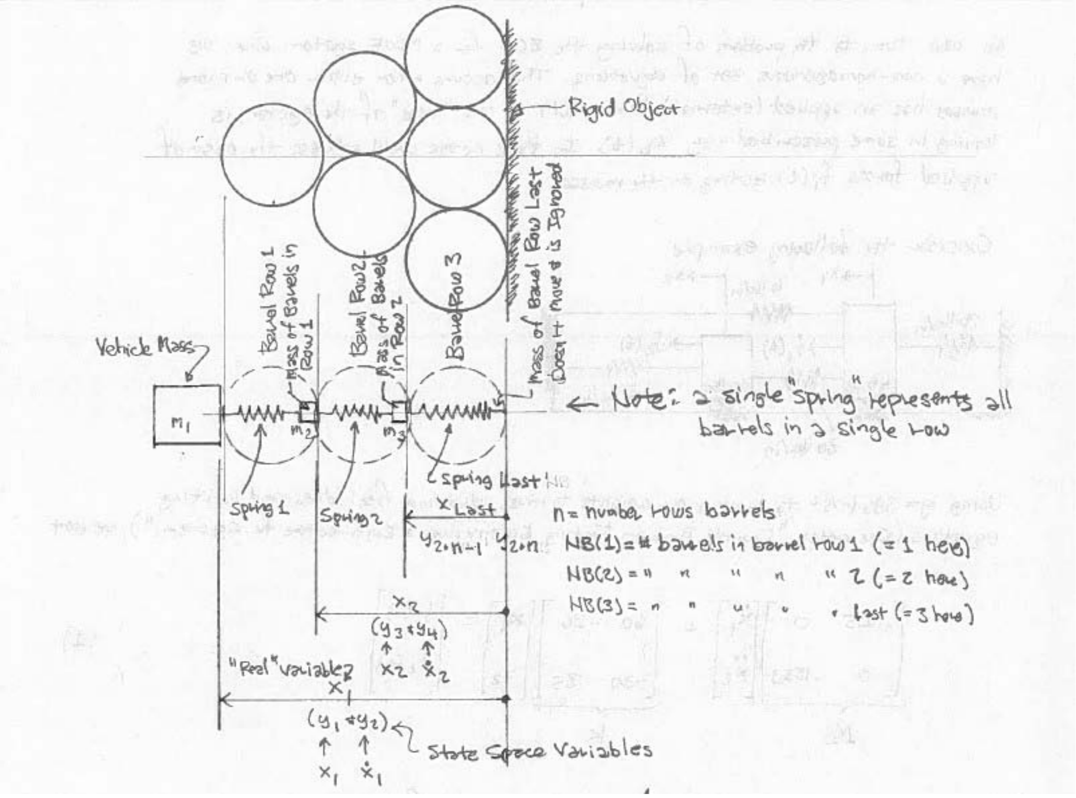


Figure 7.

One dimensional dynamic model

Figure 7 presents the variables used in such a simulation. The variable y_1 is the position of the bumper of the impacting vehicle measured with respect to the rigid restraint behind the last barrel in the system. This restraint may be the object being shielded, such as the gore at a freeway off- ramp, or one that is intentionally constructed with embedded pipes when collision damage to the protected object is desired. An additional y variable is required for each barrel added to the line. First and second derivatives of the ys give velocity and acceleration of the barrel masses, while the crush of a barrel can be computed from adjacent ys . The crush curve for a barrel can then be used to compute the force it exerts on the barrel immediately ahead and behind it. These forces can then be used to write a summation of forces on each barrel mass to create the governing equations of motion for the system. Using the impact velocity of the vehicle as the initial velocity of the vehicle mass and the undeformed diameters of the barrels to obtain initial position y values, the equations of motion can be integrated forward in time until the vehicle velocity reaches zero. After the simulation is completed, the record of the first time-derivative of y_1 provides the data needed to compute the OIV, and the second time-derivative can be used to obtain the RDA. Figure 8, 9 and 10 show a series of results from a typical simulation in Matlab.

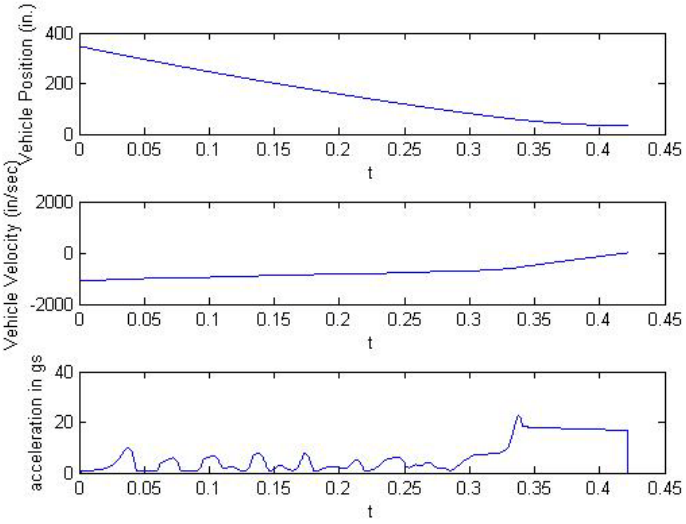


Figure 8.

Vehicle crash profiles including vehicle position, vehicle velocity and vehicle deceleration

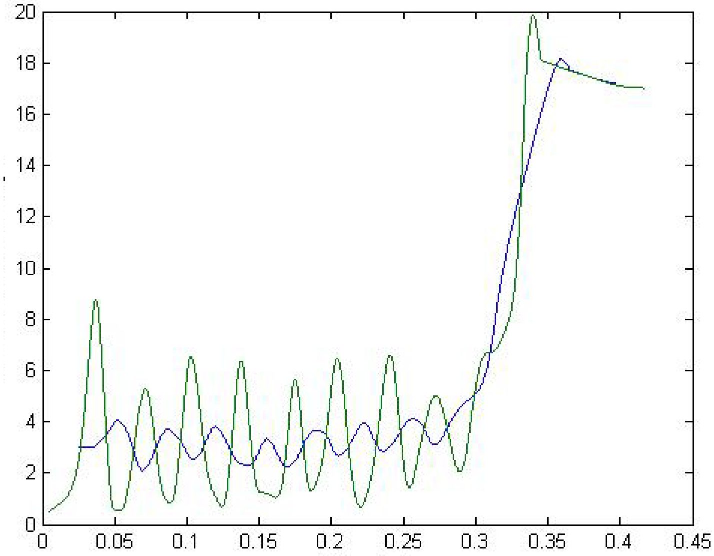


Figure 9.

Vehicle deceleration vs. 50ms and vehicle deceleration vs. 10ms

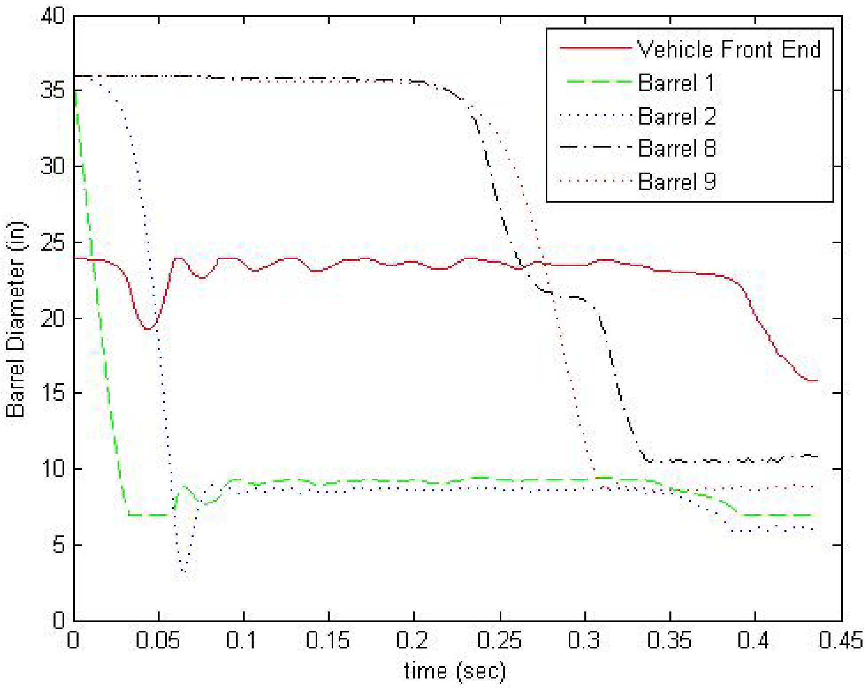


Figure 10.

Vehicle front crush and barrel deformation vs. time

Optimization of the REACT® 350 system

The optimal design of a crash cushion system of HMW/HDPE barrels can be cast as a nonlinearly constrained optimization problem. First, the number of rows of barrels and their diameter are selected. With these values set, the barrel thickness for each row is taken as a design variable. The crush curve that yields inter-barrel forces is completely defined once barrel thickness is prescribed. The problem can then be stated as

$$Minimize \sum_{i=1}^{NB} barrelweight^{(i)}$$

$$
\begin{aligned}
&\mathit{Subject\ \ to}:\\
&OIV_{4409} <= 12m/s\\
&RDA_{4409} <= 20g\\
&OIV_{1808} <= 12m/s\\
&RDA_{1808} <= 20g
\end{aligned}
$$

Extensive experimentation with 36 in. diameter barrels indicated that with randomly generated thickness between lower and upper bounds of 0.5 in. and 2.0 in. for all barrels [2]. In the literature, React® 350.9 system provided a design satisfies all four of the constraints. Using this as an initial feasible point, a search for an optimal solution to the above problem could be undertaken.

This optimization problem made more computationally demanding by the fact that the constraints are implicit functions of the design variables. As such, the advantages of using (or even existence of) gradient information to guide the search for an optimal solution is precluded. Moreover, the evaluation of constraints is computationally very expensive since it requires a simulation of the system. Problems of this sort are well suited for the new generation of direct search strategies based on evolutionary concepts, with the genetic algorithm (GA) being by far the most broadly used.

The Matlab programming language was used to create the simulation described above, and the Matlab Global Optimization Toolbox allowed application of a professionally developed GA implementation within the same language. Although this GA has a penalty based mechanism for incorporating nonlinear constraints into a problem, we found that creating our own penalty function was far more efficient.

CHAPTER III

RESULTS

Various array of RECT 350 barrels were optimized. Table 1 shows types of crash cushion systems that were optimized.

Table 1.

Types of React system optimized

REACT 350.9	REACT350.4	8 Row Optimal Design

Two set of system, 8 rows and 9 rows, were optimized for the case of head-on impacts at 60 mph from both 4,400 lb. and 1,800 lb vehicles. A barrel diameter of 36 in. was used. The other system, 4 rows were optimized for the case of head-on impacts at 45 mph from both 4,400 lb. and 1,800 lb vehicles. The GA algorithm was then used to find the optimal value of the individual barrel thickness for each barrel. Presented below are results for React 350.9 system and React 350.4 system.

React 350.9 system

Before simulation, a comparison test was conducted between our model and the model published in the paper [2] using the React 350.9 system, the results for both heavy and light vehicles have been closely matched. Thus, for the React 350.4 system, the optimized barrel thickness would serve for a reasonable comparison purpose.

A number of GA searches were performed, each starting from a different randomly generated initial population. A later independent search process may inherit the optimal result from the previous run if the previous run lead to optimal results, which satisfied constraints. The initial barrel thickness values were drawn with equal likelihood from the range of 0.8 in. and 1.4 in. Tables 2 and 3 presents the optimal solution found and the sum of the barrel weight over the 9 rows. Figure 11 is the optimizer windows, which shows the 50 generations of optimization process for React 350.9 system.

Table 2.

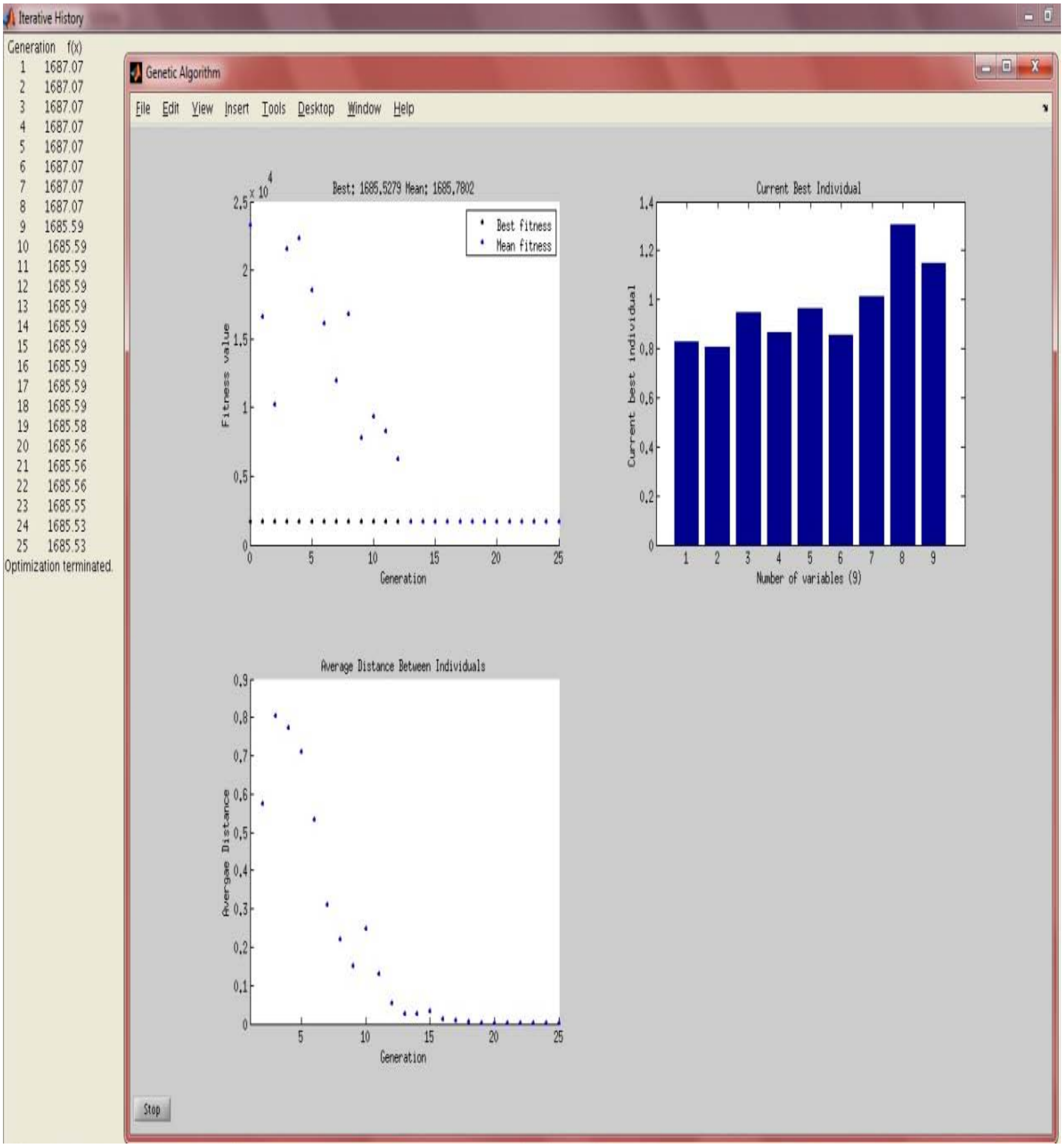
Comparison between barrel thicknesses of optimal design and barrel thicknesses in use for React 350.9 system

Optimal Barrel thickness (in.)	Original design thickness (in.)
0.8	0.828
0.8	0.807
0.9	0.948
0.9	0.867
1	0.965
1	0.857
1.2	1.014
1.3846	1.306
1.3846	1.148

Table 3.

Comparison between original weight and optimal weight for React 350.9 system

	Optimal design weight (lbs)	Original design weight (lbs)
Total weight	1685.5	1802



```
Generation   f(x)
  1     1687.07
  2     1687.07
  3     1687.07
  4     1687.07
  5     1687.07
  6     1687.07
  7     1687.07
  8     1687.07
  9     1685.59
 10     1685.59
 11     1685.59
 12     1685.59
 13     1685.59
 14     1685.59
 15     1685.59
 16     1685.59
 17     1685.59
 18     1685.59
 19     1685.58
 20     1685.56
 21     1685.56
 22     1685.56
 23     1685.55
 24     1685.53
 25     1685.53
Optimization terminated.
```

Figure 11.

Optimization window of React 350.9 system

After verification process, the OIVs for both heavy and light vehicle are 6.138 m/s and 8.176 m/s respectively, both of which are below the 12 m/s design limit. And Maximum Ridedown acceleration are 19.87 g and 13.23 g for heavy and light vehicle, both of which are within 20 g design limit.

Optimal design of 8 rows barrel system

Since there is not an original design for 8 rows in React 350.9 system, this set of optimal system was not designed for comparison purpose. Instead, it shows the possibility of reducing the length while still keeping the same safety factors. I have discovered that using the simulation conditions for React system for 9 rows, a optimal design of 8 rows exists. The 8 rows barrel system not only satisfy the required constraints to keep the safety priority, but also the system has less weight than React 350.9 system, thus reducing the manufacturing cost.

2 GA search were performed over 8 rows of barrel. Table 4 and 5 presents the findings.

Table 4.

Comparison between barrel thicknesses of optimal design and barrel thicknesses in use for 8 rows optimal design

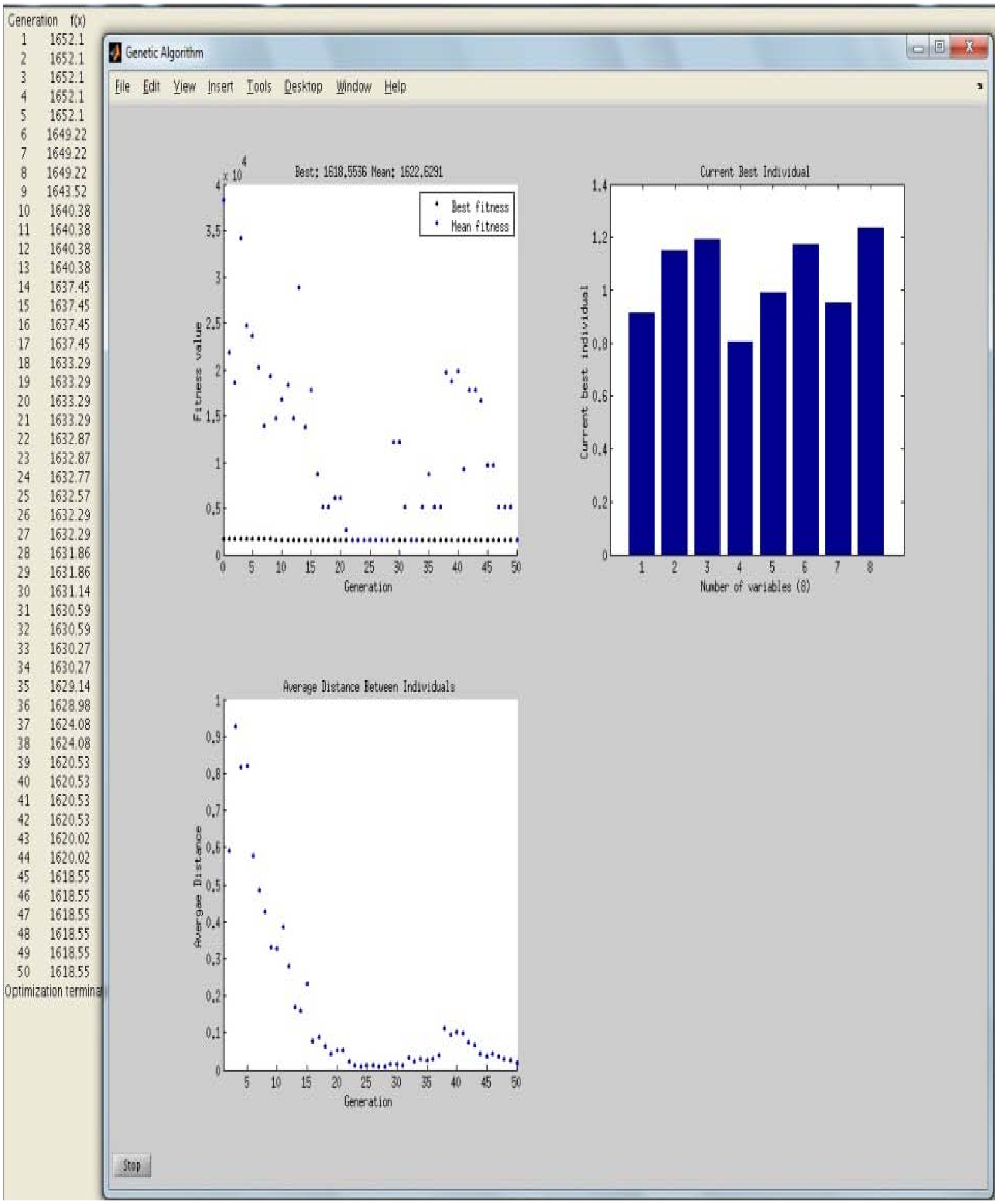
Optimal Barrel thickness (in.)	Original design thickness (in.)
0.913	0.979
1.149	1.099
1.192	0.965
0.803	0.987
.991	1.012
1.173	1.109
.952	1.005
1.237	1.267

Table 5.

Comparison between original weight and optimal weight for 8 rows optimal design

	Optimal design weight (lbs)	Original design weight (lbs)
Total weight	1618.55	1621.5

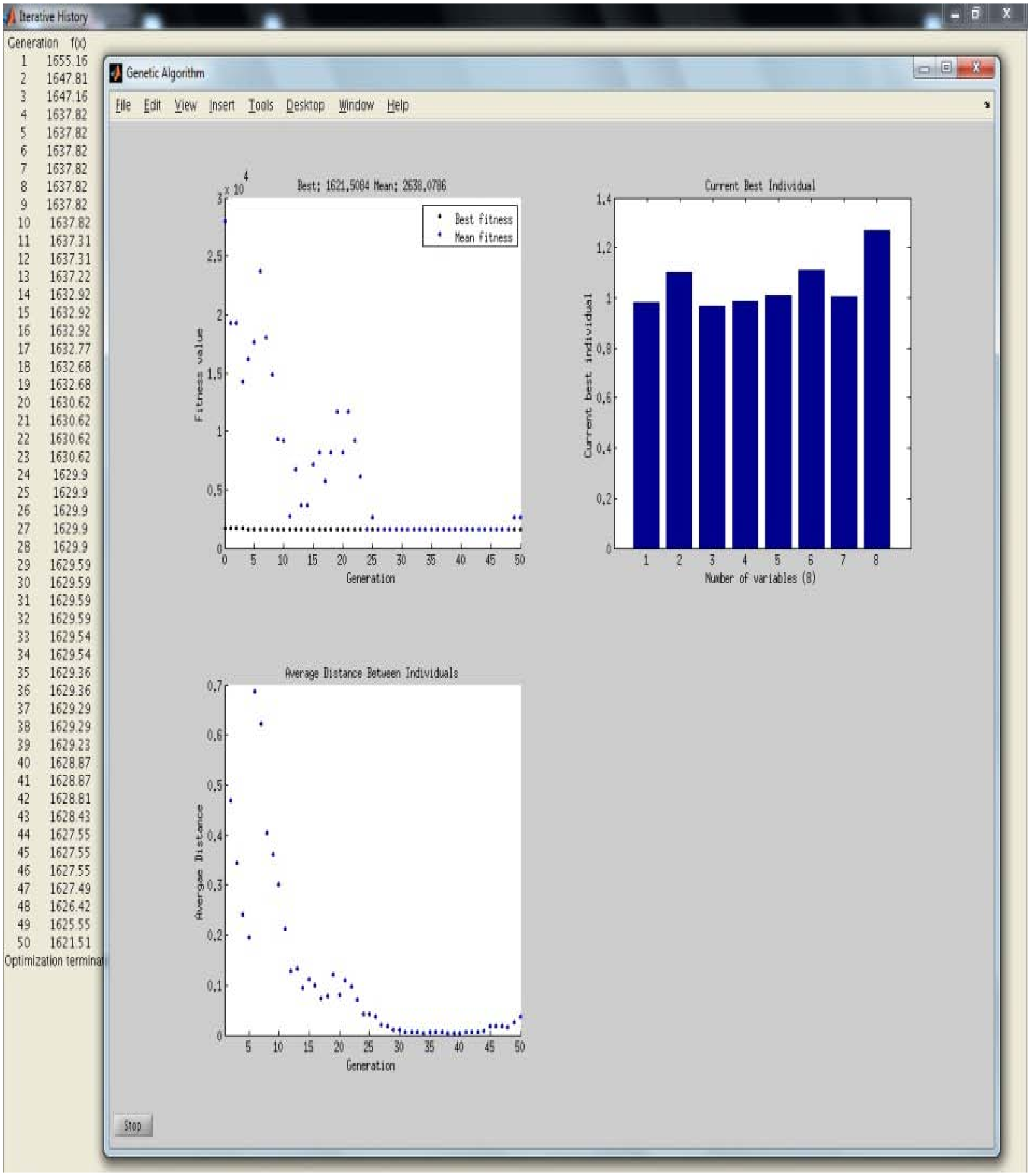
Figures 12 and 13 are the optimizer windows, which shows the 50 generations of optimization process.



```
Generation   f(x)
    1     1652.1
    2     1652.1
    3     1652.1
    4     1652.1
    5     1652.1
    6    1649.22
    7    1649.22
    8    1649.22
    9    1643.52
   10    1640.38
   11    1640.38
   12    1640.38
   13    1640.38
   14    1637.45
   15    1637.45
   16    1637.45
   17    1637.45
   18    1633.29
   19    1633.29
   20    1633.29
   21    1633.29
   22    1632.87
   23    1632.87
   24    1632.77
   25    1632.57
   26    1632.29
   27    1632.29
   28    1631.86
   29    1631.86
   30    1631.14
   31    1630.59
   32    1630.59
   33    1630.27
   34    1630.27
   35    1629.14
   36    1628.98
   37    1624.08
   38    1624.08
   39    1620.53
   40    1620.53
   41    1620.53
   42    1620.53
   43    1620.02
   44    1620.02
   45    1618.55
   46    1618.55
   47    1618.55
   48    1618.55
   49    1618.55
   50    1618.55
Optimization terminat
```

Figure 12.

First run of optimization window of optimal design for 8 rows system



```
Generation   f(x)
   1      1655.16
   2      1647.81
   3      1647.16
   4      1637.82
   5      1637.82
   6      1637.82
   7      1637.82
   8      1637.82
   9      1637.82
  10      1637.82
  11      1637.31
  12      1637.31
  13      1637.22
  14      1632.92
  15      1632.92
  16      1632.92
  17      1632.77
  18      1632.68
  19      1632.68
  20      1630.62
  21      1630.62
  22      1630.62
  23      1630.62
  24       1629.9
  25       1629.9
  26       1629.9
  27       1629.9
  28       1629.9
  29      1629.59
  30      1629.59
  31      1629.59
  32      1629.59
  33      1629.54
  34      1629.54
  35      1629.36
  36      1629.36
  37      1629.29
  38      1629.29
  39      1629.23
  40      1628.87
  41      1628.87
  42      1628.81
  43      1628.43
  44      1627.55
  45      1627.55
  46      1627.55
  47      1627.49
  48      1626.42
  49      1625.55
  50      1621.51
Optimization terminat
```

Figure 13.

Second run of optimization window of optimal design for 8 rows system

Separate simulations performed showed that both design are satisfied the safety factors. Table 6 lists the simulation results.

Table 6.

Simulation results for two optimal designs for 8 rows of barrel

	Design 1		Design 2	
	OIV	MaxRideDownGs	OIV	MaxRideDownGs
Heavy vehicle	6.289 m/s	19.77 g	6.264 m/s	19.93 g
Light vehicle	8.97 m/s	13.04 g	8.637 m/s	13.05 g

React 350.4 system

Before simulation, a comparison test was conducted between our model and the model published in the paper [2] using the React 350.4 system, the results for both heavy and light vehicles have not been closely matched. Thus, for the React 350.4 system, the optimized barrel thickness would not serve for a reasonable comparison purpose.

A quite few of GA searches were performed, each starting from a different randomly generated initial population. The initial barrel thickness values were drawn with equal likelihood from the range of 0.8 in. and 1.4 in. We increased the MaxRideDownGs for the heavy vehicle here in order to achieve a better design, and also this allow us to further study the behaviour of GA.

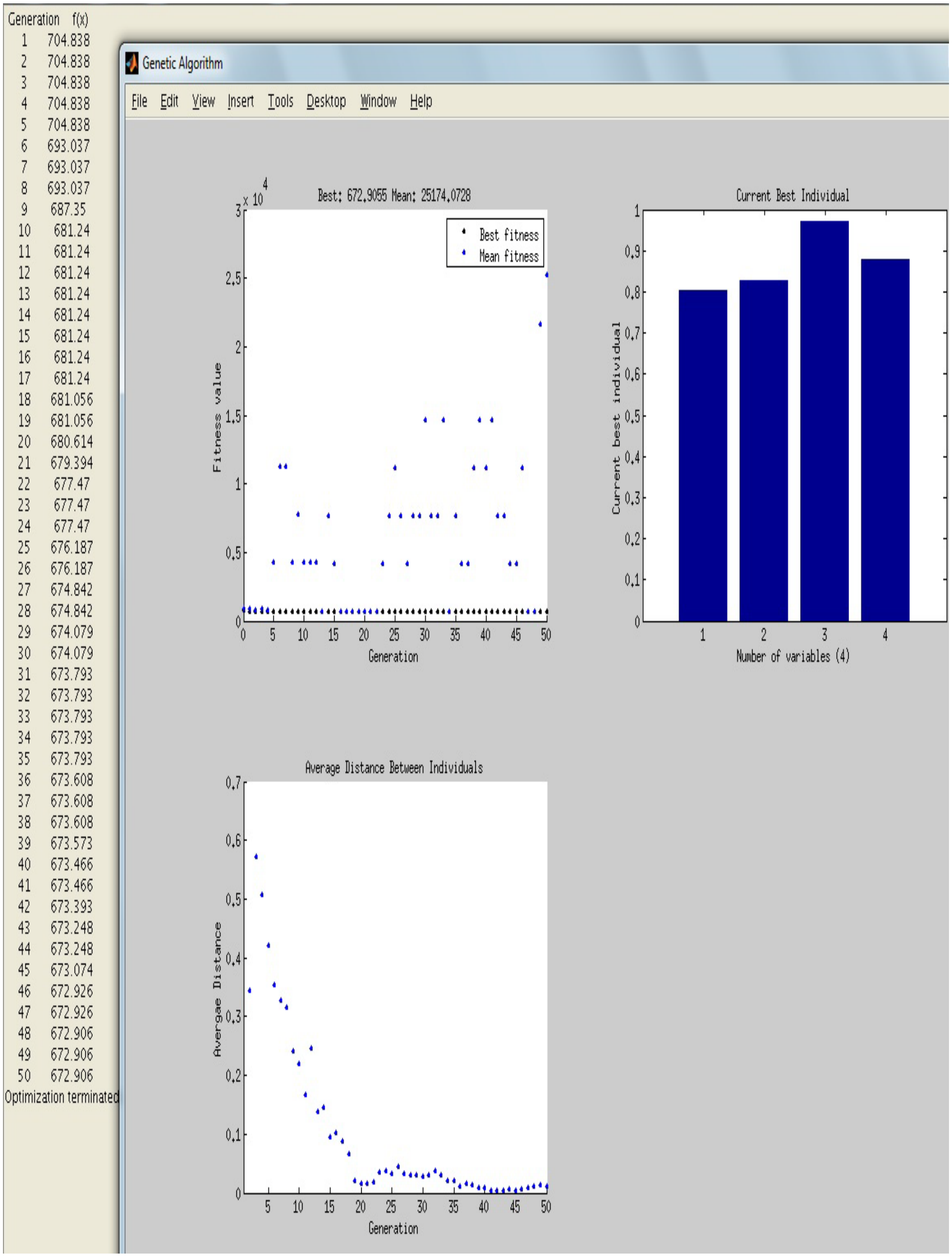
Table 6 and 7 presents the optimal solution found and the sum of the barrel weight over the 4 rows.

Table 7.

Comparison profiles between optimal design and React 350.4 system with ridedownG as 23 g

Optimal Barrel thickness (in.)	Original design thickness (in.)		Optimal design weight (lbs)	Original design weight (lbs)
0.802	1.714	Total weight	672.9	954.8
0.826	1.385	When the maximum ridedownG constraint over heavy vehicle was raised up to 23 g		
0.971	1			
0.878	0.9			

Figure 14 is the optimizer window, which shows the 25 generations of optimization for optimal design result in Table 7.



```
Generation   f(x)
  1   704.838
  2   704.838
  3   704.838
  4   704.838
  5   704.838
  6   693.037
  7   693.037
  8   693.037
  9    687.35
 10    681.24
 11    681.24
 12    681.24
 13    681.24
 14    681.24
 15    681.24
 16    681.24
 17    681.24
 18   681.056
 19   681.056
 20   680.614
 21   679.394
 22    677.47
 23    677.47
 24    677.47
 25   676.187
 26   676.187
 27   674.842
 28   674.842
 29   674.079
 30   674.079
 31   673.793
 32   673.793
 33   673.793
 34   673.793
 35   673.793
 36   673.608
 37   673.608
 38   673.608
 39   673.573
 40   673.466
 41   673.466
 42   673.393
 43   673.248
 44   673.248
 45   673.074
 46   672.926
 47   672.926
 48   672.906
 49   672.906
 50   672.906
Optimization terminated
```

Figure 14.

Optimization window of React 350.4 system with ridedownG as 23 g

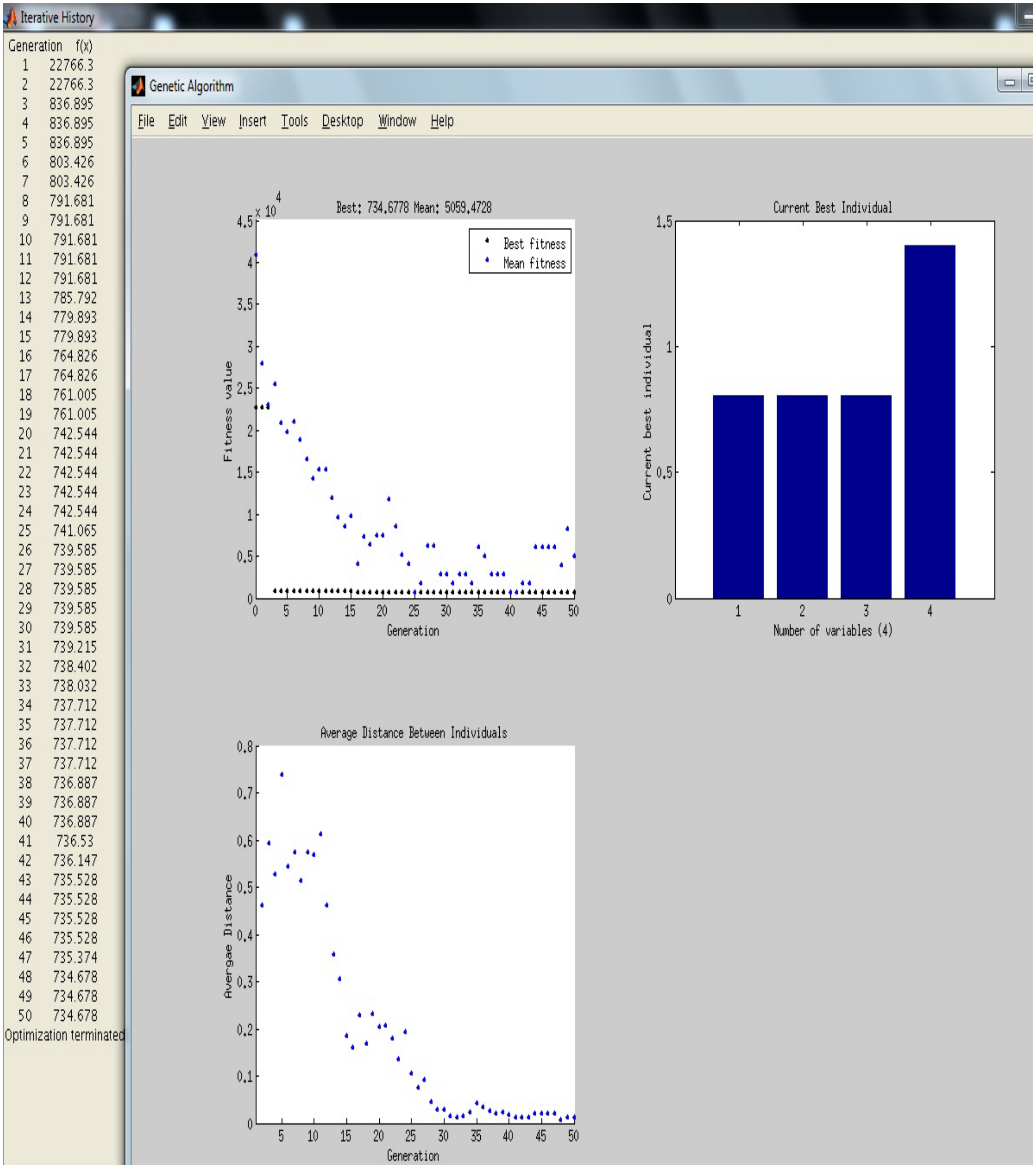
Table 8 presents the optimal solution found and the sum of the barrel weight over the 4 rows when the maximum ridedownG constraint for heavy vehicle was raised up to 21.5 g.

Table 8.

Comparison profiles between optimal design and React 350.4 system with ridedownG as 21.5 g

Optimal Barrel thickness (in.)	Original design thickness (in.)		Optimal design weight (lbs)	Original design weight (lbs)
0.806	1.714	Total weight	734.7	954.8
0.802	1.385	When the maximum ridedownG constraint for heavy vehicle was raised up to 21.5 g		
0.804	1			
1.401	0.9			

Figure 15 is the optimizer window, which shows the 25 generations of optimization for the optimal design result in Table 6.



```
Generation   f(x)
  1   22766.3
  2   22766.3
  3   836.895
  4   836.895
  5   836.895
  6   803.426
  7   803.426
  8   791.681
  9   791.681
 10   791.681
 11   791.681
 12   791.681
 13   785.792
 14   779.893
 15   779.893
 16   764.826
 17   764.826
 18   761.005
 19   761.005
 20   742.544
 21   742.544
 22   742.544
 23   742.544
 24   742.544
 25   741.065
 26   739.585
 27   739.585
 28   739.585
 29   739.585
 30   739.585
 31   739.215
 32   738.402
 33   738.032
 34   737.712
 35   737.712
 36   737.712
 37   737.712
 38   736.887
 39   736.887
 40   736.887
 41   736.53
 42   736.147
 43   735.528
 44   735.528
 45   735.528
 46   735.528
 47   735.374
 48   734.678
 49   734.678
 50   734.678
Optimization terminated
```

Figure 15.

Optimization window of React 350.4 system with ridedownG as 21.5 g

CHAPTER IV

CONCLUSIONS

New sets of barrel thickness are proposed for React 350 systems for 9 rows and 4 rows, and independent design and they are presented in Result Section. Simulations of specified testing speeds and vehicle weights in accordance with NCHRP Report 350 are conducted in MATLAB® and are presented in the tables below. The following implications are discovered through this study:

- Whether GA is highly dependent on initial randomly generated population is dependent on mutation rate.

- Although local optimum of distribution of barrel thickness exists and their distribution is not purely monotone increasing or decreasing, GA is still able to provide the best optimal solution with a unique distribution of Barrel thickness.

- Local optimum can be alternatively useful to design crash cushions and satisfy complex real site requirement as long as it satisfy the four constraints.

- The non-constraint problem with penalty functions proves to have greater efficiency and accuracy than the constraint problem for GA.

- This optimized problem is highly parameter-sensitive, any slight change made to inputs will lead to a remarkable change; this makes the design able to be easily adjusted for further studies.

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